An Adaptive Approach to Define Thermal Comfort Zones on Psychrometric Chart for Naturally Ventilated Buildings in Composite Climate of India.

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Abstract

Thermal comfort standards such as ASHRAE 55-2013 defines comfort boundaries which are based on the experimental results conducted in climatic chambers and field studies. The current comfort standards do not reflect the cultural and climatic diversity of India. A thermal comfort field study was conducted in 32 naturally ventilated buildings, collecting a total of 2610 samples spread over a total period of four years, covering all seasons, wide age groups, clothing types, and building types. In the present study, ASHRAE comfort boundaries at three different air speeds - still air (up to 0.2 m/s), natural air flow (0.2 m/s-0.5 m/s) and forced air flow with ceiling fan assist (0.5 m/s-1.5 m/s) are investigated. The method of calculation suggested by the ASHRAE 55-2013 and ISO-7730 were followed to determine extended acceptable temperature ranges for comfort at elevated air speed. Comfort boundaries are defined based on climate specific adaptations, the role of air speed and thermal preferences. Results from this study indicate that subjects in naturally ventilated buildings of this region are comfortable at temperatures different from those suggested by ASHRAE 55 and ISO-7730 standards. New extended boundaries of comfort zones are proposed considering various adaptations specific to this region, including the role of air speed to offset the temperature. The proposed comfort zones show that subjects are comfortable up to 32°C at still air condition (0 m/s-0.2 m/s) and up to 35°C at higher speed (up to 1.5 m/s) in naturally ventilated buildings in the composite climate of India.

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1 Introduction

The ‘steady state’ thermal comfort theory proposed by Fanger [1] has become the foundation for the internationally accepted thermal comfort standards such as ASHRAE 55 [2] and ISO 7730 [3]. Nicol and Humphreys [4] in 1972 put forth the concept of the adaptive model which challenged the steady state comfort theory. After that, various studies on adaptive comfort across the world in last decade has revealed that occupants in naturally ventilated buildings are more flexible towards variations in the outdoor environmental conditions. Occupants use several adaptive controls to make their indoor environment thermally comfortable [5-8]. Subsequently, an adaptive thermal comfort model for naturally ventilated buildings has been developed based on thermal comfort data of 21 countries under the ASHRAE RP-884 project [5]. Currently, the adaptive model is widely accepted as an efficient tool in predicting indoor comfort conditions for naturally ventilated buildings [9-10].

1.1 Existing comfort standards: ASHRAE 55 comfort boundaries

The comfort zone is defined as the range of climatic conditions within which a majority of persons would feel thermal comfort. ASHRAE 55-2013 [2] sets out an acceptable comfort zone on a psychrometric chart, specifying boundaries of operative temperature and humidity for sedentary activity (1 met-1.3 met) and defined clothing (0.5 clo -1 clo). The PMV model used in ASHRAE Standard 55-2013 considers the air speed up to 0.2 m/s whereas, the Graphical Elevated Air Speed method and the Standard Effective Temperature (SET*) method allows the use of elevated air velocities for comfort improvement [2-3]. While this psychrometric chart was constructed for designing the indoor environment of conditioned buildings (commercial and residential), it has gradually begun to be used in evaluating the indoor climate in naturally ventilated buildings as well [11-13].

It has been investigated through literature study that some problems exists; when these comfort standards are used to evaluate the indoor conditions in naturally ventilated buildings especially in tropical countries [11,14-15]. People; particularly in hot and warm climates; feel comfortable under free-running conditions while environmental parameters were found far away from traditional comfort zones. The comfort zones defined on existing psychrometric chart does not account for the acclimatization, comfort expectations and behavioural adaptation of the inhabitants in such countries [16-18]. Also, the role of higher air speed for expanding the range of comfortable temperatures in tropical climate countries is still not considered in most of the building standards. Results from the comfort studies in such climates found subjects, expressing a desire for greater air movement and comfort zones increasing with the aid of air movement [16, 19, 20]. The bioclimatic building design’s

environmentally friendly approach with natural ventilation and dynamic indoor climatic conditions are inconsistent with these conventional comfort standards [12, 21].

1.2 Thermal comfort: Indian scenario

Buildings account for 35% of total final energy consumption in India today, and building energy use is growing at 8% annually [22]. About 73 % of the energy consumed in Indian residential buildings is used for providing thermal and visual comfort indoors [23]. Economic prosperity in urban India will lead to rapid growth in the use of mechanical air conditioners. It can have a substantial impact on energy consumption.

