Thermal Comfort in Naturally Ventilated Classrooms

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ABSTRACT

Thermal comfort study is very important because it correlates occupants comfort in built environment to the functioning of the building and energy consumption. PMV-PPD method works fairly well for conditioned buildings. However, this method does not provide expected results when applied to naturally ventilated buildings. Naturally ventilated buildings are much more dynamic compared to conditioned buildings in terms of thermal environment and occupant's behaviour in the built environment. In this study, questionnaire based thermal comfort survey has been carried out in naturally ventilated classrooms of Tezpur University during the months of February and May 2013 i.e. at the end of the winter season and the beginning of summer. Thermal sensation and preferences of 228 students are recorded on ASHRAE thermal sensation scale. Various associated parameters like indoor and outdoor air temperature, humidity, clothing and metabolic rate are also measured. The results reveal that the subjects did not feel extreme levels of thermal discomfort during this period. It has been observed that there is a large variation in the clothing pattern (0.83 to 1.52 clo in winter and 0.43 to 0.68 clo in summer) in both the seasons which justify the behavioural, physiological and psychological adaptation of the respondent. It is also found that the other adaptive means like use of fans, closing or openings of windows etc are used quite often. This study concludes that the comfort temperature range varies from 22 to 23.5 °C in winter month and 27.3 to 30.7 °C in summer month. It also concludes that most of the objects recorded cool thermal sensation and preferred a warmer climate in winter and warm thermal sensation and preferred a cooler environment in summer.

INTRODUCTION

Thermal comfort is defined by ASHRAE as "*state of mind that expresses satisfaction with existing environment*" (ASHRAE 55, 2013). This definition is subjective because state of mind is widely driven by perception as well as expectations of the person in question. It also can be mentioned that the dissatisfaction can be associated with warm or cool sensation of the habitants in general and it is expressed by PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied) indices (Fanger, 1986). Hence, it is not possible to specify an environment that will satisfy everybody's thermal comfort. Considering the discreatness of thermal comfort, it can be stated that the same thermal environment may be perceived differently by different people or different people may perceive same thermal comfort at different thermal environments (ASHRAE 55, 2013). However, it may be possible to specify environments to be predicted acceptable, if at least 80% of the occupants feels comfortable

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(Fanger, 1986). At present, the definition of thermal comfort can be approached in two different ways, each one with its own advantages and limitations: the heat-balance approach and the adaptive approach (Singh et al., 2011). The PMV-PPD model (laboratory based) established by Fanger was based on heat balance model (ISO 7730, 2005). The subjects considered in laboratory experiment were European and American students and experiments were conducted in a controlled climate chamber. This method of evaluating comfort is best suitable for conditioned buildings and deviates largely in case of naturally ventilated buildings. The interactions between occupant and immediate environment in a naturally ventilated building are much more dynamic and the occupant's behavioural, physiological and psychological adaptations are more wide compared to conditioned buildings (Alfano et al., 2013; Singh et al., 2011; Singh et al., 2015**)**. Singh *et al.* developed theoretical adaptive thermal comfort models explaining the reason behind the deviation of PMV to that of Actual Mean Vote (AMV) for same set of environmental parameters (Singh et al., 2011). Alfano *et al.* also reported that Fanger's thermal comfort model can be made effective in naturally ventilated environments by adding the right expectancy factor with the model (Alfano et al., 2013).

