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Thermal comfort assessment for naturally ventilated classrooms during summer in composite climate of Jaipur

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Abstract: Background: Considering the importance of comfort requirements in classrooms and the fast growing number of institutes for higher education in India, classroom thermal comfort needs serious attention.
Methodology: Thirty classrooms in three university buildings with a total of 900 students participated in field study: 729 males, 171females. The transverse type surveying was used. Thermal environment variables were recorded according to Class-II protocol of ASHRAE 55. We statistically analyzed occupant's thermal sensations, preferences and acceptability for prevailing indoor conditions.
Objective: Assessing occupants' thermal comfort conditions in classrooms under naturally ventilation mode during peak summer season in composite climate of India.
Results: About 80 % subject's responses were found in comfort band (±1 sensations) during field study in naturally ventilated classrooms. The mean comfort temperature, as predicted by Griffith method was 29.8 ˚C.
Conclusion: The results show that the subjects in naturally ventilated classrooms are comfortable at temperatures different from those suggested by the current Indian and international codes/standards.

I. INTRODUCTION

More than a third of India's electricity consumption is in residential and commercial sectors and the electricity demand of these sectors has been growing at more than 8% annually [1]. In both of these sectors, a significant portion of the energy demand is from buildings while more than half the buildings India will have in 2030 are yet to be built [2]. All these statistics and estimations prove a great urgency for energy saving measures in Indian buildings. Naturally conditioned buildings consume less energy in comparison to conditioned buildings and thermal comfort is an important aspect of these typologies other than security and safety [3]. Occupants from naturally conditioned buildings are more flexible towards varying outdoor environmental conditions and use various adaptive controls to make the indoor environment thermally comfortable [4], [5], [6].

Designers in India still have to follow the National Building Code of India,2005 (NBC) [7] for defining thermal comfort range in these buildings which is based on 1992 version of ASHRAE 55 which is now superseded by ASHRAE 55-2013. However, the standards such as ISO 7730 [8] and ASHRAE 55-2013 [9], which primarily define human thermal comfort conditions, are internationally accepted and play a crucial role in building sustainability [10], [11]. According to ASHRAE 55-2013, thermal comfort is defined as that "condition of mind which expresses satisfaction with the thermal environment" and is assessed by subjective evaluation. ASHRAE 55 also includes the adaptive comfort concept supported by large number of field experiments conducted by researchers for ASHRAE RP 884 databases [4]. The energy saving potential in the building will be enormous by switching over to these adaptive comfort standards [12].

India had 14.6 million students enrolled in its 544 universities (or equivalent institutes) and 31,324 colleges residential buildings and are of great interest to architects and designers for sustainability in this sector. Further, data shows that both the number of institutions and enrolments in them are growing at more than 5% annually [13]. Thermal condition in classrooms has to be considered carefully mainly because of the high occupant density in classrooms and because of the negative influences that an unsatisfactory thermal environment has on learning and performance [14]. Several studies done for naturally ventilated classroom occupants in tropical regions have borne out significant levels of adaptation amongst occupants [15-17]. These studies have come up with comfort zones between 22 and 31℃ and neutral temperatures in the range of 26.5-29℃. Mishra et al. [18] carried out a field

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study inside a naturally ventilated laboratory in the tropical climatic region of India with total of 121 acclimatized subjects during the months of spring. Results show a comfort zone broader than 10 ˚C as well as a high correlation between indoor comfort temperature and outdoor conditions.

Considering the importance of comfort requirements in classrooms and the fast growing number of institutes for higher education in India, classroom thermal comfort needs serious attention. Our study was aimed at finding the level of thermal comfort and acceptance amongst students of an undergraduate course during their regular semester classes. Our main objectives for this study were:

A. Assessing occupants' thermal comfort conditions in classrooms under naturally ventilation mode.

B. Determining the neutral temperature and range of temperature found most suitable by these occupants.

II. STUDY METHODOLOGY

A. Location, buildings surveyed and sample size description

1) Field study location: The field study of thermal comfort was performed in the composite climate of Jaipur (26.82 °N, 75.80 °E and 390m mean sea level) for three university campus buildings in peak summer months from 4th April to 25th June 2015. Jaipur- located in the western Indian state of Rajasthan and known for its cultural heritage background. Meteorological conditions under this climate vary from scorching hot during summer to chilling cold during winter. Summer peak temperature soars above 45 ºC, and then falls to about 4 ºC in winter. In present study, three peak summer months were selected for study i.e. April, May, and June. During these months, conditions are very harsh, and average mean monthly temperature remains above 33 ˚C [19]. Maximum discomfort conditions occurred during this period and it creates the challenges for architects and building designers to make indoor environment conditions comfortable during early design phase of buildings.

