

AN APPROACH TOWARDS DEVELOPMENT OF PMV BASED THERMAL COMFORT SMART SENSOR

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Abstract

ASHRAE 55-2004 and ISO 7730 standards failed to predict actual comfort level and lead to oversize design of HVAC system. So proper thermal environment monitoring is an important subject to have right size of HVAC systems. A prototype thermal EM system has been developed. Thermal environment parameters such as: temperature, relative humidity, CO and CO₂ are measured by using the developed system. These data are used to calculate the thermal comfort index. The subjective judgments and the calculated PMV are compared with the results. The results showed the possibility of using PMV based thermal comfort smart sensor.

Index terms: Predicted mean vote (PMV), Environment monitoring system (EMS), Indoor environment quality, Thermal comfort index.

I. INTRODUCTION

Thermal comfort and indoor air quality are important factors for energy efficient buildings design [1]. Indoor environment has become an important area of research because of its influence on human health and energy consumption profile [2-4]. The indoor environment affects indoor physical environment, subsequently health and quality of life of its occupants.

The problem has become acute in recent past because of the rapid un-sustainable growth in building sector. This is primarily due to changes in lifestyles, increased dependence on artificial energy and also health related issues [5-7].

Achieving comfort is the result of combination of various environment conditions, such as air quality, air temperature, relative humidity, mean radiant temperature, air velocity, illumination, sound etc. [7]. A widely accepted definition of thermal comfort is that '*it is a state of mind that expresses satisfaction with the thermal environment*' (ASHRAE 55-

calculate the PMV value. The output of the monitoring system is compared with the subjective responses and calculated PMV value. It has been found that the output of monitoring system is overestimate as compared to subjective responses collected during the experiments. However, this clearly put forth the possibility of using thermal comfort smart sensor.

II. THERMAL COMFORT INDEX

The predicted mean vote (PMV) is a well recognized thermal comfort index and is used for measuring comfort levels inside a conditioned space [7, 8]. In case of built environment, occupants always try to achieve a thermally comfortable environment [19]. Due to the increasing expectation of the occupants from the indoor environment, the comfort standards have become more and more stringent. This has lowered the tolerance limit of occupants who live in the conditioned space and has tremendously increased the running energy cost of the buildings [9]. There is a huge potential for energy saving, if real time assessment of the indoor environment has been done. So, it has been attempted to measure the PMV in real time using major environmental variables (temperature and relative humidity) and indoor air pollutants CO₂ and CO through a thermal comfort smart sensor. These values are different for different people corresponding to the thermal environment. PMV index can be determined when the metabolic rate and the clothing label are estimated and the environmental parameters air temperature and relative humidity are measured [6]. The PMV is calculated by the followings relations:

$$PMV = (0.303e^{-0.036M} + 0.028)\{(M - W) - 3.05 \times 10^{-3}[5733 - 6.99(M - W)P_a] - 0.42[(M - W) - 58.15] - 1.7 \times 10^{-5}M(5867 - P_a) - 0.0014M(34 - t_a) - 3.96 \times 10^{-8}F_{cl}[(t_{cl} + 273)^4 - (t_{mr} + 273)^4] - F_{cl}h_c(t_{cl} - t_a)\} \quad (1)$$

where

$$t_{cl} = 35.7 - 0.028(M - W) - I_{cl} \{3.96 \times 10^{-8}F_{cl}[(t_{cl} + 273)^4 - (t_{mr} + 273)^4] - F_{cl}h_c(t_{cl} - t_a)\} \quad (2)$$

$$h_c = \begin{cases} 2.38(t_{cl} - t_a)^{0.25} & \text{for } 2.38(t_{cl} - t_a)^{0.25} > 12.1(v_{ar})^{1/2} \\ 12.1(v_{ar})^{1/2} & \text{for } 2.38(t_{cl} - t_a)^{0.25} < 12.1(v_{ar})^{1/2} \end{cases} \quad (3)$$

sensitivity. These sensors also have a fast response time, high stability, long life, low cost, low dependency on humidity, low power consumption and compact size [25].

The conductivity of a sensing element, which is formed by the metal-oxide semiconductor material changes according to gas concentration. The relationship between output voltage and gas concentration (ppm) is [27];

$$c = \left[\left(\frac{V_C R_L / V_{OUT}}{R_0} - 1 \right) \frac{1}{K} \right]^2 \quad (6)$$

Where - R_0 - Electrical resistance of sensor at zero ppm (Ω) , R_L - Load resistance ($K\Omega$), V_{OUT} - Output voltage (volt), V_C - Input voltage (volt), C - Gas concentration (ppm), K - Gas proportionality factor (dimension less)

National semiconductor's LM 35CZ has been used for sensing the temperature. It is an integrated circuit sensor that is used to measure temperature with an electrical output proportional to the temperature ($^{\circ}C$). The output voltage is converted to temperature ($^{\circ}C$) by this relation [26].