The National Building Code of India, 2005 specifies a narrow comfort temperature range between 21°C - 23°C in winter and 23°C - 26°C for summer for all types of buildings [24]. One of the earliest studies on thermal comfort in tropical countries includes work by Sharma and Ali's [16]. Their research was focused on naturally ventilated buildings in North India and reported high comfort temperature bandwidth (25°C–30°C) as compared to comfort zone suggested by ASHRAE 55. Among the studies conducted in past one decade from the Indian sub-continent focused mainly on: (1) residential apartment buildings in Hyderabad [18], (2) vernacular housing in the north-east region [25], (4) students dormitories/ laboratory [26], (5) hostels & residential buildings [27-29] and (6) office buildings [30, 31]. A summary of such studies with their climatic region, comfort range, and building types are presented in **Table 1**. Researchers have revealed that the occupants of naturally ventilated buildings in tropical sub-continent are tolerant to higher temperature [16, 18, 25-31]. This generates the need for an alternative standard that would have more relevance to the variable indoor environments in naturally ventilated buildings, including natural ventilation and other contextual adaptations in which occupants have a higher degree of control over their indoor environment.

Table 1

In the present study, we have considered comfort zones at different air speed, viz. still air (0 m/s-0.2 m/s), natural air flows(0.2 m/s-0.5 m/s) and mechanical air flows through fans (0.5 m/s-1.5 m/s) with extended acceptable temperature range as obtained by ASHRAE 55 and ISO-7730 calculation method [2,3]. To analyze the applicability of these extended comfort zones at elevated air speeds; the comfortable votes (corresponding to three central categories ± 1) from a thermal comfort study in this climatic region are overlaid on conventional psychrometric comfort zones. One of the advantages of using these comfort zones is that it considers all parameters (operative temperature, relative humidity, air speed, clothing insulation and activity of subjects) utilized in the PMV/PPD model, well accepted in defining acceptable thermal comfort ranges.

This study proposes the extension of comfort boundaries based on adaptive thermal comfort realities in the composite climate of India, established through the following tasks:

- a. Test the applicability of existing comfort boundaries/zones namely ASHRAE 55 comfort zones in naturally ventilated buildings.
- b. Development of new boundaries of comfort zones to reflect region-specific adaptation and preferences of building inhabitants.

2 Methodology

2.1 Field study description

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 18 offices and 14 residential buildings (**Appendix 1**). Meteorological conditions under this climate vary extremely hot during summer and to chilling cold winter seasons. Summer peak temperature soars above 45°C, and then falls to below 4°C in winter. Due to this significant variation, months across the year are segregated into three categories, namely, summer, moderate, and winter. In the present study, a particular month is considered winter if the daily mean outdoor temperature varied between 4°C-25°C for minimum 20 equivalent days (480 hours). Likewise, a particular month is considered summer if the daily mean outdoor temperature was more than 27°C for more than or equal to 20 equivalent days. If any month, is neither winter nor summer as per above criteria, it is considered as moderate [29, 32]. Following this approach, in Jaipur, the summer season is over six months (April-September), winter of four months (November-February), separated by the moderate season of two months (March and October). The present thermal comfort surveys were conducted covering all the three seasons.

2.2 Questionnaires and Scales

The transverse type questionnaire was used as per the study conducted by Dhaka et al. [27]. Section-A of the questionnaire consists of thermal sensation and preference votes for environment conditions such as air temperature, relative humidity, and air speed on ASHRAE seven-point sensation scale and five-point preference scale, respectively as shown in **Table 2**. Section-B of the survey form is used to measure the environmental parameters and the environmental conditions surrounding the study subjects.

A detailed description of how surveys conducted and the field measurements were taken can be found in the early study by Dhaka & Kumar et al. [28,29].

Table 2

2.3 Sample size description

The subjects were all Indian nationals well acclimatized to the composite climate of Jaipur for more than one year and were in the age group of 18-70 years. Each subject participated in the survey after they had settled in the environment for more than 20 minutes. The sample size varied across the

seasons, and a total of 2610 fully completed survey forms were obtained including responses from 2013 males and 597 females. The mean age of male subjects was found to be 25 years (SD=7.8) while that of female subjects 21 years (SD= 4.9), respectively. A total of 2610 questionnaire were completed by occupants in all seasons from naturally ventilated buildings. Comfort parameters around occupants were measured during filling in survey questionnaires.