2) Buildings surveyed: Thirty classrooms in three university buildings named, GYV, SKT and GIT, located within a radius of 10 km of the area, were selected for the field study as shown in Figure 1. Buildings considered for the study were naturally ventilated at the time of field surveying and no heating or cooling equipments were in use. All the selected buildings were multi-storeyed (~ G+3 - G+5 floors) and wherever possible surveys were conducted on all floors. The floor area of the classrooms surveyed varied between 80-250 m^2. The details of surveyed buildings and indoor environmental parameters observed are shown in Table 1 The surveyed buildings were naturally ventilated and provide adaptive controls for the occupants such as opening or closing of windows and doors, control of ventilators, the operation of fan and fan speed regulators, etc. Ceiling fans serve area of occupancy during class hours with speed controllers.

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Figure 1 Pictorial view of surveyed building and their plan layout.

Table 1 Building details and indoor parameters observed during field study.

Building Name	No. of floors surveyed	Floors area of classrooms (m2)	T_o		T_a		T_g		V_a		RH		$I_{cl,tot}$ (clo)
			Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean
GYV	G+ 3	100-400	35.8	4.38	29.6	3.3	30.3	3.4	0.4	0.19	37	7.0	0.41
SKT	G+4	75-200	33.5	3.20	30.0	2.9	30.8	2.9	0.69	0.38	40	4.5	0.39
GIT	G+2	100-300	35.5	2.95	31.7	2.2	32.0	2.7	0.70	0.25	42	2.8	0.42
All			34.9	3.50	30.4	3.0	30.7	3.1	0.6	0.3	40	5.5	0.40

T_o: Outside Temperature; T_a: Indoor air temperature; T_g: Indoor globe temperature; V_a: Indoor air velocity; RH: Indoor relative humidity; $I_{cl,tot}$: Total clothing value

3) *Sample size Description:* All subjects were found to be belonged to Indian sub-continent, though they came from different provinces. All were well acclimatized to the composite climate of Jaipur for more than one year and were in the age group of 18-26 years. The sample size varied from months to months i.e. April, May and June and in different building campuses. A total of 900 students participated in field study: 729 males (~81%), 171females (~29%). Male students and female students found in average age of 20.7 years (SD =2.6) and 19.6 years (SD =2.3), respectively.

B. Data collection

1) *Objective Data: Indoor& outdoor environmental parameters:* The thermal comfort objective parameters measured were air temperature, mean radiant temperature, air velocity and relative humidity. Thermal environment variables were recorded at the height of ~1.1 m from the floor level according to Class-II protocol of ASHRAE 55[7]. The measurement period took at least 1h in each classroom. Calibrated quick-response digital instruments were used to measure the indoor environment. The measurements were recorded after the instruments and their readings had stabilized in the surveyed area at least for 10 min. The following four indoor environmental parameters were measured: air temperature (Ta), relative humidity (RH), globe temperature (Tg) and air speed (Va). Table 2 demonstrates the details of instruments used in this study to measure the indoor conditions.

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Table 2 Details of instruments used during field study.

S. No.	Parameter	Instrument	Make	Range	Accuracy
1	Outdoor temperature	Weather station (MNIT,Jaipur)	Virtual instrumentation	-40-123.8 ºC	± 0.5 ºC(5-40 ºC)
2	Indoor air temperature	HMT 103CTH	HTC	-10-50 ºC	± 0.5 ºC
3	Globe temperature	Black painted tennis ball with thermometer	HTC	0-100 ºC	± 0.5 ºC
4	Relative humidity	HMT 103CTH	HTC	0-100% RH	±(1.0 % RH+0.7 % reading)
5	Air velocity	Vane Anemometer (AVM 8)	HTC	0-5 m/s	±(0.03 m/s+4 reading)
6	Lighting level	LX-101A	HTM	0-50000 lux	±5% of 2 digit

The outdoor environmental data consisting of temperature and humidity for the entire duration of the survey was extracted from a meteorological website [25].

2) *Subjective questionnaire:* The students were from different regions of India and from different cultural & bilingual backgrounds. The language for developed questionnaire and the medium of instruction in all classes was English, and most of the students found comfortable with it. The questionnaire thus developed was based on McCartney and Nicol [20] and used by various studies [15,16,20,21] conducted in this tropical subcontinent. The transverse type surveying was used. Section-A of the questionnaire consists of thermal sensation and preference votes for environment conditions such as air temperature, relative humidity, air velocity and overall comfort on ASHRAE seven-point sensation scale(+3 to -3) and five-point preference scale(+2 to -2), respectively. Table 3 shows the thermal sensation and preferences scales used in this comfort study.

