Building and Environment 45 (2010) 320–329

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Thermal performance study and evaluation of comfort temperatures in vernacular buildings of North-East India

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ARTICLE INFO

Article history:
Received 21 April 2009
Received in revised form
12 June 2009
Accepted 13 June 2009

Keywords:
Thermal performance
Comfort temperature
Naturally ventilated buildings
Vernacular architecture
North-East India

ABSTRACT

Solar passive techniques are being used in vernacular buildings throughout the world. Researchers have done extensive study on thermal performance of vernacular buildings in the different parts of the world. Vernacular architecture of North-Eastern India represents the principle of climate-responsive architecture, which still lacks experimental validation and quantitative analysis. Thermal comfort not only makes the occupants comfortable but also governs energy consumption in the building. Detailed field studies on thermal performances of typical traditional vernacular dwellings in different bioclimatic zones have been undertaken. This field study includes detailed survey of 150 vernacular dwellings, field tests and thermal sensation vote of 300 occupants on ASHRAE thermal sensation scale. Field test includes measurement of temperature, humidity, illumination level and building design parameters. Thermal performances of these vernacular dwellings were evaluated for winter, pre-summer, summer/monsoon and pre-winter months of the year 2008. This evaluation is based on '*adaptive approach*', which is the outcome of the field studies and is now part of ASHRAE standard 55/2004 for predicting comfortable temperature of naturally ventilated buildings. This study also tried to find out the range of comfort temperature in these vernacular buildings for different season of the year. It has been found that these vernacular dwellings perform quite satisfactorily except in the winter months and the occupants feel comfortable in a wider range of temperature.

1. Introduction

Vernacular buildings are the structures built by local people using locally available material and affordable technology to deal with the local and day-to-day needs [1]. The design of vernacular buildings is the outcome of the traditional knowledge based on trial and error approach. This type of architecture addresses the local climate constraints and shows maximum adaptability and flexibility. This provides uniqueness to these vernacular architectures and is often used as a symbol to represent a particular community or cultural setup [2]. Bioclimatism integrates the micro-climate and architecture to human thermal comfort conditions [1,3]. Recent studies on vernacular buildings conclude that bioclimatism is an integral part of vernacular architecture and a deciding parameter towards achieving sustainability of modern architecture [2,4]. Building sector in developing countries accounts for one-third of total energy consumption and consumes more than half of the electricity consumption [5]. Now climate-responsive building design has become a necessity to meet this increasing energy demand.

In recent years number of studies have been carried out on climate oriented building design to enhance thermal comfort conditions in living space and at the same time to reduce both the embodied and operational energy consumption [2]. But the results reported in these studies often deviate from the actual scenario [6–8]. This discrepancy arises because most of the available thermal comfort standards are suited for air-conditioned buildings [9]. The situation leads to difficulty in estimating the thermal environments due to lack of adequate field experiments and long-term data collection [10]. In naturally ventilated buildings the occupants' ability to modify the indoor environment is limited. An uncomfortable indoor environment might not be possible to control only by passive means because of different socio-economic background and climatic condition. However, people living in naturally ventilated buildings are likely to be more tolerant [11–13].

The vernacular dwellings of North-East India represent the principle of climate oriented architecture [1]. These are naturally ventilated buildings and are in accordance with traditional lifestyles. Socio-economic background and traditional lifestyles have considerable effect on occupants' thermal comfort perception.

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doi:10.1016/j.buildenv.2009.06.009

However, no study has been done on thermal performance of these buildings. A study on thermal performance of these vernacular houses has become a necessity. For bioclimatic building design, one must have site specific design data like comfort temperature range, wind speed and direction, topography, outdoor maximum and minimum temperatures, rainfall, solar radiation, etc. Present research work has been carried out to find the thermal performance of the traditional vernacular houses of the region quantitatively. '*Adaptive approach*' method is used to evaluate the thermal performance of these vernacular buildings. This '*adaptive approach*' is the outcome of field studies and is now the part of ASHRAE standard 55/2004 and ISO 7730 for predicting comfortable temperatures of naturally ventilated buildings [14–18]. The primary data were collected in the vernacular buildings of all the three bioclimatic zones of the region. In each bioclimatic zone, one house was selected for carrying out long-term measurements [1]. Predictive formulae based on outdoor and indoor climate data are used to evaluate the thermal performance of these buildings. The research work also includes questionnaire based comfort survey. Finally the results are used to define the comfort temperature range in these vernacular buildings for different seasons of a year.