2.4 Measurement of environmental and personal parameters

Physical measurements of environment variables were recorded surrounding the subject using high accuracy instruments. The measurements were taken at the height of 1.1 m above the ground level following the Class-II protocol [2, 3]. The measurement of environmental parameters such as air temperature, globe temperature, air speed, and personal variables such as clothing level and metabolic activity (T_a , T_g , V_a , RH, clo, met) were recorded at the same time and place as the questionnaire administered to the subjects. **Table 3** demonstrates the details of instruments used in this study to measure the indoor conditions. Outdoor environmental data consisting of temperature and relative humidity for the entire period of study has been taken from a weather station located at MNIT, Jaipur, India.

Table 3

For clothing insulation and metabolic rates, we used the standard checklists provided in ASHRAE 55 [2]. Clo-values for Indian women clothing including the cotton salwar –kameez, saari, etc. that are not available in ASHRAE 55 and ISO 7730 standard checklist, were taken from other India specific studies [18, 26]. The mean activity of the subjects was observed to be nearly sedentary activity, i.e. 1.06 met (1 met=58.2 W/m²) and it shows that the subjects were mostly seated or doing light office work.

3 Results & Analysis

3.1 Assessment of physical environmental measurements

During the field study period, minimum and maximum outdoor dry bulb temperatures were 12°C and 45°C. Room air temperature varied between 14.4°C to 39.1°C and relative humidity was recorded 8% to 96%. This, large variation in outdoor dry bulb temperature affected indoor temperature and thereby occupant comfort temperatures. **Figure 1** depicts the change in indoor and outdoor environmental parameters for all seasons during the field study.

Figure 1

The naturally ventilated buildings experience a higher fluctuation in mean indoor temperature, from winter (Mean T_{op} =22.1°C, SD=3.60) to moderate (Mean T_{op} =29.2°C, SD=2.89) to summer

(Mean T_{op} =31.8°C, SD=2.86) during the study period. Subjects in naturally ventilated buildings experienced higher indoor air speeds apparently through cross ventilation of opening doors and windows, and through the use of fans. This phenomenon is more pronounced at the higher temperatures and relative humidity in the summer season. Correspondingly, the mean air speed was observed to be higher during the summer (Mean V_a =0.62 m/s, SD=0.39) than during the moderate season (Mean V_a =0.57 m/s, SD=0.37) and winter (Mean V_a =0.27 m/s, SD=0.19), respectively. **Table 4** shows the statistical analysis of seasonal variation in outdoor and indoor variables observed during the field study.

Table 4

3.2 Subjective thermal variables

3.2.1 Thermal sensation and preference for temperature (TSV & TPV)

About 79%, 92%, and 70 % of the subjects responses were found in comfort band (± 1 sensations) in summer, moderate and winter season, respectively. A total of 82 % of the subjects felt comfortable (including ± 1 sensations) at prevailing indoor temperature conditions.

Figure 2

Figure 2 shows the distribution of subject responses collected for sensation and preference of temperature during summer, moderate and winter season, respectively at 95% confidence interval. Over an annual cycle, average thermal sensation varied between slightly warm to slightly cool. During the summer season, the subject's mean thermal sensation was higher than neutral but less than slightly warm (Mean TSV=+0.67, SD=0.92), and during winter, it was lower than neutral but less than slightly cool (Mean TSV=-0.75, SD=0.76). The preference for a cooler environment dominates across the seasons, with a mean value of - 0.22. Using the scale described above, the mean preference for temperature change was -0.84 in summer, - 0.51 in moderate seasons and +0.37 in winter. **Table 5** presents the mean values of thermal sensation along with other subjective variables for all seasons in naturally ventilated buildings.

Table 5

Kumar et al. [29] reported the preliminary findings of this comfort study by addressing thermal comfort expectations, air speed variability and control, seasonal clothing and behavioral adaptations at personal level i.e. changing clothing levels, use of personal environmental controls like the opening of window/door and use of the fan, etc.