Table 3 Surveys questionnaire of sensation and preferences for indoor parameters

Description of scale					
Scale Value	Temperature	Humidity	Air Velocity	Overall Comfort	Thermal acceptance
−3	Cold	Very Dry	Very still		
−2	Cool	Moderately Dry	Moderately still	Very uncomfortable	
−1	Slightly cool	Slightly Dry	Slightly still	Uncomfortable	
0	Neutral	Neutral	Neutral	Comfortable	
+1	Slightly warm	Slightly humid	Slightly moving	Slightly comfortable	Acceptable
+2	Warm	Moderately Humid	Moderately moving	Very comfortable	Unacceptable
+3	Hot	Very Humid	Much moving		

A brief introduction was given to subjects about study and necessity, before their filling out the questionnaire to minimize the chances of human error in understanding of the survey.

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3) *Assessing clothing insulations and activity level:* For clothing insulation and metabolic rates, we used the standard checklists provided in ASHRAE-55 and ISO -7730. Students mostly attired in western style outfits: combinations of shirts/t-shirts, trousers/jeans. Clo-values for Indian women clothing including the cotton salwar –kameej, saari, etc. which are not available in ASHRAE 55 and ISO 7730, were taken from other India specific studies [16, 22]. Girls were found either in western outfits, or they preferred the traditional ensemble of salwar- kameez with traditional *Dupatta*. Extra insulation for a dupatta [30] was added when found in use along with the salwar-kameez. The mean activity of the subjects was observed to be nearly sedentary activity, i.e. 1.2 met (1 met=58.2 W/m^2), and it shows that the subjects were mostly seated and doing writing or light work according to ISO 7730

III. RESULTS AND ANALYSIS

A. *Indoor and outdoor parameters observed*

1) *Outdoor environment conditions:* Jaipur city lie close to hot and dry desert area of India, so, the temperature during summer season often remains very high and above comfort limits. This adds the intense discomfort conditions during summer especially in peak summer months like April, May and June. Direct normal radiation during this period adds to the heat discomfort. Figure 2 presents the outdoor and indoor temperature and relative humidity conditions observed during study period. Daily mean temperature and relative humidity during the three-month survey period varied between 26˚C - 38˚C and 20-70 %.The daily outdoor diurnal swing of temperature was 8-17 ˚C during study period characteristic of hot and dry summer period.

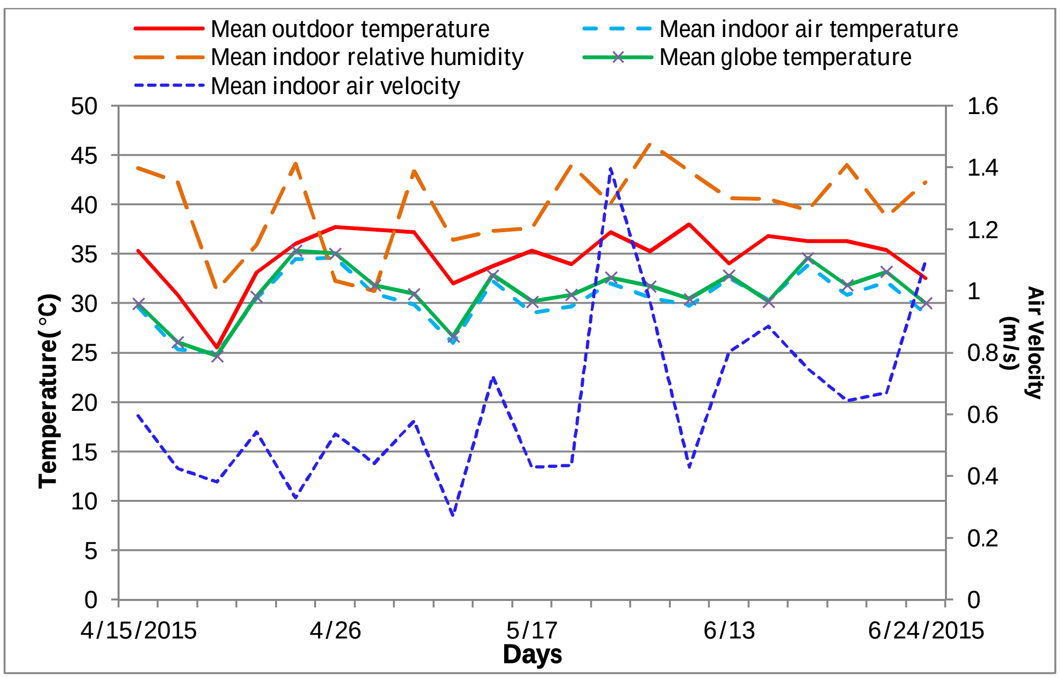

Figure 2 Details of daily mean outdoor and indoor environmental parameters observed during field study

