Characteristics of thermal comfort in the warm and humid climate of North-East India.

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Abstract

The building sector is considered to be one of the most energy-intensive sectors across the world. The building sector consumes about 40% of the world's primary energy and is responsible for a third of total CO2 emissions. Unprecedented high temperatures and heat waves experienced in many parts of India have disrupted everyday life and increased the energy consumption of buildings further. This posed a big question on the persisting indoor environment quality. North-East India is developing very rapidly, and the government of India is also looking to develop it as a hub to connect South Asian countries. The present study is conducted in Tezpur's naturally ventilated office buildings in warm and humid North-East India. Year-long thermal comfort surveys were carried out in 12 naturally ventilated office buildings, collecting 790 samples from July 2016 to June 2017. Data analysis shows that for Tezpur, neutral temperature through regression analysis and Griffiths method is 26.4°C. Tezpur offices' preferred temperature and relative humidity are 24°C and 55%, respectively. Probit analysis showed that occupants are more adaptive toward the warmer side of the thermal sensation scale. It was also found that the office subject's clothing behaviour was a non-linear function of temperature and impacted by local discomfort, creating a temperature difference between the occupant and back wall surface temperature. Data analysis also concluded that ceiling fan use increases exponentially as the indoor globe temperature in the offices reaches 24°C and plateaus or reaches almost 100% at the indoor globe temperature of 32°C.

Keywords - Adaptive thermal comfort, Offices, North-East India, Probit analysis, Preferred temperature.

1. Introduction

Buildings, for ages, have been an integral part of society because they provide shelter and ensure security and safety, socio-economic and sociocultural status [1–3]. Since industrialization and economic prosperity occupants, lifestyles are changing rapidly, requiring occupants to spend considerable time inside built environments. In recent years, more than 90% of the time is spent inside the built environment because of lifestyle and work-related requirements [4]. Buildings are simultaneously expected to meet the functionality requirement of occupants to support their day-to-day activity at an enhanced level of comfort. Typically, a building's life is about 70 years or more. It becomes very difficult for a building designer to apprehend and incorporate future energy requirements and energy efficiency laws into the buildings. This aspect and limitation have made the building hugely primary energy-intensive and one of the highest carbon emitters [5]. In India, buildings consume more than 33% of the nation's primary energy use, with an annual growth of 8% [6]. The residential and commercial sectors consumed about 32% of total generated electricity, and most of the increase in electricity consumption is due to the growing use of air conditioning in the building [6]. Over the past two decades, several studies have shown that climate change has severely impacted the building sector, leading to a shift in energy consumption because of heat stress and unpredictable extreme weather events [7–12].

North-East India is strategically crucial for India as it has the potential to become the gateway to Southeast Asia. Minimized energy consumption and occupant well-being must be ensured in all critical infrastructures. To address this research gap, the present study is being carried out in Tezpur, which lies in the warm and humid climatic zone of North-East India.

https://doi.org/10.62744/CATE.45273.1119-238-249

2. The objectives of the study

Looking at the importance of thermal comfort in office buildings and its relation to the office subjects' productivity and well-being, it becomes important to carry out a thermal comfort study based on long-term data collection. In the present study, yearlong data collection and questionnaire-based surveys (July 2016 to June 2017) were carried out in North-East India's naturally ventilated and free-running office buildings. A study based on yearlong monitoring and data collection is critical because it captures the broad spectrum of thermal adaptation the subjects go through in the built environment. The present research is carried out with the following objectives.

a) To study the status of thermal comfort in the offices of warm and humid climate based on a yearlong thermal comfort survey and data collection.

b) Estimate the thermal preferences and comfort temperature range in an office environment.

c) Study the adaptative actions of subjects in an office-built environment.

d) To compare the developed adaptive comfort model against the IMAC model.

3. Methodology

Questionnaire-based thermal comfort study was carried out at Tezpur (26°37'N, 92°47'E), which lies in a warm and humid climate zone in North-East India. Tezpur is in the state of Assam (Figure 1). The elevation from the mean sea level of Tezpur is 48m. Thermal comfort surveys were done in naturally ventilated offices with assistance from the local support team. Socio-culturally, North-East India is very diversified and distinct compared to the rest of India, so it was exciting and challenging to coordinate and complete the thermal comfort surveys on time. To analyze the data IBM SPSS® statistical software platform SPSS V26 is used.