Wong and Khoo conducted thermal comfort survey in classrooms which are mechanically ventilated by fans in Singapore (Wong and Khoo, 2003). It is found that the occupants' acceptable temperature range lies beyond the comfort zone of ASHRAE standard 55. Corgnati *et al*. carried out surveys in two University classrooms in Turin, Italy applying both objective and subjective surveys confirming that thermal comfort condition and high energy performance are complimentary to each other (Corgnati et al., 2009). Jung *et al.* investigated subjective responses of thermal comfort of students in a University in Korea (Jung et al., 2011) This study found that the mean Thermal Sensation Vote (TSV) of respondents is almost neutral when the PMV in the classroom moves to neutral and slightly cool, and the TSV is almost '+1.5' when the PMV moves to slightly warm. It is also reported in this study that the acceptability ratio of thermal environment is slightly different from ASHRAE Standard 55-2004. It is found from thermal comfort survey at school that children are more sensitive to changes in their metabolism than adults, and their preferred temperature is lower than that predicted by the standard models (Teli et al., 2012; Yun et al., 2014). Wang *et al.* study on thermal environment of University classrooms and offices suggested that the neutral temperature varies with the indoor temperature variations (Wang et al., 2014). This study also concludes that the indoor environment has influences on human adaptability, and this determines different neutral temperatures in winter and spring. Mishra and Ramgopal have done a thermal comfort survey inside a naturally ventilated laboratory in the tropical climatic region of India (Mishra and Ramgopal, 2014). This study found that large number of respondent found their indoor thermal environment to be acceptable. The comfort temperatures obtained in the study are used to develope adaptive comfort equation. This equation shows satisfactory results with the predictions from similar equations in comfort standards. Raja *et al.* studied the use of controls to modify the surrounding environment and how thermal sensation varies with application of these controls (Raja et al., 2001). Pellegrino *et al.* did a small-scale field survey on occupant's comfort and related perceptions in two University buildings in Calcutta, India and found that occupants in naturally ventilated schools show acceptability to a wider range of environmental conditions than specified by ASHRAE and ISO standards (Pellegrino et al., 2012). Hwang *et al.* investigated the adaptive model of thermal comfort for naturally ventilated school buildings in Taiwan and found that the main reason behind discomfort in the classrooms was because most students have to thermally adapt in a naturally ventilated environment when attending school because most of the families in Taiwan have air-conditioners in their household (Hwang et al., 2009).

Thermal comfort assessments of classrooms are important because extreme discomfort conditions may affect the learning ability of students. Since the classrooms thermal environment requirement is completely different to that of residential and office environment, so it demands a separate thermal environment assessment study to be carried out. In this study, thermal comfort survey through questionnaire has been carried out in naturally ventilated classrooms of Tezpur University during the months of February and May 2013 i.e. during the end of the winter season and the beginning of summer.

The thermal sensation and preference of 228 students are taken into account, in terms of the ASHRAE scale and various parameters like indoor and outdoor air temperature, humidity, clothing and metabolic rate are measured. The subjects chosen for this survey were all university students, both male and female belonging to the age group 20 to 26 years. The thermal sensation votes recorded on the ASHRAE 7 point scale during comfort survey is considered as actual mean vote (AMV). These AMV values along with other set of indoor environmental conditions are used to calculate PMV values using ASHRAE 55 and ISO 7730 standard.

METHODOLOGY

Thermal sensation is primarily related to the thermal balance of the body. This balance is influenced by the physical activity and clothing pattern of the habitants. Along with these two variables, the environmental parameters like air temperature, mean radiant temperature, air velocity and relative humidity also has an effect on thermal sensation. Thermal sensation of the occupants can be predicted, if all the above parameters are known. Hence, it is important to find out the response of the occupants about the indoor thermal environment. It has to be kept in mind that judgment of the occupant depends on his perception and expectation about thermal comfort. During field study, questionnaire is administered to subjects and simultaneously other micro-climatic parameters are measured. The subjects were asked to express their level of thermal sensation characterized in ASHRAE thermal sensation scale as shown in Table 1. It is also important to understand that the habitants are always active to the changes in existing thermal environment and always try to adapt themselves to changing environmental conditions to feel thermally comfortable. In naturally ventilated buildings, occupant's preference and expectations about comfortable thermal environment keep on changing with the change in outdoor conditions or seasons (Singh et al., 2010, Singh et al., 2011). During the comfort survey, respondent were advised to sit idle for 20 minutes, and the activity of 1.2 met is considered for the analysis. Clothing insulation is measured in terms of '*clo*' unit, and is used to estimate the insulating properties of clothing by using the tables provided in ISO 7730 standard (ISO 7730, 2005). The clothing value is determined based on an occupant's garment checklist in the questionnaire. Table 2 represents the details of the thermal comfort survey.