2) *Indoor environmental conditions:* The statistical summary of indoor and outdoor environmental parameters in naturally ventilated classrooms during the entire study period is shown in Table 4. The naturally ventilated buildings experienced a higher fluctuation in mean indoor temperature ranged between 26.6 ˚C and 37˚C, across different classrooms and buildings. “Windows opening” and “Fan on” were commonly used adaptive actions exercised by occupants during classrooms. During field study, all classroom spaces were found under “fan on” condition. Subsequently, mean air velocity was observed to be higher during the study period. Under ceiling fan operation, the mean air velocity in classrooms ranged between 0.4 - 0.9 m/s . Increased rate of air velocity at high temperature and humidity leads to increase in skin evaporation heat exchange. Madhavi [16] and Kumar et al.[21] also observed similar results for summer season during their field study in naturally ventilated buildings in composite climate of India.

Table 4 Description of indoor and outdoor environmental parameters observed during field study.

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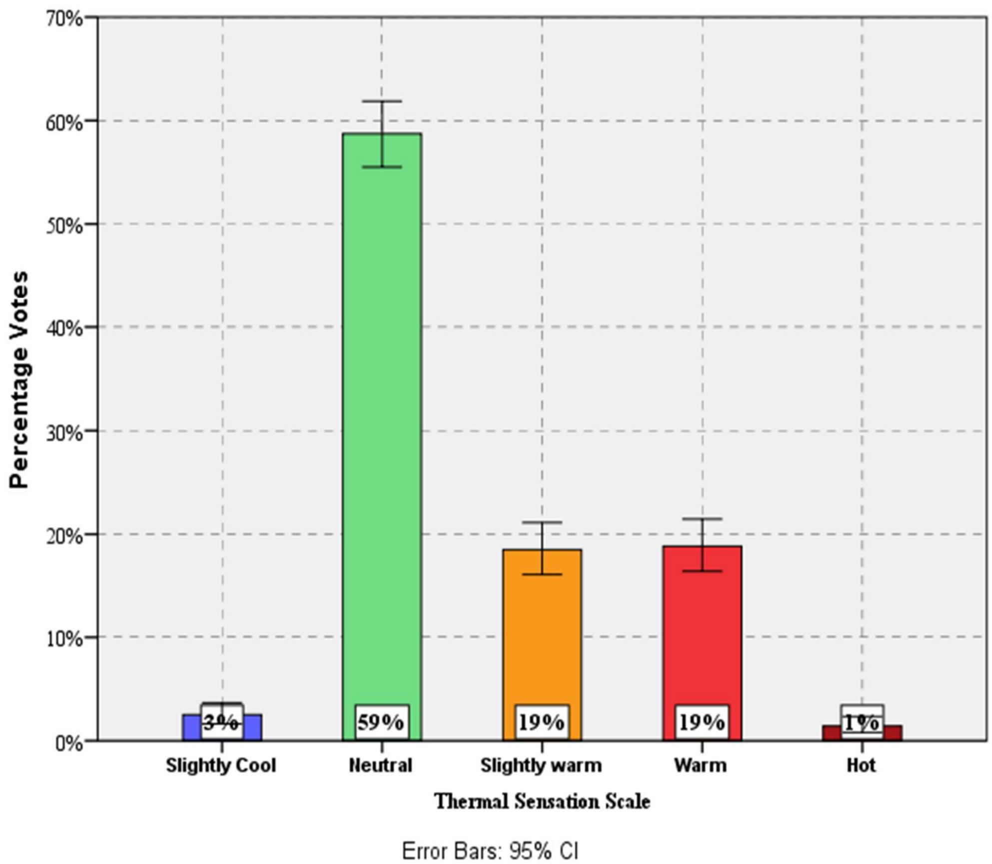
Parameters	Summer season							
	April		May		June		All months	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Sample size	350		260		290		900	
T_o (°C)	35.0	3.65	34.3	2.77	34.0	2.08	34.9	2.83
T_a (°C)	30.4	3.24	29.1	2.97	28.5	3.62	30.4	3.03
T_g (°C)	30.6	3.40	29.3	3.00	29.0	3.60	30.7	3.14
RH (%)	37	6.9	41	4.5	41	4.7	39.4	5.5
Va(m/s)	0.47	0.21	0.55	0.40	0.60	0.47	0.59	0.31
$I_{cl,tot}$ (clo)	0.34	0.15	0.37	0.12	0.35	0.14	0.36	0.15
Activity(Met)	1.2	0.09	1.1	0.08	1.1	0.05	1.2	0.06

T_o :Outdoor temperature (°C); T_a :Indoor air temperature(°C); T_{op}: Indoor operative temperature; T_g: Indoor globe temperature (°C); RH: Indoor relative humidity; V_a: Indoor air velocity(m/s); $I_{cl,tot}$:Total clothing insulation(clo); Met: Metabolic activities.