2. Vernacular architecture of North-East India

North-East India is classified into three bioclimatic zones: warm and humid climate, cool and humid climate and cold and cloudy climate [4]. Entire North-East India has more than 50 ethnic groups which have distinct cultural and social setup. All the houses have provisions to satisfy their cultural and social needs. Most of the houses of the region are constructed in direct response to the climatic constrains [1]. The entire region experiences heavy rainfall, so all vernacular houses have steeply inclined and extended roofs. Houses of each climatic zone are distinct in its built form [1]. Building materials and their processing is also different in each climatic zone. Houses in warm and humid climate zone are open structures with courtyard. Courtyard serves socio-cultural needs and provides support to day-to-day activity of the occupants. It also serves as a collector of cool air at night and a source of shade in the daytime. Houses are provided with sufficient number of windows and doors for proper ventilation. Baked bricks, mud, wood, cane and bamboo are the main building materials. False ceiling arrangements are present in most of the houses to minimize the heat gain during daytime [1]. In cool and humid climate zone urban and rural built forms are different from each other. For rural houses, courtyard is an integral part of every house plan but in urban houses it is not so common. Building materials for rural vernacular houses are of processed mud, bamboo (sandwiched between two layers of processed mud), cane, and wood. For urban houses processed mud and bamboo are replaced by backed bricks and cement. Vernacular houses in cold and cloudy zone are compact and have minimum surface to volume ratio [1]. This helps in increasing the heat gain in daytime and minimizes the heat loss during night. Almost all the houses are constructed of stone chips, rock slabs, wood, cane and bamboo. Houses are constructed on the south side of slopes to receive maximum solar radiation. All building materials used to construct the vernacular houses are available locally. This provides an edge on environmental front as less energy is involved in processing and transportation and henceforth minimal environmental degradation [1]. Selection of vernacular houses for long-term monitoring is based on common building plan and functionality. These houses layout designs are still very popular and are widely constructed. Vernacular house considered for monitoring in warm and humid climate zone is constructed in the year 1990, for cool and humid zone in the year 1992 and for cold and cloudy zone in the year 1993. Figs. 1–3 represent the selected houses' photographs in the different bioclimatic zone, respectively. Fig. 4 represents the wall construction techniques in the different climatic zones.

3. Methodology

Vernacular houses of North-East India across the three bioclimatic zones are widely varied in its built forms and functionality. These vernacular houses are still very popular and are being constructed as they fit well into the socio-cultural setup. No serious study has been done so far related to thermal performance of these vernacular houses. Through this study we have tried to assess the thermal performance of these vernacular houses in all the seasons of a year, the comfort status of occupants living in these vernacular houses, comfort temperature range and neutral temperature. We also tried to explore the different behavioral adaptations of occupants that influence the thermal comfort perception in indoor environment.

Fig. 1. House selected for long-term monitoring (warm and humid climate).

Fig. 2. House selected for long-term monitoring (cool and humid climate).

Recent studies reveal that the results from the field measurements are widely accepted to predict the comfort temperature of naturally ventilated buildings [6]. To define the comfort temperature range in an existing building is very difficult as it involves various environmental parameters, human adaptations, perception and expectations [6,12,19]. So, in this study both objective and subjective measurements were carried out simultaneously during the field survey. The measurements were carried out at representative vernacular houses in each bioclimatic zone and the comfort survey has been conducted in similar houses of each bioclimatic zone followed by extensive interaction with the occupants of these buildings.

The field test includes the measurements of temperature (indoors and outdoors house), relative humidity (indoors and outdoors house) and illumination level (indoors and outdoors house) for 25 days in all the seasons (January: winter, April: pre-summer, July: summer/rainy and October: pre-winter) of the year 2008 through data loggers (HOBO RH/Temp/Light/External Data Logger, USA). The temperature sensor accuracy is $\pm 0.7\,^{\circ}$C, the humidity sensor accuracy is $\pm 5\%$ RH and the light intensity measurement accuracy is ± 2 lumen/ft^2, respectively.

Long-term data monitoring work was a necessity because buildings' response to weather and seasonal changes is slow and takes over a week [8,20]. The data loggers were well protected from external solar radiation and winds and fixed in the center of the house and outside of the house to record temperature, relative humidity and day lighting at an interval of 30 min. Secondary data for the study were collected from Regional Meteorological Centre, Guwahati, India. Various building design parameters like external wall thickness, material used for construction, inter-room partition wall thickness, false ceiling height, dimensions of doors and windows their numbers are also recorded. Table 1 represents the

Fig. 3. House selected for long-term monitoring (cold and cloudy climate).

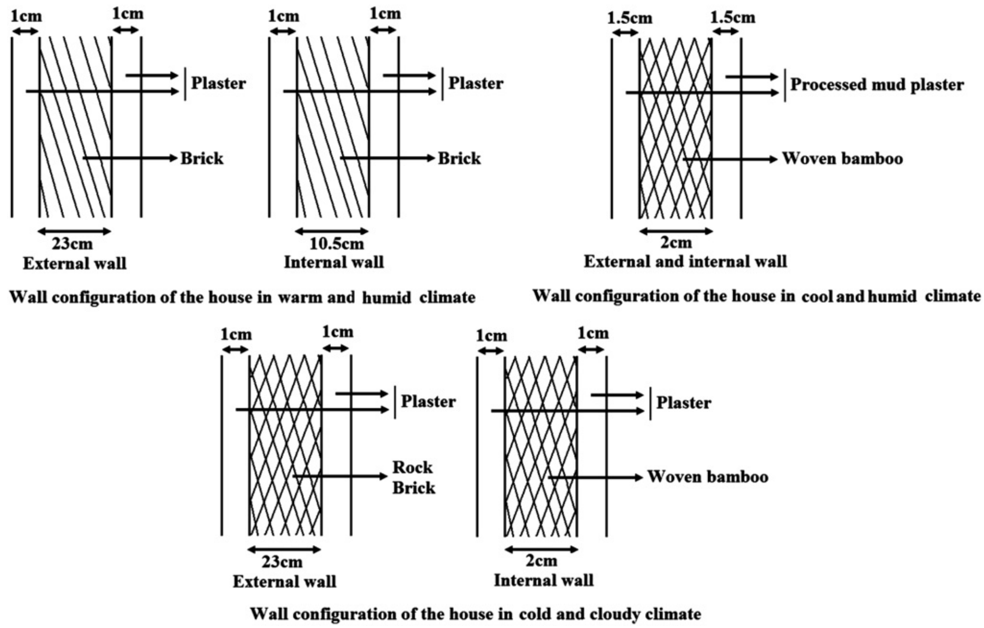

Fig. 4. Wall construction techniques in different climatic zones.

different climatic design features of these selected vernacular houses.