3.2.2 Sensation and preference for air speed (AVS & AVP)

Nicol et al. [33] noted in a study of Roorkee and Bagdad buildings that air velocities up to 1.5 m/s were acceptable for subjects in hot and warm countries. Higher air speeds are more useful for increasing the heat loss and evaporation from skin, even at higher operative temperatures. In the surveys, mean air speed was found to increase with the season getting warmer. It was 0.27 m/s in winter, 0.57 m/s in moderate seasons and 0.62 m/s in summer, respectively. The corresponding occupant mean sensation of air speed for the different seasons was -0.35 ($SD=1.09$) in summer, -0.25 ($SD=1.01$) in moderate seasons and -0.10 ($SD=0.62$) in winter, respectively. We have measured the air speed sensation (AVS) and air speed preferences (AVP) in all the surveys using ASHRAE seven point and five point scales. During the field study, whenever the velocities were found below 0.2 m/s, still air condition was assumed. This scenario was commonly observed during the winter season and when there was no cross ventilation of air through windows or door opening or ceiling fans were remain closed for most of the time. Also, mean air speed observed was below 0.5 m/s in occupied spaces whenever only windows or door were found open. Fans offer a significant adaptive opportunity for users at high indoor temperatures, especially during summer season. In the present study, during summer, the mean air speed observed during fan operation was more than 1 m/s and reached to a maximum of 2 m/s.

So, the indoor air speed data was regrouped into three groups: 0.2 m/s and lesser, 0.2 m/s-0.5 m/s, and 0.5 m/s -1.5 m/s or higher for further analysis. The air velocities up to 0.2 m/s are assumed to still air, for 0.2 m/s-0.5 m/s are with natural air flow through the opening of windows or doors and more than 0.5 m/s are fan assisted or fan forced air flow.

Figure 3 presents the frequency distribution of the AVS and AVP votes across different air speed groups at 95 % confidence interval. It was observed that prevailing air velocities in building space were sensed as lower than required by about 45% of the occupants in naturally ventilated buildings. In addition, as temperatures rise from winter to summer, the preference for more air speed increases. About 50-60% occupants in all speed groups, desired more air movement than prevailing indoor air movement. Indraganti et al. [34] found during their field study of offices in South India that about 60-70% people desired increased air movement in natural ventilation mode. Zhang et al. [35] noted more than 50% of the office population wanting more air movement in their analysis of the ASHRAE database. This also corroborate with studies conducted in tropical countries and reporting that inhabitants in hot and warm countries prefer higher air speed to make themselves comfortable at elevated temperatures [14-18, 27-29].

Figure 3

3.2.3 Sensation and preference for humidity (HSV & HPV)

In present comfort study, sensation for humidity and preferences were asked on ASHRAE seven point and five point scale, respectively. Relative humidity during the study was found varying between 8% and 96%. Mean humidity sensation (HSV) for all data sets in all naturally ventilated buildings was +0.13 at relative humidity of 43.2%. Mean humidity sensation for summer, moderate and winter season was found to be +0.21, -0.23, and -0.35 respectively. Also, mean humidity of 47%, 33%, and 43% was observed for summer, moderate, and winter season, respectively. A maximum of 65% subjects accept the prevailing humidity conditions during the study and still want no change in humidity. Very few subjects accept and prefer to be stay in slightly dry humidity conditions (18%) and slightly humid conditions (10%). The reason is acclimatization of subjects for such a wide variation in humidity conditions, prevailing for this region.

3.3 Subjective evaluation and ASHRAE 55 comfort zones

ASHRAE 55-2013 [2] provides a graphical method to use the PMV-PPD model. The comfort zone is defined by the combinations of air temperature and mean radiant temperature for which the PMV is within the recommended limits. This comfort zone is limited to air speeds not greater than 0.20 m/s (40 fpm). However, ASHRAE 55 allows elevated air speed method to increase the maximum temperature for acceptability if the affected occupants are able to control the air speed. In the present study, the method of calculation suggested by the ASHRAE 55-2013 and ISO-7730 was used to determine extended acceptable temperature ranges for comfort at elevated air speed. Hence, different comfort zones were estimated on conventional psychrometric chart at various clothing, activity and air speed combinations i.e. 0.5 m/s, 1 m/s and 1.5 m/s.