Table 1 ASHRAE Thermal sensation scale

Value	Sensation
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

Table 2 Thermal comfort survey details

Climatic zone	Warm and humid
Number of subjects	228 (114 in winter and 114 in summer)
Age group of the subjects	20 – 26 years
Range of clothing (during summer)	0.4 – 0.7 clo
Range of clothing (during winter)	0.8 - 1.5 clo
Number of male respondent	46 (winter); 46 (summer)
Number of female respondent	68 (winter); 68 (summer)

The thermal sensation votes recorded during comfort survey is considered as actual mean vote (AMV). Environmental, activity and clothing level data collected during comfort survey are used to calculate the PMV-PPD by using ISO 7730 standard calculation procedure. The PMV value is calculated by using equation 1 provided in ISO standard (ISO 7730, 2005).

$$PMV = [0.303 \times e^{-0.036 \times M} + 0.028] \times L \qquad (1)$$

Where L is the thermal load difference between the internal heat production and the heat loss to the actual environment and M is the metabolic rate. The PPD is calculated by using the equation 2.

$$PPD = 100 - 95 \times e^{-(0.03353 \times PMV^4 + 0.2179 \times PMV^2)} \qquad (2)$$

The PMV and PPD results are cross checked using the CBE/Berkley PMV-PPD calculation tool (CBE/Berkley, 2013). PMV values calculated by these methods over estimate the thermal condition in summer season and under estimate the thermal condition in winter season. This may be due to the model fails to consider the adaptive opportunities, preferences and expectations of the habitants in naturally ventilated buildings. It has been tried to use adaptive thermal comfort model which is combination of physics of the body's heat balance plus local climatic behaviour, preference and expectations, past thermal experiences, social and cultural practices to overcome this discrepancy. Hence, it is important to calculate the adaptive coefficient (λ = factor for adaptation) that needs to be added to PMV to make the result close to AMV. Singh et al. 2011 proposed the following relation to calculate the cPMV for naturally ventilated buildings of North-East India.

$$cPMV = \frac{PMV}{1 + \lambda \times PMV} \qquad (3)$$

The adaptive coefficient is positive means the indoor temperature is greater than comfort temperature. This case is generally common in summer for naturally ventilated buildings. It also can be concluded that at this situation, the value of cPMV is lower corresponding to the PMV or cPMV is giving cooler feeling than PMV, i.e. cPMV votes are towards comfort to that of same PMV. Similarly, the adaptive coefficient is negative means; the indoor temperature is lower than comfort temperature.This condition occurred in winter season for naturally ventilated buildings. In this situation, it is observed that cPMV is giving warmer feeling than corresponding PMV.

RESULTS AND DISCUSSION

The thermal comfort survey was carried out among the students in naturally ventilated classrooms of six departments of Tezpur University during the months of February and May 2013 i.e. during the end of the winter season and the beginning of summer. The thermal sensation and preference of the students are taken into account, in terms of the ASHRAE 7 point scale. The indoor temperature was in the range 22°C to 23.5°C during Februray and 27.3°C to 30.7°C during May. The indoor humidity during the winter season ranged from 56% to 63% and it was higher in the summer season ranging from 77% to 84%. The outdoor air temperature was found to be slightly higher than the indoor air temperature. It was observed that factors like building orientation and shading affected the indoor temperature.

Clothing level adjustment is one of the important and most effective adaptation processes to maintain the comfort at different temperatures. Figure 1 represents the relationship between outdoor temperature and clothing pattern. It has been found from the comfort survey that the clothing values are largely scattered and varies from 0.43 to 0.68 clo in summer and 0.83 to 1.52 clo in winter. The outdoor temperature variation in winter is from 21.9 to 24 °C and 28.5 to 32°C in summer. It is observed from the Figure 1, that there are two distinct clothing profiles in these two seasons. In summer, the clothing profile decreases, as the outdoor temperature increases and vice versa in the winter season. It can be concluded that there is a strong relation between the clothing pattern and outdoor temperature. The dependence of clothing pattern with the outdoor temperature has been examined through linear and polynomial regression and presented in equation 4 and 5 (where T_0 is the outdoor temperature). The coefficient of regression (CC) is low as this analysis is based on only two seasons of the year.