Questionnaire based subjective measurements for this study was carried out in 150 households (50 houses in each climatic zones) covering over 300 occupants. The questionnaire was prepared based on ASHRAE 55-2004 Informative Appendix E '*Thermal Environment Survey*' [21]. The regional parameters like socio-economic and socio-cultural setup that affects the thermal comfort perception were added as necessary modification in the questionnaire. This addition makes the study more relevant and appropriate to this region. The field surveys conducted between 6:00 h and 19:00 h, due to limited access to these vernacular houses. The respondents were asked to vote on ASHRAE 7 point thermal sensation scale followed by extensive interaction and filling up the questionnaire. This interaction helped us to record the common behavioral adaptations. Before recording thermal sensation, the respondents were advised to sit ideal for about 20 min. This is a necessary protocol to minimize the error and to maintain uniformity throughout the study. The surface temperatures of the enclosure surrounding the respondent (i.e. if the respondent is sitting in the living room on wooden chair then the surface temperature of chair, surface temperatures of nearest wall, floor temperature, if the window is closed then temperature of curtain) were recorded by non-contact infra-red thermometer and air temperatures (five times) by digital thermometer during this survey process. The average of these five measured temperatures is used for the analysis. Similarly, the relative humidity, clothing level and illumination level are also measured.

The occupants always try to provide themselves the thermal environment customary to their own socio-cultural context and local climate during the residential building design [19,22,23]. Occupants of the house have a propensity to adapt to the changes in thermal environment and try to be more comfortable. The temperatures corresponding to comfortable thermal environment are not fixed but are continuing response to changes in both indoor and outdoor environmental condition modified by climate and social custom. Sudden changes in the ambient temperature imposed on the occupants actually lead to discomfort [6,24,25]. So, during the survey care has been taken about the clothing level. Respondents are allowed to wear the normal clothing according to their cultural, social and traditional setup. The opening and closing of doors and windows are not controlled but the operation of fan is not allowed during the thermal sensation vote recording. Table 2 represents the different comfort survey indicator.

4. Thermal performance of vernacular architecture

The adaptive approach is based on statistical analysis of large number of thermal comfort field studies. Field studies have more immediate relevance to living conditions. The adaptive approach is

Table 1
Climatic design features of the vernacular architectures.

Bioclimatic zone	Warm and humid	Cool and humid	Cold and cloudy
Built up area (m^2)	94	77	44
Wall (material and thickness)	Brick, cement and sand (0.127 m)	Processed mud and bamboo (0.076 m)	Rock slab, cement and sand (0.20 m–0.25 m)
False ceiling and roof type	Asbestos sheet/wood. Galvanized tin sheet and tilted on two sides	Rare. Galvanized tin sheet and tilted on three sides	Asbestos sheet/cane/bamboo mat/wood. Galvanized tin sheet and tilted on four sides
Ventilation	High ventilation	Medium ventilation	Low ventilation
Layout and orientation	Open layout with courtyard. No specific orientation	Courtyard in rural housing only. East–west orientation and south facing	No courtyard. South sloping and east–west orientation
Prominent passive features	Air gap in ceiling, shading, extended roof used as overhang, chimney arrangement for effective ventilation	Houses are compact, proper care for ventilation	More compact, minimum surface to volume ratio, south sloping to receive maximum sun

Table 2
Comfort survey indicator.

Bioclimatic zone	Warm and humid	Cool and humid	Cold and cloudy
Clothing level (clo)	0.3	0.5	0.7
Metabolic rate (met)		1.0	
Number of subjects		100	
Number of houses		50	
Survey time	January (winter), April (pre-summer), July (summer/monsoon) and October (pre-winter) months of 2008		
Respondent age (%)			
<20 years	11	12	14
>20–40 years	77	70	63
>40 years	22	18	23
Respondent gender (%)			
Male	65	51	42
Female	35	49	58

Table 3
Indoor and outdoor temperatures at different places.

Station	Month	Mean outdoor temperature (°C)[a]	Mean indoor temperature (°C)[b]	Mean outdoor temperature (°C)[b]
Tezpur	January	17.1	17.2	16.3
	April	24.8	25.7	25.3
	July	28.2	29.4	29.0
	October	26.1	25.4	24.4
Imphal	January	13.6	13.7	14.5
	April	21.2	24.9	24.2
	July	25.2	26.1	25.6
	October	22.9	22.4	22.5
Cherrapunjee	January	11.6	15.0	13.7
	April	18.6	25.1	24.2
	July	20.5	24.1	23.2
	October	19.6	23.6	21.6

[a] Data based on Regional Metrological Centre, Guwahati.
[b] Measured at the selected house.

a behavioral approach and rests on the observation that people are not passive in relation to their environments; but they express direct response to make themselves comfortable at the given time and opportunity [14]. They do this by making adjustments (adaptations) to their clothing, activity and attitude [26]. The adaptive opportunity may be provided for instance by switching fans or operable windows or ventilators in summer or by temperature controls in winter. An increasingly wide range of temperature is permissible as the adaptive opportunities increased. Individual control is more effective in advancing comfort than group control [6,14].