The mean thermal sensation of acclimatized populations in any geographical area has been found to be hovering around the neutral point in ASHRAE's thermal sensation scale [4, 5]. Owing to individual preferences, it is impossible to specify a thermal environment that will satisfy everybody [5, 6]. As a result, ASHRAE 55 and ISO standard 7730, for example, recommends that the PPD should be lower than 20 %, i.e. PMV within the range ± 1 can be considered as comfortable. On ASHRAE seven point scale, the traditional assumption is that people voting within the central three categories of the thermal sensation (± 1) are comfortable. In the subsequent section, we segregated all thermal comfort data corresponding to three central categories (± 1) by summer, winter and moderate seasons, plotted on the psychrometric chart. Segregation of data is done by clothing level and airspeed groups (still air, natural flow and fan assisted flow) for each season. **Table 6** represents the distinct conditions or “cases” considered for plotting comfortable votes on the ASHRAE 55 comfort zone.

Table 6

3.3.1 Summer thermal sensation votes and ASHRAE-55 comfort zone

During the summer seasons, outdoor temperatures varied from 25°C to 45°C whereas room temperature fluctuated from 26°C to 38°C. Neutral and comfortable votes, from the present study, are segregated for the summer season in two clothing levels (up to 0.6 clo) and four air speed ranges (0 m/s to 1.5 m/s) as shown above in **Table 6**. These comfortable votes are plotted on the psychrometric chart with ASHRAE comfort zones. **Figure 4(a) and 4(b)** describes the distribution of subjects' comfortable votes on ASHRAE comfort zones for different air speed and clothing level up to 0.6 clo in the summer season. It was found that during the summer season, more than 90% comfortable votes were found outside the ASHRAE comfort zone for still air condition for all clothing levels (up to 0.6 clo). Similar observations were recorded for air velocity range of 0.2m/s-0.5m/s (natural air flow) and 0.5m/s-1.5m/s (fan forced air flow) as shown in **Figure 4(a) and 4(b)**. These observations indicate that comfort zone for occupants in naturally ventilated buildings in composite climate of India is larger than one proposed by ASHRAE 55. Some votes were found comfortable at higher relative humidity (more than 80%) even at low air speed (~0.2m/s), this is because of acclimatization of occupants to their environmental conditions.

These results are consistent with the findings of Nicol [14] and Khedari et al. [36] in hot and humid locations, greater air movement not only aids convective heat transfer from skin, but it also increases evaporation of sweat making occupants comfortable. Also, inhabitants of this region are accustomed to its environmental conditions and can tolerate higher temperature and humidity, feeling comfortable in naturally ventilated buildings [16, 29, 30]. Numerous field studies have shown that fan use in naturally ventilated buildings shifts the comfort temperature limit up to 4°C [14-16, 29, 30]. Chow et al. [37] found that more air movement could cause an inherent pleasant sensation of freshness in addition to thermal comfort.

Figure 4(a)

Figure 4(b)

3.3.2 Moderate thermal sensation votes and ASHRAE-55 comfort zone

Conditions during the moderate season are pleasant. Mean clothing levels for this season are 0.34 (Mean clo=0.34 clo, SD=0.15), and the mean thermal sensation is slightly towards a little warmer side of the thermal sensation scale. Occupants adaptively used window opening and fan operation at increasing temperature to make their surrounding comfortable. So mean indoor air speed (Mean V_a =0.57, S.D. =0.37) observed during this season were higher than 0.2 m/s. More than 70% of the comfortable votes for low clothing levels up to 0.3 clo lie outside the ASHRAE comfort zone at air speeds of 0.5 m/s to 1.0 m/s, as shown in **Figure 5(a)**. However, most of the comfortable votes were found in ASHRAE comfort zone at elevated air speed up to 1.5 m/s (**Figure 5(a)**). A closer look

at **Figure 5(b)** reveals that at higher clothing levels, from 0.3 clo to 0.6 clo, even with higher air speed, comfort votes shifted towards a lower temperature range, almost ignoring the effect of air movement. This is because the clothing acts as insulation to the body, restricting the pleasant effect of air speed in producing comfort by increasing evaporation loss from exposed skin.