3.1 *The climate and offices of Tezpur*

North-East India has mountainous terrain and is heavily vegetated. This region also receives relatively high rainfall and has relatively high humidity throughout the year. Figure 1(a, b) shows the location of Tezpur in the warm and humid climate of North East India. Table 1 lists the range of climatic parameters corresponding to warm and humid climate zone. Figure 1 shows the sitting arrangement, working environment and traditional clothing of subjects in the offices. Offices in this part of India are designed to operate under NV mode throughout the year. Almost all the offices have operable windows with curtains and ceiling fans. A ceiling fan is shared among the office subjects. For lighting, all the offices are fitted with Fluorescent or LED lights. Subjects in the offices are free to wear a dress per their socio-cultural requirements and maintain public office decorum.

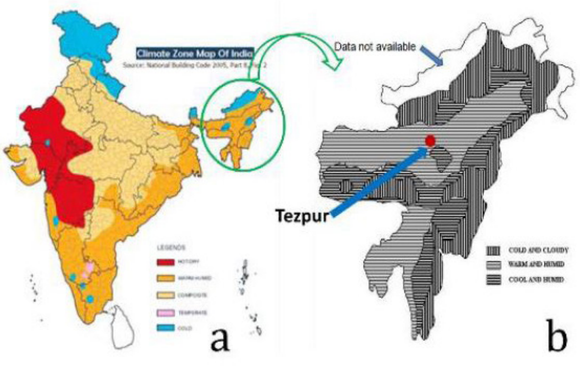

Figure 1: Location of Tezpur

Figure 2: Office environment

A thermal comfort study was conducted in 12 naturally ventilated office buildings across Tezpur. The office buildings were randomly selected out of normal office building stock for the study. All the selected offices were government buildings. Most of the selected office buildings in Tezpur are single-storey. Before the data was collected, it was ensured that the selected office building was operated as usual. The surveys were conducted only on clear and sunny days only.

Table 1: Climatic parameters specifications of bioclimatic zones of north-east India

Bio-climatic Zones		**Warm and humid**
Temperature Range	Summer	Maximum 30°C – 35°C Minimum 22°C – 27 °C
	Winter	Maximum 25°C – 30°C Minimum 10°C – 15°C
Relative Humidity (%)		75 – 90
Rainfall (mm)		1700 to 2100
Sky Condition		Generally clear sky but overcast during monsoon
Wind Direction		Low wind during summer and from SE, N & NE direction
Vegetation		Heavy vegetation

3.2 Questionnaire, protocol and scales

The questionnaire for the present study was sourced from ASHRAE standard 55-2020 information appendix L [14]. A transverse type of questionnaire was designed to capture the required information about the subject's present sensations (about the thermal environment, air movement, humidity, air quality), preferences (about the thermal environment, air movement, humidity, air quality), preferred adaptive actions to restore comfort and their views about probable reasons of discomfort. Most of the region's offices have open seating plans, and if the separation between the office occupants is more than 1.5 meters, then thermal environment parameters were recorded for each subject. Only those subjects sitting in the same place for over a year were selected. This was done to ensure a balanced response from the subject, as they would have experienced the variation in the thermal condition of the place across the four seasons of a year.

Corresponding to each subject, an average of 3 measurements were taken at an interval of 1 min. An interval of 3 min was considered for recording globe temperature. From moving one subject to another for recording the subject's thermal preferences and corresponding physical parameters, a gap of 20 min was considered to stabilize the globe temperature. It was also ensured that the subject was sitting at the same place and doing the same work/activity for at least 20 mins. Scales corresponding to thermal sensation and preferences were sourced from ASHRAE and Nicol [14, 15]. Nicol's five-point preference scale was used to record the preference of office subjects. Table 2 shows the different scales with their corresponding numerical values.

Table 2: Scales used in this study to record the response of the subject

Scale values	Thermal sensation	Thermal preference	Air movement preference	Humidity preference	Thermal acceptability
-3	Cold	-	-	-	-
-2	Cool	Much warmer	Much less air movement	Much more humid	-
-1	Slightly cool	A bit warmer	A bit less air movement	A bit more humid	-
0	Neutral	Neutral	Neutral	Neutral	Unacceptable
1	Slightly Warm	A bit cooler	A bit more air movement	A bit drier	Acceptable
2	Warm	Much cooler	Much more air movement	Much drier	-
3	Hot	-	-	-	-

3.3 Clothing value and Instruments

In the Indian subcontinent, clothing value estimation is the biggest challenge in thermal comfort surveys. The difficulty level was minimal for men in North-East India offices because very few male subjects wore traditional attire. However, in the case of female subjects, it was a challenge because traditional attire individual insulation values are absent in the database. During the field surveys, if the female subject was wearing a "Sari" (an Indian Clothing), then the values calculated by Indraganti et al. [16] were used for analysis. In North-East India, each state has distinct traditional clothing patterns for males and females, and they are allowed to wear traditional dress in offices. Instruments used in this study to record built environment parameters (air temperature, relative humidity, air velocity, globe temperature, CO2 concentration) are listed in Table 3. Figure 2 shows the deployment of the instruments at the field surveys. Ambient temperature and relative humidity at 30-min intervals were measured at each location using HOBO U12 data loggers for the entire study period.