Humphreys and Auliciems both reported strong positive correlations between the observed comfort temperature and the mean temperature prevailing in indoors and outdoors during the field studies [12,27]. Adaptive model makes use of mean monthly outdoor temperature to estimate the comfort temperature for the purpose of practical prediction [12]. This input data can be obtained from the nearest weather station or can be measured at the location. The adaptive model is based on extensive field measurements. The relationship between expected clothing and outdoor climate is already in-built into the empirical relation [11,19].

Humphreys developed a model using the available database of more than 30 comfort surveys done around the world. Humphreys proposed a series of simple correlations of thermal comfort prediction. The comfort temperature (T_{co}) can be estimated from mean monthly outdoor temperature (T_m) in °C, using the following equation for naturally ventilated buildings [12].

$$T_{CO} = 0.53 \times T_m + 11.9 \quad (r = 0.97) \tag{1}$$

The prediction claims to have a standard error of 1 °C and applies to temperature range of 10 °C < T_m < 34 °C [12].

Auliciems tried to reanalyze the Humphreys data by removing some incompatible information. These results are based on more recent field studies and combines data for both types of buildings with active and passive climate control [12]. The absence of thermal discomfort is predicted by simple equation in terms of mean indoor (T_i) and outdoor temperature (T_m) in °C [12].

$$T_{CO} = 0.48 \times T_i + 0.14 \times T_m + 9.22 \quad (r = 0.95) \tag{2}$$

Both Eqs. (1) and (2) are used to evaluate the applicability of adaptive models in predicting comfort temperatures in-built space of the three vernacular buildings of the region.

Table 3 represents the mean indoor and outdoor temperatures at the different places. The mean outdoor temperatures are based on the secondary temperature data obtained from the Regional Metrological Centre, Guwahati and the primary temperature data measured at different location. Figs. 5–7 represent the temperature profile (outside and inside of the selected house) of Tezpur, Imphal and Cherrapunjee for the month of January, April, July and October for the year 2008, respectively.

5. Evaluation of neutral temperature and comfort temperature

Neutral temperature is defined as the temperature at which a person feels thermally comfortable at fixed variables like environmental parameters, clothing and activity level. Since clothing and activity levels are region specific and driven by socio-cultural setup and climate, it is very difficult to find a single value for comfort temperature. Different respondents vote according to their own physiological, psychological and behavioral adaptations. Because of this fact, it has been found that at same temperature; different respondents have different thermal sensation or same thermal sensation at different temperatures. The comfort votes are recorded on ASHRAE 7 point sensation scale. Dry bulb temperatures (DBTs) on X-axis and ASHRAE sensation scale on Y-axis are plotted. Figs. 8–10 represent the plot of temperature and corresponding sensation votes and the corresponding linear regression plots for Tezpur, Imphal and Cherrapunjee, respectively. The neutral temperatures are calculated from the linear regression plots of thermal sensation votes and temperature. In most of these

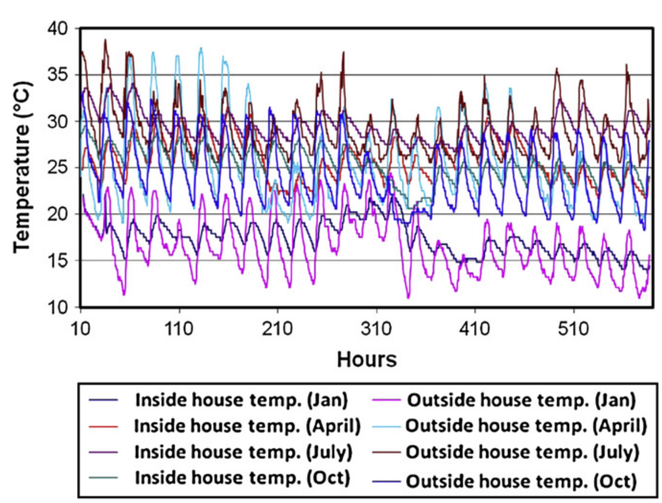

Fig. 5. Temperature profile (outside and inside house) in Tezpur.

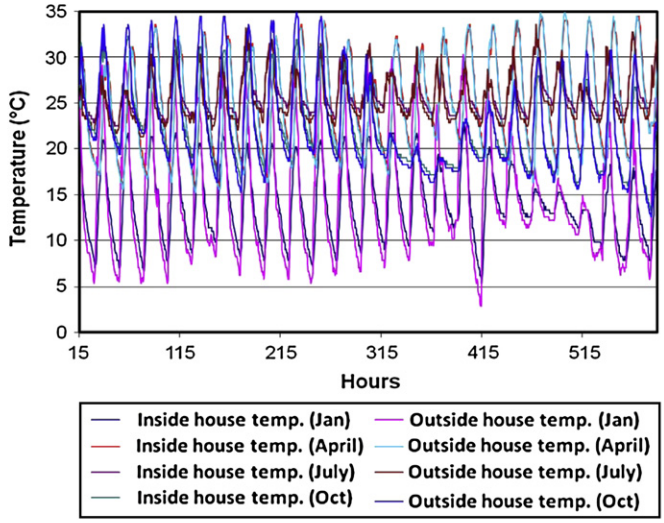

Fig. 6. Temperature profile (outside and inside house) in Imphal.

regression plots, the R^2 value is close to 0.9 representing a strong positive correlation between these two parameters.