$$clo = -0.091T_0 + 3.2941 \qquad \text{CC: 0.7449} \qquad (4)$$

$$clo = 0.0081T_0^2 - 0.5253T_0 + 9.0534 \qquad \text{CC: 0.7721} \qquad (5)$$

It is observed that when the clothing level is less than 0.8, the thermal sensation lies from 0 to 2. This shows that during summer when the subject is feeling warm they tend to lessen their clothing insulation to attain comfort. During winter when the temperature is low and the respondent feel cool or cold thermal sensations, the clothing level is high. The respondents wear more clothes to keep themselves warm but in some cases it is observed even though when the temperature is low the students felt warm and the less clothing level is observed. This is justifying the physiological adaptation of the respondent which is resulted from long-term exposure to certain thermal environment which made the respondents habituated. It is found that the CC value is less in the present study than what observed in case of naturally ventilated residential buildings in same climatic zone (Singh et al., 2011). This happens because of restrictions in clothing pattern in University classrooms and sitting positions (sitting near or away from window with varying temperature). However, it can be observed from Figure 1 that the polynomial regression curve bents inwards suggesting the adjustments a subject undergoes and make themselves adapted to reduce discomfort created by high clothing insulation level even at relatively high temperature. This also put forth the argument that in naturally ventilated buildings, the relation between clothing level and outdoor temperature is not linear.

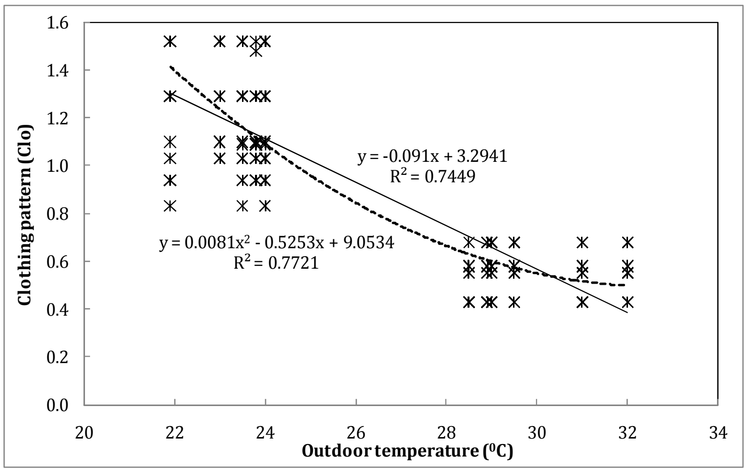

Figure 1 Relationship between outdoor temperature and clothing pattern

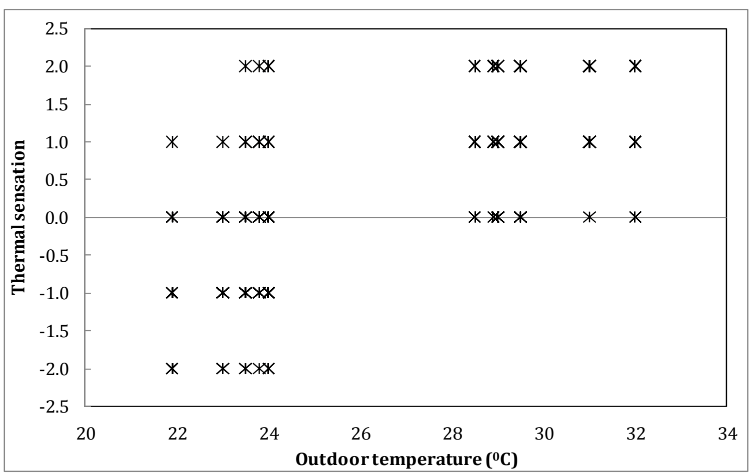

Figure 2 Relationship between outdoor temperature and thermal sensation

Figure 2 represents the thermal sensation profile against outside temperature. It can be observed from the Figure 2 that there are two distinct profiles for two different seasons of the year. In case of winter month, thermal sensation varies from -2 to +2 with the variations of outdoor temperature from 21.9 to 24 °C. Similarly, in summer month, thermal sensation varies from 0 to 2 with the temperature variation from 28.5 to 32 ^{0}C. Perception and expectation about comfort differ from person to person (behavioural, physiological and psychological adaptation). Hence, it can conclude that the same temperature perceived different thermal sensations by the occupants or different occupants perceived same thermal sensation at different temperatures. This also justifies from the clothing level variation in winter and summer months. It is also found from the comfort survey that the AMV is as high as +2 for few respondents. This may be due to the past experiences of cooler thermal environment of these respondents.In this study, inside classrooms the comfort temperature range is found to be 22-23.5 °C in winter and 27.3 -30.7 °C in summer (PMV lies between -1 to 1, or more than 80% of the people satisfied in this temperature range). This comfort temperature range is closely agreed with range of comfort temperature in naturally ventilated buildings reported in different studies (CBE/Berkley, 2013; Hwang et al., 2009; Pellegrino et al., 2012; Raja et al., 2001; Singh et al., 2011).