Table 3: Details of instruments used for environmental parameters measurement

Description	Make	Parameter measured	Range	Accuracy
Thermo-hygro-CO_2 meter	TR-76Ui	Air temperature	0~55°C	±0.5°C
		Humidity	10~95% *RH*	±5% *RH*
		CO_2 level	0~9,999 ppm	±50 ppm + 5%
Globe thermometer	Tr-52i, Globe (ø75 mm)	Globe temperature	-60~+155°C	±0.3°C
Fluke 61 Infrared Thermometer	Fluke 61	Surface temperature	-18 ~+275°C	±2°C; Temperature: -18 ~+275°C
Testo 405-Thermal anemometer	Testo	Air velocity	0.01~10.00 m/s	0.01 m/s
		Air Temperature	-20 ~ +50°C	±0.1°C
HOBO U12 4-Channel loggers	HOBO U12	Air Temperature	-0 ~+50°C	±0.35°C; Air Temperature ~ 50°C
		Relative humidity	5% ~ 95%	3.5%; RH: 10 ~ 90%
		Lighting level	0~48 klx	±5%

3.4 Sample size characteristics

A total of 1156 valid thermal sensation votes were collected in warm and humid climate zone. The sample size contains about 32% female and 68 % male subjects. Looking at Figure 3, we see that the maximum number of subjects falls in the age bracket of 41-50 years at Tezpur. This ensures that occupants have spent a considerable amount of time in the same climate and can give a balanced response towards thermal sensation and preferences.

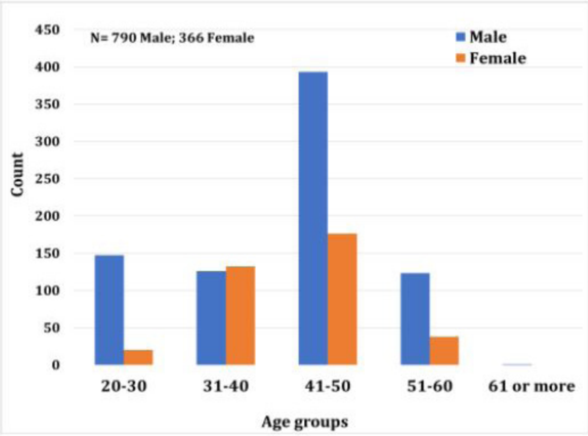

Figure 3: Sample size and characteristics

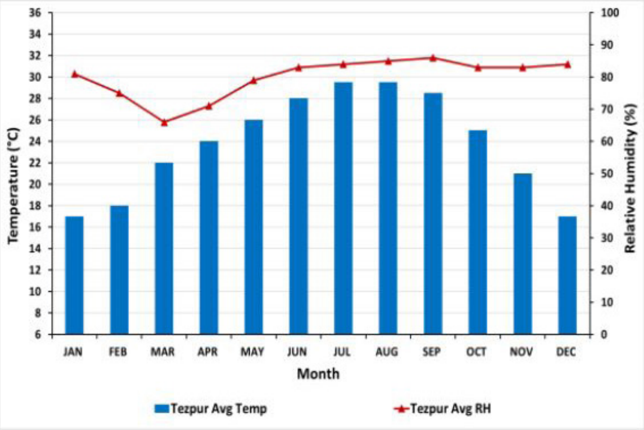

Figure 4: Tezpur outdoor temperature and relative humidity profile

4. Results and discussion

4.1 Outdoor and indoor environmental conditions

North-East India lies in the eastern part of India and is characterized by heavily vegetated uneven topography. Table 1 represents the climatic parameter specifications for the warm and humid climatic zone. Figure 4 shows Tezpur's monthly mean outdoor temperature and relative humidity profiles. The monthly relative humidity profile shows that relative humidity ranges from 70% to 95%. In the rainy season (May to September), relative humidity stays more than 80%. In the offices of Tezpur, the indoor air temperature varied from 19.8 °C to 35.2 °C. Maximum indoor air velocity in the offices of Tezpur varies from 0 m/s to 3.2 m/s. Similarly, the relative humidity in Tezpur's offices varies from 36% to 85%. High air velocity in the offices of Tezpur is evident because it helps subjects overcome discomfort due to persistent high temperatures and high relative humidity. To analyze the relationship between indoor air temperature, mean radiant temperature and indoor globe temperature, they are plotted against each other. It was found that indoor globe temperature better describes the variation in indoor air temperature. So, it is decided to use globe temperature to analyze further and report the results.