Comfort temperature always associated with adaptations and calculated based on Humphreys and Auliciems adaptive comfort models. However, in the case of naturally ventilated buildings, it is always advisable to apply the concept of *range of comfort temperatures*. Here the term '*range of comfort temperature*' is used because it involves the physiological, psychological and behavioral adaptations of the habitants. It is found that in vernacular buildings, when a respondent votes −1 on thermal sensation scale it actually means that though respondent is feeling slightly cool but he/she can make himself/herself comfortable by putting on some warm cloths (increasing clothing insulation), closing window (minimizing air movement) and so on. And if a respondent votes +1, means he/she will opt for decreasing clothing level, drinking water, opening window, running ceiling fans etc. The temperature values corresponding to −1 and +1 sensations are always ±3 °C–3.5 °C of neutral temperature.

In this study, the comfort temperatures are calculated by using the Humphreys and Auliciems adaptive comfort models. The neutral temperatures are calculated by using linear regression analysis between observed Thermal Sensation Votes (TSVs) as

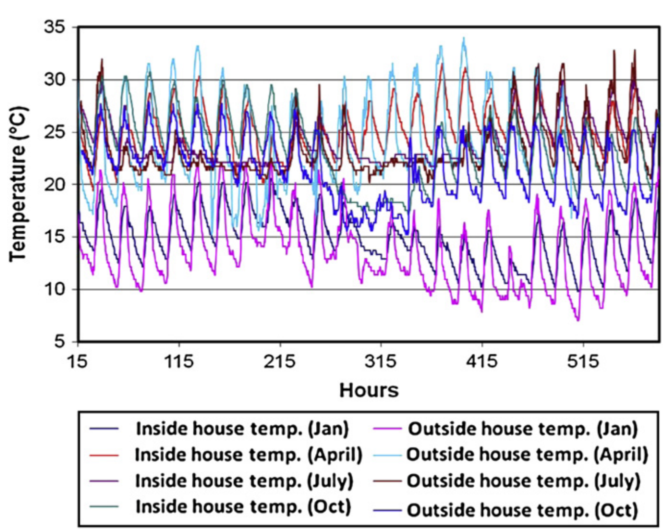

Fig. 7. Temperature profile (outside and inside house) in Cherrapunjee.

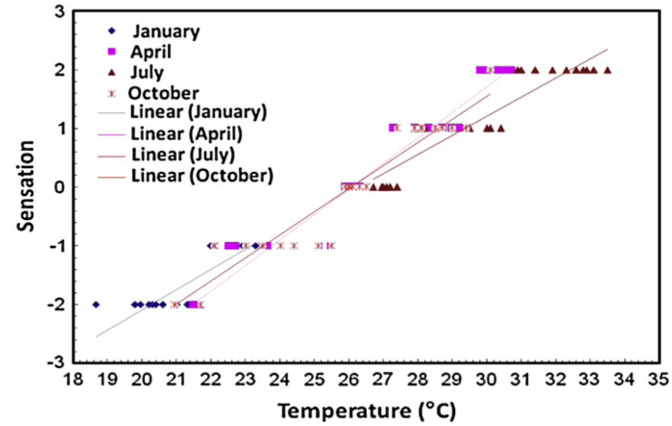

Fig. 8. Thermal sensation votes vs. indoor temperature in Tezpur (warm and humid climate).

dependent variable on *Y*-axis and DBT as independent variable on *X*-axis. Table 4 represents the comfort temperature based on adaptive comfort model, neutral temperature based on the regression analysis and comfort survey. Table 5 represents the range of comfort temperature based on the comfort survey at different climatic zones.

6. Results and discussions

Thermal performance and thermal comfort status in the selected houses of all the three climatic zones are reported in this section. Humphreys and Auliciems adaptive models are used to predict the comfort temperature and these models are also used to predict the percentage of thermally comfortable time in these houses. Comfort survey analysis based on questionnaire results has also been reported. This comfort survey analysis defines the *range of comfort temperature* that is pre-requisite for comfortable indoor environment.

6.1. Thermal performance at different climatic zones

Temperatures are recorded (indoors and outdoors house) for 25 days in different seasons (January: winter, April: pre-summer, July: summer/rainy and October: pre-winter) of the year 2008. These temperature profiles provide important information regarding

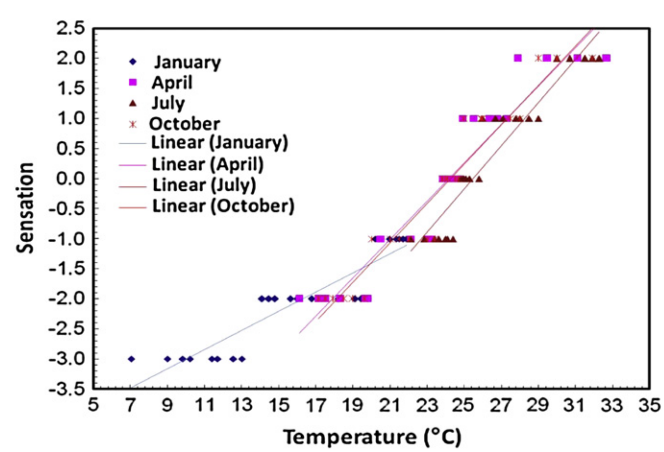

Fig. 9. Thermal sensation votes vs. indoor temperature in Imphal (cool and humid climate).