B. Subjective evaluation: sensation & preferences

1) *Thermal sensation & preferences:* The occupants responded to the question "*How do you feel the present temperature of this room*?" on ASHRAE seven-point scale. A comfortable subject usually voted within the central three categories of the scale. Figure 3 shows the frequency distribution of thermal sensation (TSV), thermal preference (TPV), and thermal acceptability (TA) for naturally ventilated classrooms for all data combined, with error bars indicating 95% confidence. About 80 % subject's responses were found in comfort band (±1 sensations) in all naturally ventilated classrooms during summer. In addition, only 19% subjects swayed away from the central band on the scale (TSV_{mean} (all data, all buildings) =+0.58, SD=0.89) and perceived conditions uncomfortable. The mean of thermal sensation vote in different buildings was found towards slightly warmer side of thermal sensation scale.



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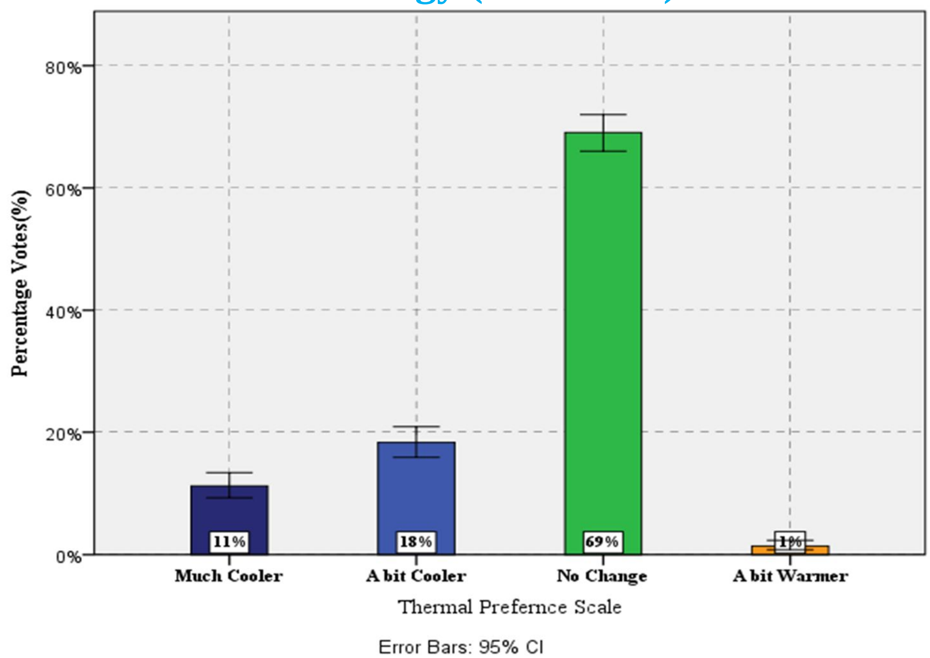

Figure 5 Distribution of (a) thermal sensation votes and (b) preference votes at 95% CI.\

In response to thermal sensations recorded, the corresponding thermal preferences were captured with the question "How would you prefer to feel?" Mean thermal preference(TP_{mean}) was found to be around -0.53 (SD=0.71) for all buildings and all data combined. **Figure 6** shows the cross distribution of the thermal preference vote on thermal sensation votes using ASHRAE seven point and five point scales. In present study, more than 90 % of the respondents preferred'0. No change' for their '0. neutral' thermal sensation; 20% of the respondents who described their thermal sensation as '1. Slightly warm' preferred '1. slightly cooler' conditions and 4% preferred 'Much cooler' conditions. A preference for cooler environments was evident throughout the survey, even while a significant number of subjects were voting on the cooler side of the sensation.