4.2 Metabolic rate and clothing characteristics

In this study, the activity level of office subjects at all three locations varies between 1 met (seated, reading) to 1.4 met (filing, standing). These activity values correspond to everyday office activity [14]. Estimating the clo values of the traditional attire was a challenge and a limitation in the study. For traditional dress, such as "saree" and "salwar-kameez" clothing, insulation was sourced from Indraganti et al. [6] and Kumar et al. [17 – 19]. Clothing insulation values vary throughout the year for Tezpur in the range of 0.29clo to 1.32clo. To understand the clothing behaviour of office subjects at all three locations, the mean clothing values with standard deviation are plotted against thermal sensation and indoor globe temperature. Figure 5 shows that the deviation in the clo value is higher on the cooler side of the thermal sensation scale. The reason for this behaviour can be attributed to the availability of more options for clothing in autumn and winter. From Figure 6, the inflexion points for Tezpur 24°C - 32°C. We also find that the difference between inflexion points at low and high temperatures is about 8°C for the climatic zone. The indoor globe temperature corresponding to inflexion points are the temperatures at which the clothing insulation value changes direction with a slight change in globe temperature. This also gives information about behavioural adaptation in the context of clothing insulation.

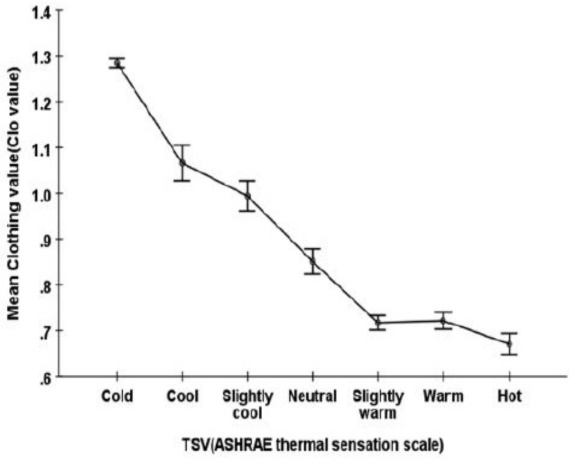

Figure 5: Clothing insulation corresponding to different sensations for Tezpur

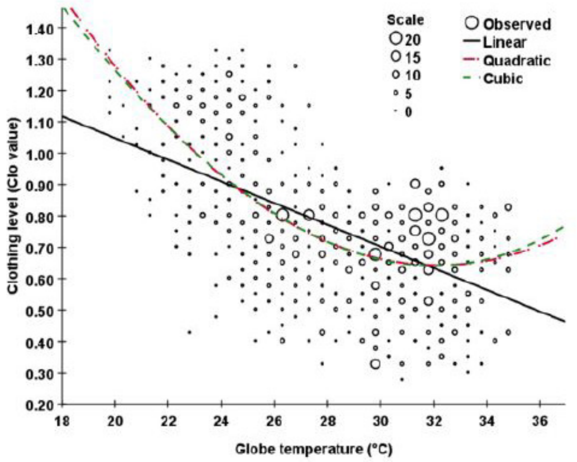

Figure 6: Relationship between clothing and globe temperature for Tezpur

4.3 Estimation of preferred temperature and relative humidity

One of the objectives of the study is to estimate the preferred temperature and relative humidity. Statistical methods can be used effectively on the data to estimate the same. In most cases, preferred environmental conditions are different but lie within the acceptable environmental conditions for the subjects in different built environments. A probit analysis technique was used to evaluate the preferred temperature and relative humidity [19, 20]. To apply this technique, it is required that the data must be in binary form. For this, the preference votes of the office subjects are transformed into binary format. The transformed binary data is now used to carry out ordinal regression with probit as the link function, and the proportion of votes is calculated using equation (1)