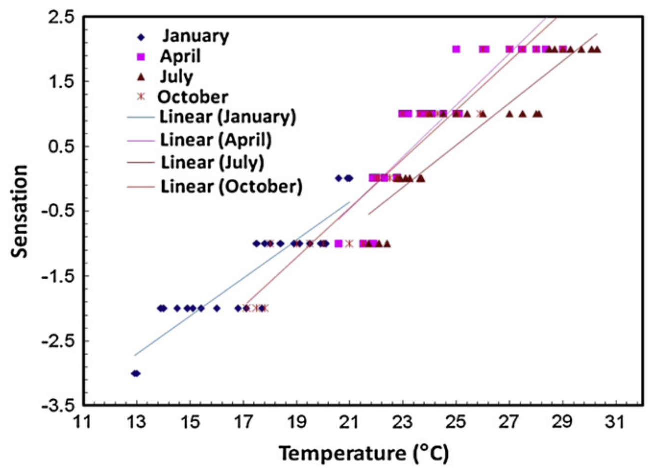

Fig. 10. Thermal sensation votes vs. indoor temperature in Cherrapunjee (cold and cloudy climate).

temperature swing and time lag between maximum temperatures of both indoors and outdoors of each house.

6.1.1. *Warm and humid climate*

Fig. 5 shows the recorded temperature profiles both outside and inside a house at Tezpur (warm and humid climate). Temperature is recorded during the months of January (8th January to 3rd February), April (5th April to 29th April), July (7th July to 3rd August) and October (13th October to 7th November) of the year 2008. For the month of January outdoor temperature varies from 8 °C to 25 °C, in April from 18 °C to 37 °C, in July from 26 °C to 38 °C and in October from 21 °C to 33 °C representing temperature swing of 15 °C, 19 °C, 12 °C and 12 °C, respectively. Similarly indoor temperature in January varied from 13 °C to 23 °C, in April from 22 °C to 28 °C, in July from 27 °C to 34 °C and in October from 22 °C to 28 °C representing temperature swing of 10 °C, 9 °C, 7 °C and 6 °C, respectively. It is observed from the temperature profile that the indoor temperature is always lower than the outdoor temperature. Maximum temperature swing inside the house is 10 °C, which is quite acceptable for naturally ventilated vernacular buildings. Table 4 presents the comfort temperatures calculated by using Humphreys and Auliciems' comfort models. It is found that the comfort prevails for 8% of the time in January according to Auliciems and 3% according to Humphreys' comfort model. For the month of April Humphreys' model predicts 5% and Auliciems' model predicts 15% of the time to be within the comfortable range.

Table 5
Range of comfort temperatures based on comfort survey at different climatic zones.

Station	Months	Temperature swing (°C)		Time lag (h)	Range of comfort temperature (°C)
		Outside	Inside		
Tezpur	January	15	10	5–6	22.8–NA
	April	19	09	5–6	24.0–28.4
	July	12	07	5–6	NA–29.1
	October	12	06	5–6	23.7–28.4
Imphal	January	25	15	2	21.1–NA
	April	20	15	2	22.2–26.2
	July	11	08	2	23.5–27.6
	October	19	14	2	21.8–26.5
Cherrapunjee	January	16	11	5–6	19.0–NA
	April	19	10	5–6	21.3–24.1
	July	10	07	5–6	22.1–26.2
	October	07	07	5–6	19.8–24.3

NA: not available.

For the month of July only Auliciems' model predicts 15% of time within the comfortable range. Again for the month of October Humphreys and Auliciems' comfort models predict 23% of the time within the comfortable range. From the temperature profile, it is also observed that the maxima of outdoor temperature and maxima of indoor temperature have a time difference of 5–6 h. This time difference or time lag provides critical information regarding the insulation level of the house. In this house window to wall ratio is 0.216. Ventilation has been achieved by providing sufficient number of doors, windows and ventilators which accounts for about 50% of the floor area.

6.1.2. *Cool and humid climate*

Fig. 6 represents outside and inside temperature profile of a house at Imphal (cool and humid climate). Temperatures are recorded during the months of January (6th January to 1st February), April (3rd April to 27th April), July (5th July to 1st August) and in October (11th October to 6th November) months of the year 2008. Outdoor temperature variations are 25 °C, 20 °C, 11 °C and 19 °C for the month of January, April, July and October months, respectively. Similarly, indoor temperature variations are 15 °C, 15 °C, 8 °C and 14 °C for the above months, respectively. In this climatic zone, higher temperature variations are observed due to light weight external and inter-room partition walls. It is also observed that in this kind of vernacular houses there is seldom use of false ceiling. The inside room volume is directly exposed to galvanized tin roof. The dwellings of this climatic zone are well ventilated as window constitutes about 30–40% of the

Table 4
Comfort and Neutral temperatures at different climatic zones.

Station	Months	Comfort temperature (°C) (Humphreys)	Comfort temperature (°C) (Auliciems)	Neutral temperature (°C) (regression analysis)	Neutral temperature (°C) (survey)
Tezpur	January	20.9	19.9	26.0	NA
	April	25.1	25.1	26.1	26.1
	July	26.9	27.3	26.3	27.1
	October	25.7	25.0	26.1	26.1
Imphal	January	18.8	17.7	28.9	NA
	April	23.1	24.1	24.2	24.2
	July	25.3	25.2	25.5	25.2
	October	24.0	23.2	24.3	24.2
Cherrapunjee	January	18.0	18.1	22.2	20.8
	April	21.8	23.9	22.2	22.4
	July	22.7	23.7	23.4	23.2
	October	22.3	23.3	22.2	22.4

NA: not available.

floor area. The window to wall ratio in this selected house is approximately 0.15. There is a need to reduce heat gain during daytime and heat loss at nighttime to maintain the internal temperature swing below 10 °C. This can be achieved by providing false ceiling, high thermal mass walls and minimizing the unwanted heat leakage. From the temperature profile, it is found that the time lag is 2 h. For the month of January, Auliciems' model predicts 5% and Humphreys' model predicts 3% of the time comfortable. For the month of April, July and October, Humphreys and Auliciems models predict 40%, 15% and 5% comfortable time, respectively.