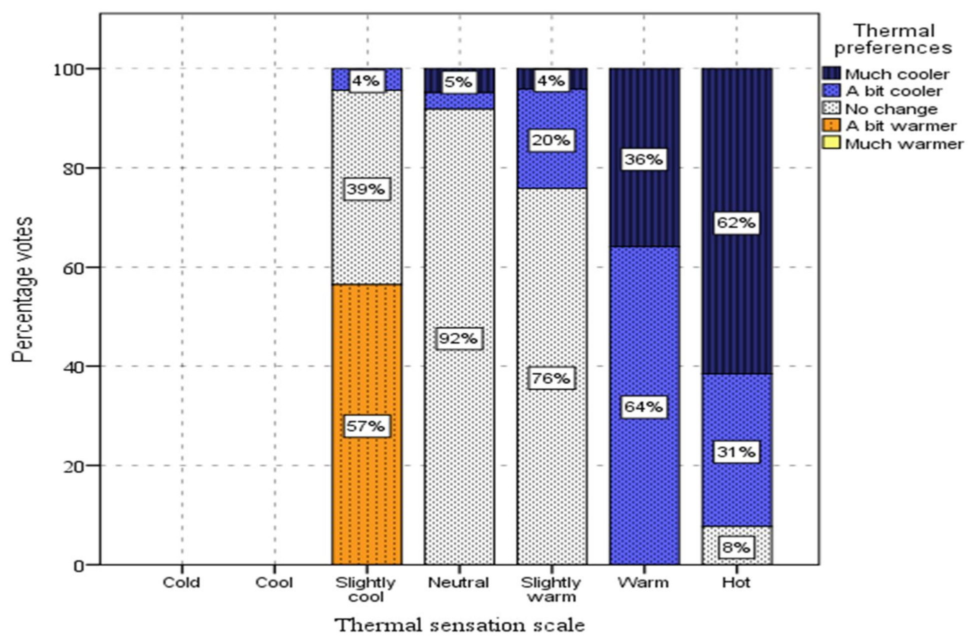

Figure 6 Cross tabulation of thermal preference votes on thermal sensation scale

Results are consistent with the findings of study conducted for summer periods across the country [16, 20, and 21]. This shows that

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respondents were satisfied with their current neutral thermal sensation and did not want to change conditions.

C. Comfort temperature

The comfort temperature can be defined as 'the indoor air temperature' at which, an average subject will vote neutral on the thermal sensation scale (TSV). The thermal responses of subjects in the form of an acceptable temperature range, neutral temperature and thermal sensitivity can be deduced from a linear regression model of ASHRAE scale votes against indoor air temperature.

1) *Linear regression analysis:* Linear regression of thermal sensation and indoor air temperature is one of the methods for evaluating the neutral temperature in field studies. Using the regression, neutral temperature is determined by setting the thermal sensation to neutral (zero). Our linear regression for naturally ventilated classroom buildings is:

$$AMV = 0.13T_a - 3.46 \qquad (R^2 = 0.22), p < 0.001) \qquad \text{(Eq.-1)}$$

Figure 10 presents the results from linear regression technique. Using the Eq. (1) we estimated the regression neutral temperature (T_n) for naturally ventilated classrooms for whole study period on all data set. On all data, it yielded the neutral temperature as 26. 6˚C. The slope of the Eq. (5) is comparable to others' classroom study results across the world. Yao et al. [23] noted a slope of 0.19 unit/C in university classrooms of China; Mishra et al. [18] recorded 0.18 unit/C in the laboratory environments in Kharagpur, while Dhaka [20] observed 0.30 unit/C in hostel dormitories for same region.