Figure 5 (a)

Figure 5 (b)

3.3.3 Winter thermal sensation votes and ASHRAE-55 comfort zone

In the winter season, the temperature drops to a minimum of 4°C in composite climate of Jaipur, India. So the mean thermal sensation votes shifted towards the slightly cooler side as the season changes from summer to winter. The clothing level of the subjects also changed from 0.3 clo to more than 1.2 clo providing an insulating effect towards surrounding environmental conditions. Comfortable votes for clothing level range up to 0.6 clo for different air speed ranges, are plotted on the psychrometric chart as shown in **Figure 6(a)**. It can be seen from **Figure 6 (a)** that about 87% of the comfortable votes are within expected ASHRAE boundaries for clothing level up to 0.6 clo. However, as clothing level increases from 0.6 clo to 1.2 clo, comfortable votes start deviating from ASHRAE 55 winter boundary and shift towards lower temperatures. At clothing insulation ranges of 0.6 clo to 1.2 clo, subjects feel comfortable at temperatures as low as 16°C in this region, revealing acclimatization of its inhabitants towards cold outdoor conditions as shown in **Figure 6(b)**. Rohles and McCullough [36] have also observed that as people put on more layers to counter decreasing temperatures. Several studies have found that region-specific traditional clothing gives people much more flexibility and adaptability, allowing them to withstand the broad fluctuations of temperature they face in naturally ventilated buildings [38-41].

Conditions didn't change drastically but steadily, as the season changed from moderate to winter. During pre-winter month of November and pre-moderate month of February, indoor conditions were found slightly warmer with mean temperatures higher than 26°C. Clothing values continuously increased from the moderate (Mean clo = 0.34, SD = 0.06) to winter season (Mean clo = 0.67, SD = 0.14), revealing continuous adaptation by occupants through adjusting clothing patterns. Also, during this period occupants adaptively used windows and fan at low speed to make their environment comfortable [29]. Thus, some votes were found at mean indoor air speed higher than 0.2 m/s but not more than 0.5 m/s. Comfortable votes for clothing level ranges of 0.6 clo to 1.2 clo and 0.2 m/s to 0.5 m/s air speed range are plotted on the psychrometric chart as shown in **Figure 6(b)**. At these higher clothing levels, subjects also have no exposed parts of their body, so the effect of higher air speed from 0.2 m/s to 0.5 m/s is also negligible. This can be seen from **Figure 6(b)** that almost all the votes lay in comfort zone even at higher indoor air speed of 0.5 m/s.

Figure 6(a)

Figure 6(b)

4 Discussion

4.1 Proposed comfort zones: Shifting of temperature limits for naturally ventilated buildings

In the preceding sections, detailed analyses show the fragility of ASHRAE 55 comfort zones to capture the thermal comfort expectations and adaptations taken by subjects, especially for tropical countries like India. Arguably, these comfort zones are developed mainly for conditioned buildings in cold countries with rare occurrences of naturally ventilated buildings [11, 12, 16]. Hence, this study focuses on proposing new comfort zones, modified over ASHRAE 55, to suit this region's inhabitants comfort expectation, acclimatization behavior and the role of air speed preferences, especially for naturally ventilated buildings.

4.1.1 Proposed comfort zone: still air (0-0.2 m/s)

For still air conditions up to 0.20 m/s, ASHRAE 55's existing thermal comfort zone extends from 20°C in winter to 27 °C in summer given a relative humidity range of 20 % to 80 %, with some high-temperature limitations on humidity [2]. However, at higher relative humidity, the sensation of thermally comfortable exists at lower operative temperature, which is shown along a tilted line on psychrometric chart. These tilted lines are functions of operative temperature, relative humidity, and air speed under standard clothing (0.5 clo-1.0 clo) and activity level (1 met-1.3 met), so different comfort zones have been estimated on psychrometric chart for the different combination of clothing, air speed, and relative humidity effects.

A comfort zone can correspond to either 80% acceptability or 90% acceptability (i.e., a narrower acceptable temperature range where only 10% of the people are dissatisfied). However, in most buildings this 90% satisfied rating is rarely obtained, with maximum satisfaction around 80% [2]. So, ASHRAE 55 recommends 80% acceptability for thermal environment and the percentage of people dissatisfied (PPD) should be lower than 20 per cent. We considered comfortable votes with clothing ranging up to 1.2 clo, activity level between 1 met-1.2 met and still air conditions up to 0.2 m/s across all seasons i.e. summer, moderate and winter, respectively. **Figure 7** clearly indicates that subjects are comfortable at higher temperatures than the range suggested by ASHRAE 55. We are proposing a new comfort zone, encompassing the comfortable predominant votes from 18°C to 32°C between the relative humidity of 20% to 80%. While some votes are still outside this comfort zone, the comfort zone boundaries proposed, ensures at least 80 % of the occupants will be comfortable in naturally ventilated buildings in this climatic zone. Out of the remaining 20% samples, the nearly same

numbers of samples have been left outside the comfort zone, on the cold and hot side, while deciding the boundaries of the comfort zone.