6.1.3. Cold and cloudy climate

Fig. 7 represents the temperature profile of outside and inside of a house at Cherrapunjee (cold and cloudy climate) for the months of January (12th January to 6th February), April (6th April to 30th April), July (8th July to 6th August) and October (14th October to 8th November) of the year 2008. The outdoor temperature swing for the months of January, April, July and October are 16 °C, 19 °C, 10 °C and 7 °C, respectively. Similarly, indoor temperature swings for the months of January, April, July and October are 11 °C, 10 °C, 7 °C and 7 °C, respectively. It is observed that for all the four months the indoor temperature swing lies in permissible range for naturally ventilated buildings. Window to wall ratio in this climatic zone building is 0.108 and net opening is about 30% of the floor area. Humphreys and Auliciems' adaptive comfort models predict 5% comfort time for the month of January. For the month of April both model predict about 70% of the time comfortable. But for the month of July, Humphreys' model predicts 25% of the time comfortable and Auliciems' model predicts 15% of the time comfortable. Again for the month of October, Humphreys and Auliciems models predict 10% and 15% time comfortable respectively. The time lag in this kind of vernacular house is 5–6 h.

6.2. Comfort temperature at different climatic zones

Data collected during comfort survey are analyzed to define the range of comfort temperatures for the three different bioclimatic zones. Some important and interesting results are reported in this section related to variation of neutral temperature in different seasons. These results provide evidence of strong co-relation between human thermal sensation, adaptations (combined effect of physiological, psychological and behavioral adaptations) and the local climate of the region.

6.2.1. Warm and humid climate

The comfort and neutral temperatures are calculated by three different methods and presented in Table 4. The neutral temperatures are calculated from the linear regression analysis and the average of the temperature corresponding to neutral votes on Thermal Sensation Scale (TSS) by respondent. The gradient of the slope of regression line is used to calculate the sensitivity of the occupants to the indoor temperature. It can be concluded from the regression analysis that irrespective of the climatic conditions, the neutral temperature is close to 26 °C (DBT). However, the neutral temperature corresponding to TSV shows increasing trends, i.e. lower (26.1 °C) in pre-winter and high (27.1 °C) in summer months.

Comfort temperatures calculated for the month of January by Humphreys and Auliciems' adaptive comfort models are quite low in comparison to the neutral temperature obtained from regression analysis or from TSV. Occupants never voted towards neutral during the survey in the month of January. Observing the trend of TSV, it can be assumed that the neutral temperature would be close to 25 °C. But the regression analysis gives neutral temperature 26.0 °C (Fig. 8). We also found the range of comfortable temperatures, i.e. temperature corresponding to occupants vote towards the sensation scale for the months of January, April, July and October months. This is important because between these two sensation scale occupants adaptive techniques work well. The temperatures corresponding to the sensation scale for different months are presented in Table 5. For Tezpur in the month of January, temperature corresponding to +1 sensation is missing because no occupant voted towards +1 sensation. It means that indoor temperature never reached that high. Similarly, for the month of July no occupants voted corresponding to −1 sensation. From the table, it can be concluded that in warm and humid climate (Tezpur); the comfort temperature varies from 22.8 °C to 29.1 °C or a range of 6.3 °C. It means that if a naturally ventilated building is designed where internal temperature swing is about 6.3 °C, then people of this climatic zone will feel thermally comfortable.

From the indoor temperature profile of the house in warm and humid climate zone for the month of January, April, July and October, the temperature swing is in the range of 6 °C–10 °C. From the selected building layout, it is observed that the evening sun is blocked by trees on the north-west side of the building. Hence room numbers 3, 5, 7 and 9 are cooler enough in comparison to room numbers 2, 4, 6, and 8. In winter months the rooms 2, 4, 6 and 8 are more comfortable to use because these rooms receive morning radiation and be warmer in daytime than the other section of the building. But in summer months the rooms 3, 5, 7, and 9 are more comfortable to live in as this section hardly receives any afternoon sun. So, the comfortable time can be increased considerably by adjusting the use of rooms during summer and winter months. Room numbers 6, 7, 8 and 9 does not have false ceiling. This also led to discomfort due to quick heat gain during daytime and quick heat loss at night. This house needs to improve the insulation level to minimize the leakage and heat gain. It also lowers the overall comfort level of the house. From the measurements of day lighting it is found that north side rooms have lower illumination levels in comparison to south side rooms due to shading by trees. Overall illumination in the living space is below the standard illumination level.

6.2.2. Cool and humid climate

Thermal sensation votes corresponding to the months of January, April, July and October are plotted in Fig. 9. From the linear regression plot of TSV, it is found that the neutral temperatures for the different months are different, i.e. lower for the winter months and higher for the summer months. Neutral temperature from the regression curve for the month of January assumes very high value. This is because in winter, people tend to feel more uncomfortable as they have limited option available for adaptation (i.e. higher clothing level and closing the windows to minimize the air movement). This affects the voting on the sensation scale. From the tables, it can be observed that in warmer months, there is minimum deviation of the neutral temperature from the regression analysis and from TSV. This is because for summer months the difference between mean radiant temperature and dry bulb temperature is less then 1 °C and wind speed is less than 0.1 m/s.