$$\text{Probability} = \text{CDF. Normal (Quant, mean, S.D.)} \qquad (1)$$

Where "quant" is the independent variable on which the preference votes are impacted, and "CDF" is the cumulative distribution function for normal distribution. In this case, the parameter of interest is globe temperature and relative humidity. "mean" in equation 1 is calculated by dividing the constant of the regression equation by the coefficient attached to the independent variable, such as globe temperature and relative humidity. Standard deviation (SD) is estimated by taking the inverse of the coefficient attached to the independent variable of the regression equation. To estimate the preferred temperature, the proportion of votes that preferred warmer and preferred cooler are calculated for Tezpur is plotted in Figure 7. Figure 7 shows that lines corresponding to preferred warmer and preferred cooler intersect for different locations at different globe temperatures plotted on the X-axis. From the figure, we can conclude that Tezpur's preferred temperatures and relative humidity are 24 °C and 54% (Figure 8). Table 4 presents the Probit analysis statistics for the preferred temperature and preferred relative humidity.

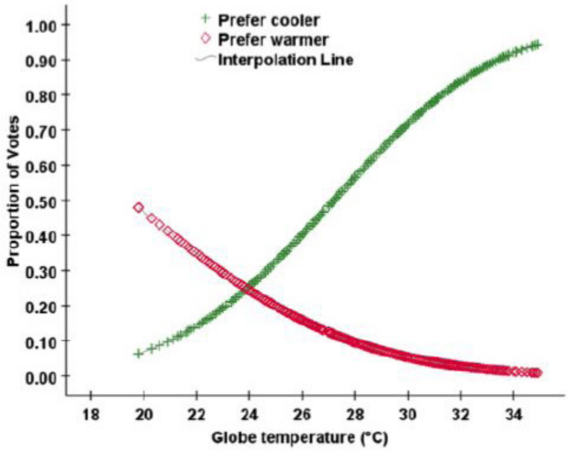

Figure 7: Preferred temperature for Tezpur

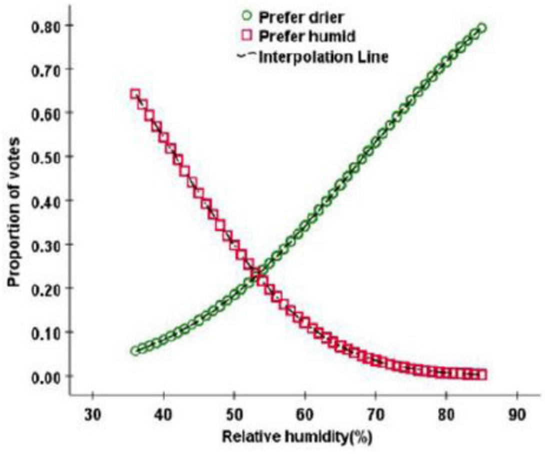

Figure 8: Preferred humidity for Tezpur

Parameter	Equation	Mean	Standard deviation estimated	Sample Size (N)	The standard error estimated (S.E.)	R^2
Temperature	$P_w = -0.15T_g - 2.98$	19.5	6.54	1156	0.016	0.09
	$P_c = 0.21T_g + 5.60$	27.2	4.85	1156	0.013	0.23
Relative humidity	$P_h = -0.04Rh - 1.17$	27.1	23.26	1156	0.004	0.05
	$P_d = 0.03Rh + 1.98$	60	30.30	1156	0.006	0.06

Table 4 Probit analysis statistics for the preferred temperature and preferred relative humidity for Tezpur

4.3 Estimation of thermal neutrality by Probit analysis

The characteristics of thermal comfort votes can also give information about adaptation limits and external thermal stimuli of subjects in a built environment. For this, ordinal regression analysis is carried out using probit as a link function to globe temperature. The process of carrying out this analysis is described in detail by Singh et al. [20, 21]. This analysis resulted in the proportion of votes for each thermal sensation corresponding to globe temperature. Figure 9 presents the plots of the proportion of votes for each thermal sensation on the Y-axis and corresponding values of globe temperature on the X-axis for Tezpur.