Figure 7

4.1.2 Proposed comfort zone: natural air flow (0-0.5 m/s)

The use of windows and ceiling fans are prevalent in naturally ventilated buildings in tropical climates, and should be considered a viable addition to the thermal comfort standards. Zhang et al. [35] re-evaluated the ASHRAE 55 database and found that temperatures in the range of 25.5°C to 28°C were deemed comfortable when ceiling fans were deployed. They further concluded that the use of personal desktop fans could enhance the upper comfort limit up to 30°C. A chamber study of warm climate comfort also reveals the effect of air speeds even higher than the 0.8 m/s threshold limit of ASHRAE 55, towards enhancing the upper comfort limit up to 32°C [10].

In this study, it has been found that subjects feel comfortable at higher temperatures whenever windows opening or fans were used in naturally ventilated buildings, in all three seasons [29]. This effect was most pronounced on summer days when conditions are hottest. **Figure 8** shows the comfortable votes plotted on the psychrometric chart for an air speed range of up to 0.5 m/s. This air speed relates to natural airflows from opening windows and doors or low fan speeds. During the summer season when clothing light (Mean clo=0.3), subjects feel comfortable at temperatures as high as 33°C and between 20% to 80% relative humidity. An extended comfort zone is outlined in **Figure 8** considering the moderate air speed effects for all clothing up to 1.2 clo and activity level of 1 met - 1.2 met.

Figure 8

4.1.3 Proposed comfort zone: fan forced air flow (0-1.0 m/s & 0-1.5 m/s)

Figure 9 shows the comfort zone, thus developed to reflect thermal comfort votes at air velocities from 0 m/s - 1.0 m/s, activity 1 met - 1.2 met, and clothing insulation up to 1.2 clo. It is evident that at such high air speeds most of the votes are from the summer and moderate seasons. The proposed comfort zone for air speed up to 1.0 m/s expands the upper comfort boundary up to 34.5°C. ASHRAE suggests, at higher air speed upper relative humidity limit for comfort can be reached up to 95%. However, in the present study, very few votes were found thermally comfortable at relative humidity more than 80%. Also, outdoor conditions in composite climate of Jaipur remain hot and dry throughout the year except few rainy days in months of July and August. So, proposed comfort zone at air speed of 1.0 m/s is drawn considering the upper relative humidity boundary up to 80%.

A final comfort zone at air velocities from 0 m/s to 1.5 m/s is shown in **Figure 10**. The proposed comfort zone for air speed up to 1.5 m/s expands the upper comfort boundary up to 35°C in comparison to ASHRAE 55 comfort limit of 31°C. Also, the present study reveals there is an only

0.5°C increase in the maximum temperature for comfort, as air speed increases from 1.0 m/s to 1.5 m/s. Since the change in the maximum temperature for acceptability when air speed changes from 1 m/s to 1.5 m/s is marginal (~ 0.5 °C). Thus, the present study limits the air speed up to 1 m/s for no paper blowing, less energy consumption and reducing noise due to fan operation in naturally ventilated buildings of composite climate in India. ASHRAE 55-2013 suggests when control of local air speed is provided to occupants, the maximum airspeed shall be 1.2 m/s. It leads to the condition when no paper is blown due to ceiling or pedestal fans to the sedentary occupants doing light office work. These results corroborate the elevated air speed limit up to 1.2 m/s defined in ASHRAE 55-2013.

Figure 9

Figure 10

4.1.4 Validation of proposed comfort zones

The present thermal comfort study was conducted for more than four years from April 2011 to July 2015 collecting a total of 2610 comfort surveys from naturally ventilated buildings. The comfort data thus obtained is used to define the comfort zones at different air speed combinations as described in previous sections. However, it can be seen from **Figure 7** that there were conditions where very few comfort votes lie in proposed zone which may produce unreliable results for defining comfort limits. Thus, this research team has continuously monitored indoor conditions and collected comfort surveys from naturally ventilated buildings. Also; the comfort surveys have been collected for conditions where we have limited votes in the proposed comfort zones. A total of 648 comfort surveys has been observed since July 2015 till June 2016. About 63 % (N=410), 6% (N=40), 31 % (N=198) of the subjects responses were observed in summer, moderate and winter season, respectively which is further used to validate the proposed comfort zones at elevated air speeds for composite climate of India.