The predicted comfort temperatures by Humphreys and Auliciems' adaptive models for the month of January (Table 4) are very low and no occupant responded comfortable at that temperature during the survey. The neutral temperature calculated from the linear regression curve for the month of January is 28.9 °C. This is not the right value because even in summer (July) neutral temperature (TSV) value is 25.2 °C. During the comfort survey in the month of January the temperature inside the house never crossed 22 °C. So, no TSV was recorded corresponding to temperature between 22 °C and 24.2 °C. Regarding the range of comfort temperatures for the month of January no occupant from the surveyed houses responded for +1 sensation, so there is no value of temperature corresponding to it. In this climate, the range of comfort temperature varies from 21.1 °C to 27.6 °C, i.e. approximately a range of 6.5 °C. From Table 5, it can be observed that for all the months, the indoor temperature swing is very high and this has lead to discomfort. For thermally comfortable indoor environment in naturally ventilated vernacular houses, the indoor temperature variation must not cross 6.5 °C across all the seasons.

The temperature profiles of the house show that the inside house temperature swing values are quite above the permissible limits. This clearly states that the house has low thermal inertia. The house has tin roofing and no false ceiling. This increases the heat gain during daytime and heat loss during nighttime. It is also found that there is a gap of 5–8 cm between floor and external walls. This gap also lowers the insulation level. This gap actually increases discomfort in winter but is good in summer as it helps in the formation of draft to promote natural ventilation. There is also a gap of 15–20 cm between wall and roof. External walls need to be of high thermal mass so that daily outdoor temperature fluctuations will be smoothened and the indoor temperature will be stable. This gap can be separated from room volume by providing false ceiling for better comfort. The windows and ventilator of the house of this zone are smaller in dimension and less in number in comparison to that of warm and humid climate zone. The daylight level in the living area is below the standard. More number of single glazed windows and ventilators are needed to improve the illumination level during daytime.

6.2.3. *Cold and cloudy climate*

TSV corresponding to the months of January, April, July and October is plotted in Fig. 10. Neutral temperature is found to be 22.2 °C from the regression curve analysis. However, the temperature corresponding to neutral TSV shows a gradual increasing trend in comfort temperature from winter to summer months. The neutral temperature for winter (January) month is 20.8 °C, for pre-summer (April) is 22.4 and for summer (July) month it is 23.3 °C. The predicted comfort temperatures by Humphreys and Auliciems' comfort models for the month of January are very low in comparison to the comfort temperature obtained from regression analysis and TSV. It is also observed that the range of comfort temperature in this climatic zone is approximately 7.3 °C, i.e. minimum temperature corresponding to −1 sensation is 18.9 °C in winter season and maximum temperature corresponding to +1 sensation is 26.2 °C in summer season. So, for comfortable indoor environment the indoor temperature fluctuation should not be more than 7.3 °C.

The indoor house temperature swing is quite satisfactory for naturally ventilated buildings of this climatic zone. The internal heat gain can be enhanced by minimizing the heat leakage and by conventional space heating like burning firewood or coal during the winter months. The house is constructed on the southern slope and receives maximum solar radiation. The daylight inside the living space is found to be satisfactory. In Fig. 7, it is observed that in the pre-winter months the indoor temperature is always high in comparison to outdoor temperature. So, it can be concluded that for the first 15–20 days of the month of October, this thermal behavior may lead to discomfort. But in later part of October and November, this provides enhanced level of comfort as outdoor temperature is low. This shows that heat gain during daytime is much higher than the loss in nighttime. This trend is absent in the house of warm and humid and cool and humid climates for pre-winter month. Based on these facts, it can be concluded that houses of cold and cloudy climatic zones are showing better thermal performance in comparison to the houses of the other climatic zones.

7. Conclusions

This study is based on the field measurements and field experiments. It clearly represents more detailed understandings of thermal environments inside the vernacular buildings in different climatic zones of North-East India during winter, pre-summer, summer/monsoon and pre-winter months. Temperature profiles for warm and humid and cold and cloudy climates show that indoor temperature swing are within permissible limits for all the months mentioned above. But for the house in cool and humid climates, the indoor temperature swing is much higher. This is due to low insulation level and low thermal inertia of walls. From the study, it can also be concluded that none of the houses are significantly comfortable in winter but are fairly comfortable in pre-summer, summer and pre-winter periods. The house in cold and cloudy climatic zone provides better comfortable time in comparison to the house in other climatic zone. From the results, it can be concluded that occupants have enhanced control over indoor environments in the vernacular houses because they have the flexibility to control their personal and environmental conditions in the form of different adaptations.

This study also concludes that Humphreys and Auliciems' models predict better results in summer. But there is a large deviation in comfort temperature in winter compared to TSV value. From the results, it can be observed that the neutral temperature corresponding to each month in each climatic zone varies by ±2 °C in comparison to same month in other climatic zone and having higher value in warm and humid climate and lower in cold and cloudy climate. It is also found that, in all the three climatic zones the range of comfort temperature lies between 6 °C and 7.3 °C. This provides greater flexibility to engineers and architects to design buildings with more energy saving options by introducing solar passive features in the building. Some design modifications is also suggested to improve the indoor environment comfort level in the existing houses based on this study. This thermal performance study provides clear picture and justification of thermal comfort status inside the vernacular buildings of North-East India. It can also be concluded that the dry bulb temperature can be effectively used to represent the comfort temperatures as it is understood widely by common people in comparison to operative temperature and mean radiant temperature. Finally this quantitative information will help engineers and architects to construct climate oriented buildings in the region.

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