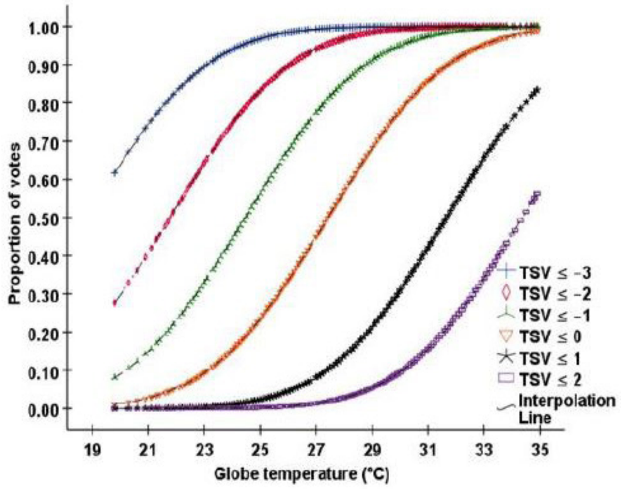

Figure 9: Probit analysis for Tezpur

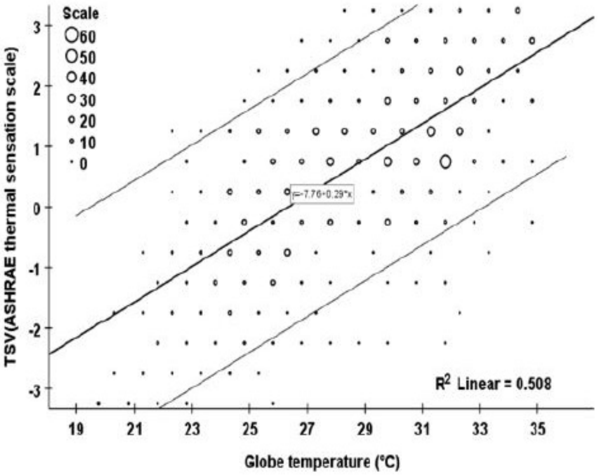

Figure 10: Plot of TSV versus the globe temperature for Tezpur

To find neutrality, if a vertical line is dropped from the sigmoid curve for "TSV = 0" at probability 0.5, the corresponding globe temperature value obtained is neutral temperature. The neutrality value for Tezpur is 27°C. On further analysis of the plots, it can be found that the width of the sigmoid curves corresponding to each thermal sensation for a particular location is not identical at probability 0.5. This means that the thermal stimuli required to shift/change the sensation on the thermal sensation scale are different. This contradicts the assumption regarding the 7-point thermal sensation scale defined in ASHRAE standard 55[22 - 24]. Figure 9 shows that different thermal stimuli (different areas under the curve for each sensation) are required to shift one sensation point on the thermal sensation. The width of each sigmoid curve corresponding to each thermal sensation represents thermal inertia/adaptation potential.

4.4 Comfort temperature estimation and analysis

In a thermal comfort study, the estimation of neutrality or neutral temperature and range of comfort temperature is one of the prime objectives. In this section, regression analysis is carried out to estimate the comfort temperature, as shown in Figure 10, with a 95% confidence interval of the data point. Regression analysis resulted in equation 2. Equation 2 implies that Tezpur subjects require a 3.3°C change in indoor globe temperature to shift one thermal sensation to another. The neutral temperature derived from the regression analysis is 26.4°C for Tezpur. The slope of the regression equations proposed in the present study is comparable to the other studies of India done in office settings.

$$TSV_T = 0.29T_g - 7.76 \text{ (N=1156, } R^2\text{=0.51, S.E.=0.009, P<0.001)} \qquad (2)$$