Figure 11(a) ; 11(b) and **11(c)** shows the comfortable (± 1) votes plotted on the proposed comfort zone for air velocities from 0 m/s-0.2 m/s; 0 m/s-0.5 m/s; and 0 m/s-1m/s respectively. It can be seen from **Figure 11(a); 11(b)** and **11(c)** that more than 80% of comfortable votes lie in proposed comfort zones which further strengthen the robustness of proposed comfort zones at different airspeed ranges.

Figure 11(a)

Figure 11(b)

Figure 11(c)

4.1.5 Enhanced comfort zones and percentage peoples dissatisfied (PPD)

The ISO standard 7730 and ASHRAE 55-2013 recommend that the percentage of people dissatisfied (PPD) should be lower than 20 percent [2-3]. PPD is derived from PMV, and is based on the assumption that thermal sensation votes of ± 2 , ± 3 represent “dissatisfied or uncomfortable”. To check the robustness of the proposed comfort zone for the composite climate of India, we also analyzed the votes which were uncomfortable, i.e. beyond the range of ± 1 category. **Figure 12(a), 12(b) and 12(c)** shows the uncomfortable votes plotted on the proposed comfort zone for air velocities from 0 m/s-0.2 m/s, 0 m/s-0.5 m/s and 0 m/s-1.5 m/s respectively. It can be seen from **Figure 12(a), 12(b) and 12(c)** that less than 10 percent uncomfortable votes lie inside the proposed comfort zone, and most of the uncomfortable votes are beyond the boundaries of proposed comfort zones when alternative conditioning would be required. **Table 7** also shows the percentage of people dissatisfied in the proposed comfort zones at different air speed ranges. In all cases, the percentage of people dissatisfied (PPD) are less than 20 percent, so these comfort zones are suitable for capturing the actual dynamic nature of naturally ventilated buildings as well as adaptation of subjects for composite climate of India.

Table 7

Figure 12(a)

Figure 12(b)

Figure 12(c)

The results indicate that subjects in naturally ventilated buildings are comfortable at higher indoor temperatures. Also, occupants use different adaptation actions like changing of clothing pattern, use of the fan, an opening of windows, etc. to make their environment comfortable at elevated temperature [18, 29]. The proposed comfort zones have extended boundaries for defining thermal comfort to reflect personal adaptation through clothing, comfort expectations and the role of air speed to offset higher temperatures. The proposed comfort zone in **Figure 13** reflects that subjects are comfortable at temperature up to 32°C (relative humidity ~ 20% - 80%) in still air conditions of 0 m/s-0.2 m/s and comfortable up to 34.5°C (relative humidity ~20% - 80%) at higher speed up to 1 m/s.

Figure 13

5 Conclusion

This paper summarizes the findings of a thermal comfort field study conducted in 32 naturally ventilated residential and office buildings in the composite climate of India using high precision instruments and questionnaires. In-depth analysis of the collected data was used to evaluate the

comfortable votes (central three categories of ASHRAE scale: ± 1) in different seasons, viz. summer, winter and moderate season. ASHRAE 55 comfort boundaries are evaluated considering this climate's specific clothing variability, the role of air speed, regional preferences, and expectations. Comfort and discomfort votes were plotted on the traditional ASHRAE 55 psychrometric comfort zone including the effects of clo, activity and air speed. The results reveal that these standards need to be expanded to capture occupant's region-specific adaptations, comfort expectations, and the role of higher air velocities in naturally ventilated buildings in tropical countries like India. Hence, the comfort boundaries have been extended reflecting the results of this study, particularly for naturally ventilated buildings. The proposed comfort zone for this particular climatic zone reflects that subjects are comfortable at the temperature up to 32°C and relative humidity of 20% - 80% in still air conditions of 0m/s-0.2 m/s. The comfort zones are further extended up to 34.5°C between the relative humidity of 20% - 80% at the higher indoor air speed of 1 m/s. Also, the present study reveals there is an only 0.5 °C increase in the maximum temperature for comfort, as air speed increases from 1.0 m/s to 1.5 m/s. So, the present study limits the air speed up to 1 m/s for comfort while no paper blowing, less energy consumption and reducing noise due fan operation in naturally ventilated buildings of composite climate in India.

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