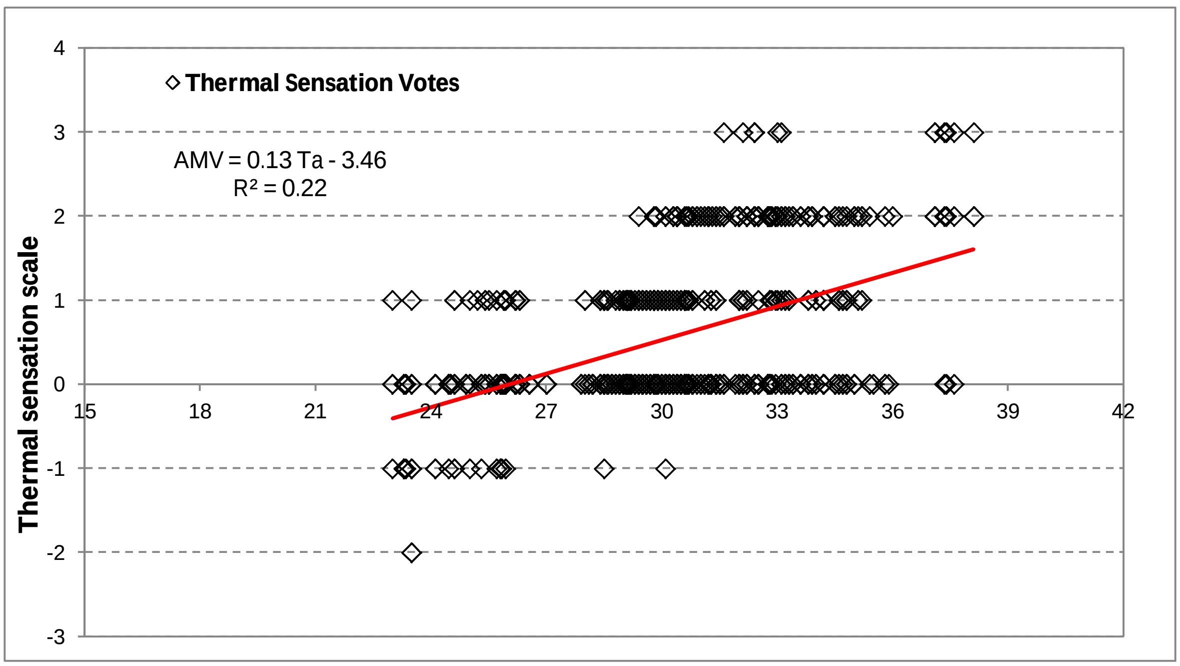

Figure 10 Linear regression for all data combined in naturally ventilated classrooms.

2) *Griffths method:* It has been stated that the presence of behavioral adaptation in the data tends to artificially lower the regression coefficients and therefore the estimates of the comfort temperature [24, 25]. Also, the mean comfort vote which is much different from the neutrality (Table 6), may also adversely affect the predictive power of the resultant regression equation. Hence, survey results of this study have again been used to re-estimate the comfort temperature using Griffith method as given below through Equation (2)

$$\boldsymbol{T_C = T_a + (0 - TSV)/G} \qquad \textbf{(2)}$$

where T_c is the comfort temperature (°C) ,T_a is the indoor air temperature (°C), TSV is the thermal sensation vote and G is the Griffith constant (0.50 ºC $^{-1}$).

In applying the Griffith's method, Nicol and Humphreys et al. [26] used the constants 0.25, 0.33 and 0.50 for a seven point thermal

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sensation scale. Analysis of mean indoor air temperature for neutral votes on the sensation scale has shown close agreement with comfort temperature while using the Griffith method with 0.50 ºC $^{-1}$ as Griffith's coefficient. The mean indoor comfort temperature by Griffith's method is 29.8 °C in naturally ventilated classrooms on all data set. The finding is in close agreement with the comfort temperature observed in Jaipur: 27.9 ˚C [21], Kharagpur: 26.6°C [18], and Hyderabad: 28.0 °C [16] in natural ventilated buildings.

Table 6 Linear regression models, Griffiths' comfort temperature, air temperature when voting neutral (T_n)

Case	N	Regression			Mean		Griffith Method			
		Models [a]	R	T_{an} (°C)	T_n	N_n	T_{an1}	T_{an2}	T_{an3}	T_{an4}
							0.13	0.25	0.33	0.50
All months data		TS=0.13 T_a-3.50	0.56	26.9	*30.3*	538	26.5	28.7	29.2	*29.8*
		TS=0.13 T_g-3.48	0.55	25.2						
April	350	TS=0.10 T_a-2.44	0.53	24.4	*30.4*	216	27.3	29.1	29.5	*30.0*
		TS=0.10 T_g-2.69	0.52	26.9						
May	260	TS=0.13 T_a-3.48	0.48	26.8	*28.9*	175	26.7	27.9	28.2	*28.6*
		TS=0.13 T_g-3.47	0.46	26.7						
June	290	TS=0.17 T_a-4.58	0.48	26.9	*30.8*	147	25.5	28.8	29.7	*30.6*
		TS=0.16 T_g-4.24	0.47	26.5						

IV. CONCLUSION

Field study of thermal comfort was carried out in thirty classrooms in three university buildings of composite climate considering using Class II protocol of field measurement during summer season. A total of 900 students participated in field study: 729 males (~81%), 171females (~29%). A questionnaire based survey was conducted in order to collect subjective and objective information of the occupants. Collected data were analyzed statistically for ascertaining neutral temperature of the group by Griffith's method. Key conclusions of the study are as follows:

A. The naturally ventilated buildings experienced a higher fluctuation in mean indoor temperature ranged between 26.6℃ and 36˚C, across different classrooms and buildings.

B. About 80 % subject's responses were found in comfort band (±1 sensations) in all naturally ventilated classrooms for all data during summer season.

C. A preference for cooler environments was evident throughout the survey period with mean thermal preference (TP_{mean}) of -0.53 (SD=0.71).