Predicted Mean Vote (PMV) predicts the mean thermal sensation vote on a standard scale for a large group of people. Predicted Percentage of Dissatisfied (PPD) index provides the number of people dissatisfied at a particular environmental condition. The PMV and PPD values are calculated using the calculation procedure provided at ISO 7730 standard and CBE/Berkley PMV-PPD tool. Figure 3 presents the PMV/PPD values obtained through ISO 7730 (equation 1 and 2) and also by using CBE, Berkley tool. It is observed from the Figure 3, that the PMV-PPD profile complies with the standard PMV-PPD graphs. In this figure, only one side of the profile is observed, as our thermal comfort survey is limited only to two seasons. The experimental results obtained through field measurement (calculated by using equation 1 and 2) are validated by using CBE, Berkley tool. In an attempt to incorporate adaptive comfort model, the PPD upper limit is increased to 20% i.e. -1 to +1 sensation which is completely in agreement with our results at +1 thermal sensation, the PPD value is near to 20 %. It shows that there is a slight variation in PMV/PPD values obtained by these two methods.

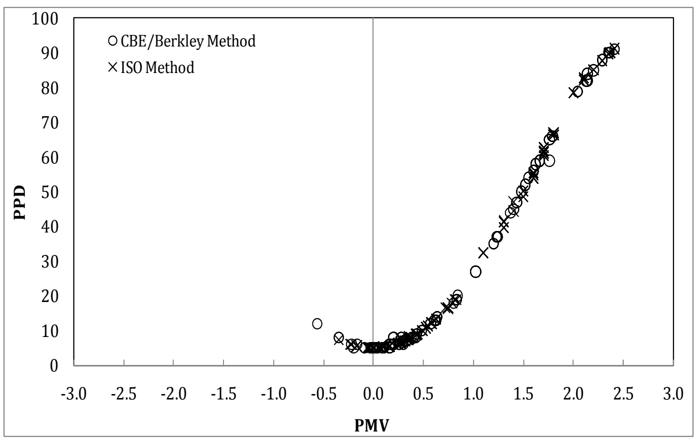

Figure 3 Relationships between PMV and PPD

In case of naturally ventilated buildings, PMV deviates widely from AMV values due to inherent limitation in assessing thermal comfort. To minimize this deviation in PMV values, Singh *et al.* proposed cPMV relation, which accommodates behavioural, physiological and psychological adaptation to calculate the adaptive coefficient (Singh et al., 2011). Equation 3 is used to calculate cPMV values. Figure 4 represents the relation between adaptive mean vote (AMV) and corrected mean vote (cPMV) with respect to PMV. The plot concludes that cPMV provides better indoor thermal sensation as this includes the adaptation of the occupants of a naturally ventilated building. The closer the cPMV to AMV mean it is assessing more correctly the real indoor thermal environment from occupant's perspective. The differences of adaptive coefficients in different seasons present the extent of adaptation of the subject. The adaptive opportunities which are available to the occupants of a naturally ventilated building actually shift the neutral temperature as well as the range of comfort temperature. It is observed from the Figure 4 that the cPMV values (-1.32 to 1.45) come closer to AMV values (-2 to +2) whereas PMV values are distributed between -1 to 3. This adaptation processes through different adaptive opportunities help the respondent to achieve required thermal comfort at a relatively lower indoor temperature in winter or higher temperature in summer month.The positive adaptive coefficient means the corrected mean vote is giving cooler feeling than the predicted mean vote. This kind of situation would occur in warm months, when the indoor temperature is higher than the comfort temperature. The reverse situation would also occur for winter months.

The thermal comfort survey has been carried out to the University students of both male and female in the age group 20 to 26. It is important to note that the age of respondent does not have any signification variations on the thermal sensation. However, as the comfort survey has been done only for two seasons, it will not be wise to make any generalized comment on this. The outdoor temperature variations during the winter days of the survey were 21.9 to 24 °C. Most of the subjects recorded cool thermal sensation and preferred a warmer climate. However, 25% voted in the neutral range and it is observed that a few subjects felt warm thermal sensation in this temperature range. Thermal comfort survey during the summer, the outdoor temperature variations recorded was 28.5 to 32 °C. Most of the subjects voted +1 or +2 i.e. slightly warm and warm thermal sensation and preferred a cooler environment. It is also observed that there is a drop of *clo* value as the temperature increase in summer months in comparison to winter months. Change in clothing pattern is a significant adaptive measure adopted by the students to increase their level of comfort. The students increase or decrease their layers of clothing in winter and summer respectively to adjust with the environment.