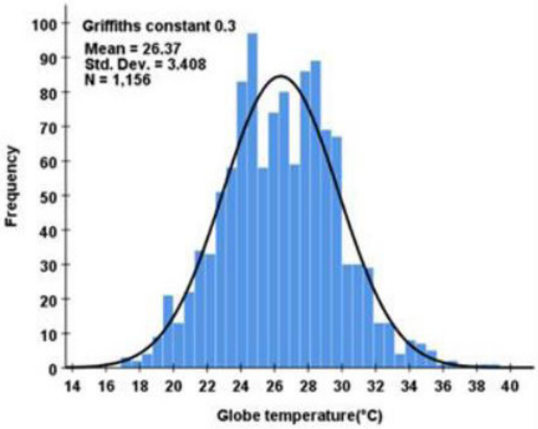

Figure 11: Griffiths comfort temperature

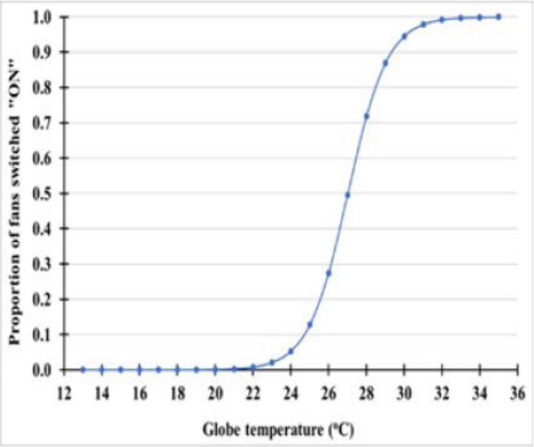

Figure 12: Fan in use characteristics

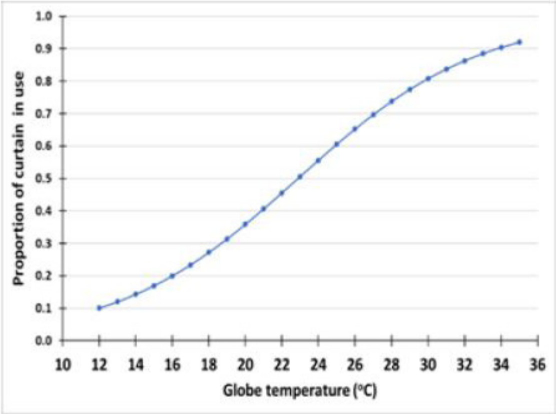

Figure 13: Window curtains use characteristics

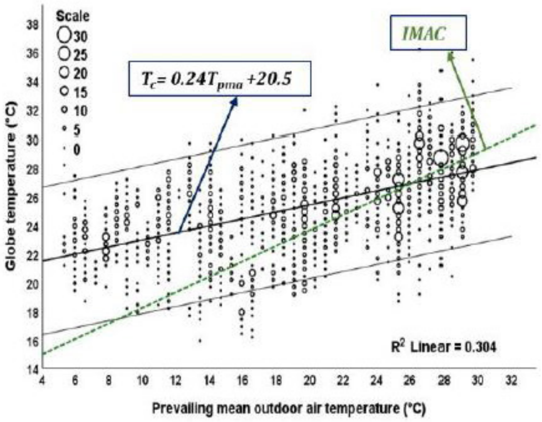

Figure 14: Comparison of the proposed adaptive comfort model with the IMAC model

Equation (3), proposed by Griffiths, is used to estimate the comfort temperature for Tezpur. Griffiths constant was found to be 0.3, for Tezpur. Figure 11 shows the distribution of Griffiths comfort temperature corresponding to the different Griffiths constants for Tezpur. Figure 11 shows that in Tezpur, many subjects expressed comfort with temperatures beyond 30°C. The reason for this can be found when the air velocity data is analysed. During the field measurements, high air velocity (maximum 3.2m/s) was recorded in the offices of Tezpur.

$$T_{cg} = T_g + \left(\frac{0 - TSV}{G}\right) \tag{3}$$

Where T_{cg}: Griffiths comfort temperature

T_g: Globe temperature

0: Neutral on the thermal sensation scale

TSV: Thermal sensation vote

G: Griffiths constant (0.3, 0.4 and 0.45)

4.5 Adaptation characteristics

In a thermal comfort study, analysis of the adaptation characteristics of subjects is important to justify the results. Adaptation of subjects is responsible for the deviation in thermal sensation votes. Adaptation also provides the opportunity and degree of freedom to the subjects in the built environment to restore their comfort [16, 25 – 33]. The use of fan and window curtain data was collected in binary form during the comfort surveys. So, to understand the characteristics of these two adaptive behaviours of subjects, logistic regression was carried out, and output in terms of probability was analyzed. Equation 4 -5 shows the mathematical expressions related to logistic regression. Figure 12 shows the ceiling fan use characteristics. Figure 12 shows that as the indoor globe temperature crosses 24°C, ceiling fans in the offices are gradually switched on, and at 31°C, almost all the fans are switched on. A similar pattern is seen in curtains used in the office windows. It can be seen in Figure 13 that some curtains are not always in use, but as the temperature increases, the window curtains are applied to block the incoming direct sun. At 31°C, more than 80% of curtains are used in the offices.

The logistic function can be written as follows.

$$F(x) = \frac{1}{1 + e^{-y}} \tag{4}$$

Where β is the coefficient and C is a constant. Now equation 17 becomes.

$$F(x) = \frac{1}{1 + e^{-(\beta x + C)}} \tag{5}$$

$F(x)$ gives the probability of the "happening of an event".