D. The mean indoor comfort temperature by Griffith's method (0.5℃$^{-1}$) is 29.8 °C in naturally ventilated classroom buildings. The comfort temperatures are much different from those specified in NBC, suggesting for revision in comfort criteria for naturally ventilated buildings.

The above results show that the subjects in naturally ventilated classroom buildings are comfortable at temperatures different from those suggested by the current Indian and international standards. India is climatologically and culturally very diverse. It may be necessary to undertake thermal comfort field studies in other climatic zones and different building typologies. Also, since India is an emerging country and there is continuous increasing demand of higher education with more than 540 universities and millions of students in this tropical country. This calls for architect's serious attention towards environmental and thermal adaptation in buildings, in the era of power paucity and prudent consumption.

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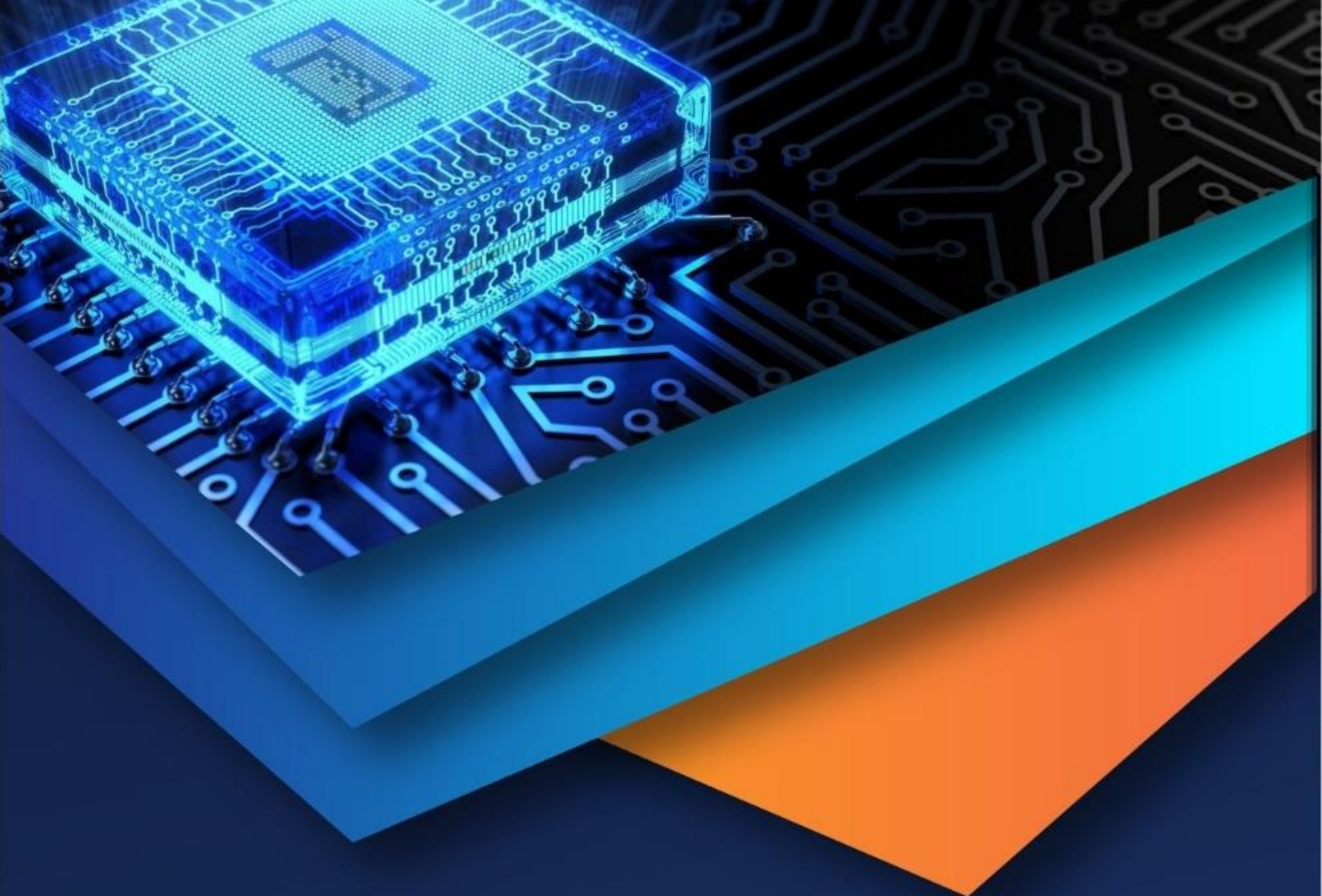

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