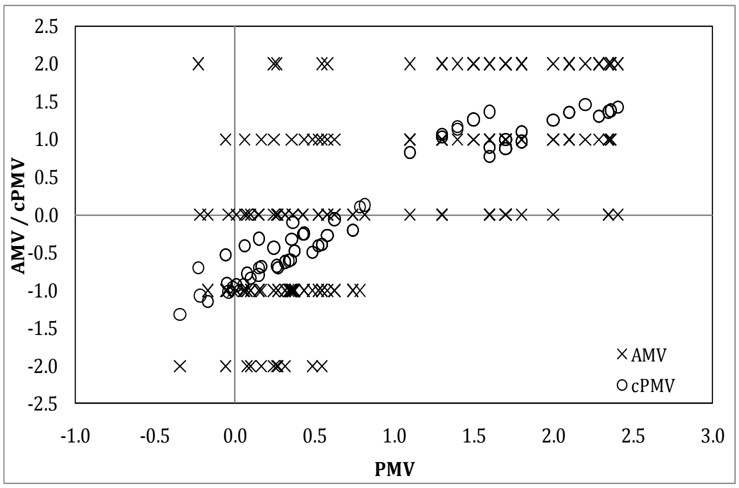

Figure 4 Relationship between PMV, AMV and cPMV

The thermal comfort temperature recommended by ASHRAE and obtained from the survey is presented in Table 3. Ranges of comfort temperature are derived from the comfort survey and corresponding measurements that were carried out during survey. The range of temperature represents the temperature corresponding to thermal sensation -1 to +1 (according to adaptive thermal comfort model, occupants can make themselves comfortable in this range by utilizing adaptive opportunities in naturally ventilated buildings). It is observed from Table 3 that the acceptable limit of comfort temperature recommended by ASHRAE is closely similar to the survey results for winter months. However, the summer months acceptable limit does not agree with the ASHRAE recommended value. This can be due to limited respondent and also for only two seasons have been covered in the thermal comfort survey. It is highly desirable that the thermal comfort survey to be done throughout the year with more respondent to get the generalized comfort temperature range.

Table 3 Comfort temperature recommended by ASHRAE and obtained from survey

Conditions	ASHRAE recommended acceptable operating temperature (°C)	Comfort temperature obtained from survey (°C)
Summer (light clothing)	Humidity range if 30% : 24.5 – 28.0 Humidity range if 60% : 23.0 - 25.5	Humidity (%) : 77 - 82.2: 27.3-30.7°C
Winter (warm clothing)	Humidity range if 30%: 20.5 - 25.5 Humidity range if 30%: 20.0– 24.0	Humidity (%) : 55 - 63: 22-23.5 °C

CONCLUSION

This study is based on the responses of the questionnaire based thermal comfort survey of 228 students of Tezpur University. The survey was carried out in six naturally ventilated classrooms at various departments located inside the University. The survey has been carried out during two different seasons of the year. It has been found that adaptation of the respondents is clearly visible in the clothing pattern which has a strong dependence on outdoor temperature. The comfortale thermal sensation (acceptable) has been observed for the temperature range from 22 to 23.5 °C in winter and 27.3 to 30.7 °C in summer month. Clothing level varies from 0.83 to 1.52 clo in winter and 0.43 to 0.68 clo in summer month. Most of the subjects recorded cool thermal sensation and preferred a warmer climate in winter. Most of the subjects voted +1 or +2 i.e. slightly warm and warm thermal sensation and preferred a cooler environment in summer. It is observed from the comfort survey that clothing pattern is a significant adaptive measure adopted by the students to increase their level of comfort. It can be concluded that the deviation in AMV to that of corresponding PMV is due to various adaptation processes used by the students to make themselves comfortable in the indoor environment. Different values of adaptive coefficient provide a better understanding about the impact of various adaptive factors on an individual to attain thermal comfort. It is felt that thermal comfort survey should be done throughout the year with more respondent to get the generalized comfort temperature range.

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