4.6 Adaptive comfort equations

In this study, authors tried to propose adaptive comfort equations for three locations in respective climatic zones. The methodology described in standard ASHRAE-55-2020, Section 5.4 and Appendix J (Occupant controlled Naturally Conditioned Spaces) was followed to develop the adaptive comfort equations. To calculate the prevailing daily mean outdoor air temperature [14], we used the following equation (6).

$$\overline{t_{pma}} = (1-\alpha)\left[t_{e(n-1)} + \alpha t_{e(n-2)} + \alpha^2 t_{e(n-3)} + \alpha^3 t_{e(n-4)} + \alpha^4 t_{e(n-5)} + \alpha^5 t_{e(n-6)} + \alpha^6 t_{e(n-7)}\right] \quad (6)$$

$$\overline{t_{pma}} = (1-\alpha) t_{e(n-1)} + t_{rm(n-1)} \quad (7)$$

Where,

$\overline{t_{pma}}$ - Prevailing daily mean outdoor temperature

$t_{e(n-1)}$ - mean daily outdoor temperature for the day before the day in question

$t_{rm(n-1)}$ - Running mean temperature for 7 days before the day in question

α = 0.7 is used to calculate the prevailing daily mean outdoor temperature. It means today's prevailing mean outdoor temperature would be the combined impact of 30% of yesterday's mean daily outdoor temperature and 70% of yesterday's running mean outdoor temperature (which is again calculated as 7 days running mean temperature before the day in question). Figure 14 shows the regression analysis where indoor globe temperature is plotted against prevailing daily mean outdoor air temperature with a 95% confidence interval and IMAC model. For plotting, we considered the comfort votes calculated by Griffiths method for all data. In this study, instead of indoor operative temperature, authors have considered indoor globe temperature because the indoor environment of the offices of North-East India is naturally ventilated, and most of the time, the indoor air speed was more than the upper threshold limit of 0.1 m/s used to calculate the operative temperature. Equation 8 represents the developed adaptive comfort equations for North-East India.

Adaptive thermal comfort equation.

$$TCA = 0.24 Tpma + 20.52 \ (N=2326,\ R2=0.30,\ P<0.001) \quad (8)$$

From the developed equation, it can be concluded that the office occupants are adapted to the outdoor temperature changes. The slope of the regression line for all data is less than that of the slope of the IMAC model [14, 34, 35]. To validate the findings, the authors compared the slope of adaptive equations developed in the present study to the studies done by authors in India in different built environments. It was found that the slope of adaptive comfort equations developed in the present study is comparable to the slope of adaptive comfort equations of other studies done in office settings [36, 37]. In the present study, the slope is lower than that of the proposed IMAC because the socio-cultural setting of the subject in North-East India is very different from that of the rest of India. The region has not that harsh summer and winter conditions compared to the rest of India. Also, the diurnal and seasonal temperature differences are lower than in other parts of India. Moreover, the IMAC model lacks thermal comfort data from North-East India.

5. Conclusions

The present study was conducted in the randomly selected naturally ventilated offices of North-East India at three locations (one in the three climatic zones). Thermal comfort surveys were conducted in 12 offices, resulting in 1156 valid responses. The field study reported here evaluated the thermal comfort condition in office buildings and provided the basic prerequisites for a customized comfort standard for the region and guidelines for designing and operating low-energy, adaptively comfortable buildings and retrofits. Various statistical techniques were employed to analyse the data, resulting in the following conclusions.

- In the offices, occupants felt local discomfort due to the significant temperature difference between external walls and occupants.

- The difference between inflexion points at low and high temperatures is about 8°C for Tezpur.

- The preferred temperatures and relative humidity for Tezpur is24°C and 54%, respectively.

- Probit analysis concludes that different thermal stimuli (different areas under the curve for each sensation) are required to shift one sensation point on the thermal sensation scale for warmer and cool climates.

- Almost 80% of office occupants are comfortable in the temperature range of 25°C to 30°C.

- Use of ceiling fans and curtains are the prominent global adaptation opportunities available to office occupants.

- Ceiling fans in the offices are switched on at 23°C, and almost all the fans are switched on at 32°C.

- The slope of the proposed adaptive thermal comfort equation is less than the IMAC model.

The study estimated the range of comfort temperature, preferred temperatures and, relative humidity and characteristics of prominent adaptive opportunities for warm and humid climates of North-East India. In future research, the authors aim to create a database of the region's traditional dress for use in similar studies. This study also put forth the potential to design NV offices in North-East India with improved comfort duration utilizing adaptive opportunities. The study's findings and utilization are not limited to India, but it enriches the global database of thermal comfort studies and subjects adaptation to the built environment. This study also gives architects and engineers the opportunity and degree of freedom to design occupant-centric, sustainable, low-energy buildings. The authors also hope that the results of this study will be helpful to researchers, architects and building engineers and motivate them to carry out their research.

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