$$Temp.(^{\circ}C) = (V_{out} \times 100) / 1^{\circ}C \quad (7)$$

The humidity sensor (HIH 4000) circuit develops a linear voltage vs. RH output that is ratio metric to the supply voltage. When the supply voltage varies, the sensor output voltage follows in the same proportion. It can operate between 4V to 5.8V supply voltage range. At 5V supply voltage and at room temperature, the output voltage ranges from 0.8 to 3.9V as the humidity varies from 0% to 100% (noncondensing). The output is an analog voltage proportional to the supply voltage. Consequently, converting it to relative humidity (RH) requires that both the supply and sensor output voltages (at $25^{\circ}C$) [26]

$$RH = \left(\frac{V_{out}}{V_{supply}} - 0.16 \right) / 0.0062 \quad (8)$$

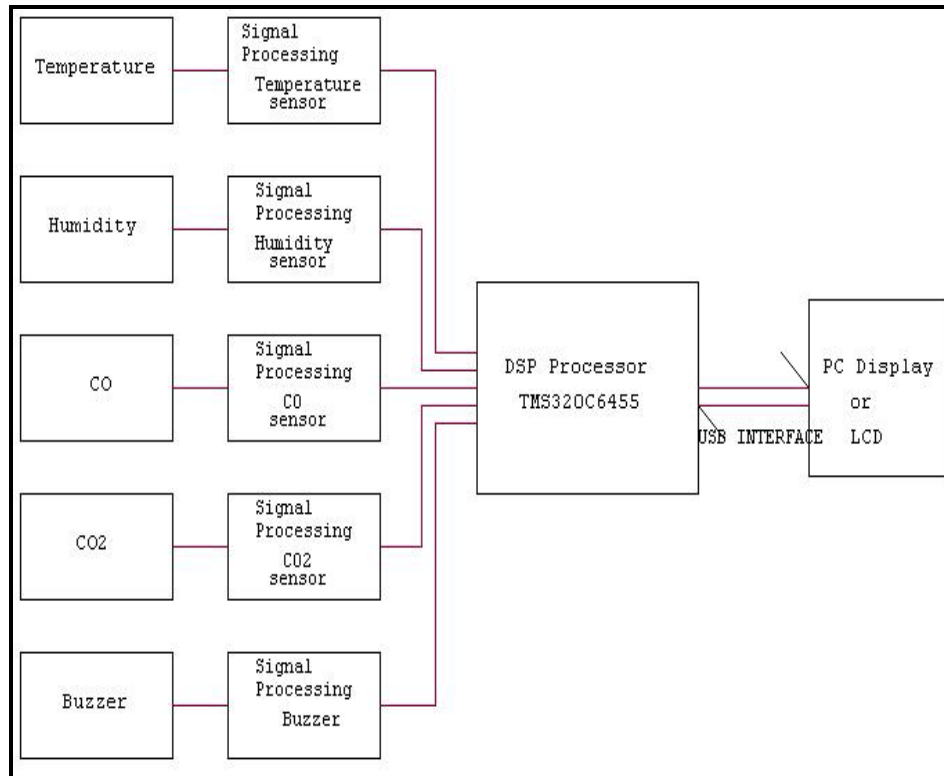


Figure 1 Block diagram of indoor Environment Monitoring System

The functioning of the DSP board is shown in Figure 2. An analog multiplexer, filter and signal transformer for level shifting are included on the DSP board. These sensors give output in analog form. The analog signals are amplified and fed to analog multiplexer. The output of the multiplexer is then fed to analog to digital converter (ADC) to get the output in digital form. The output of ADC is stored in the DSP board memory. Since these signals contains noise. So for further processing like the removal of noise, amplification and analysis of the recorded signals are done by feeding these signals to digital signal processor. For real time processing, the data collected by temperature, humidity and gas (CO and CO₂) sensor are processed according to above mentioned procedure and the resultant PMV value is displayed on LCD or monitor. A photograph of the PMV based thermal comfort smart sensor is shown in figure 3.

V. METHODOLOGY OF THE STUDY

This study tried to investigate the thermal comfort and indoor air quality of Electronics laboratory, IDDC, IIT Delhi by means of both objective and subjective approach. The study was performed during the pre-summer period in the month of April 2009. The mean outdoor temperature and relative humidity are 29°C and 40% respectively during this period. Model of the laboratory where the study was carried out, has been made in TRNSYS software. Simulation of the model is carried out to compare the temperature fluctuation and profile for the month of April 2009. Two zones were made because of the orientation of the laboratory. In zone 2 of the laboratory experiments related to subjective and objective measurements were carried out. For zone 2, the PMV values are also plotted for comparative study. Table 2 represents the thermo- physical properties of the building construction materials used as input for modeling of the laboratory. Figure 4 represent the CAD drawing of the laboratory.

Table 2 Thermo-physical properties of building material

Layer	Arrangement/ thickness (cm)	Thermal conductivity (KJ/m-K)	Density (Kg/m ³)	Specific heat (KJ/Kg-K)
External wall	Outside plaster (2)	2.6	1762	0.84
	Brick (35)	3.0	1820	0.88
	Inside plaster (2)	2.6	1762	0.84
Internal wall	Outside plaster (1.5)	2.6	1762	0.90
	Brick (23)	3.0	1820	0.90
	Inside plaster (1.5)	2.6	1762	0.84
Roof	Outside plaster (2)	2.6	1762	0.84
	Brick (11)	3.0	1820	0.88
	Inside plaster (2)	2.6	1762	0.84
Falls ceiling	Wood (2.5)	0.7	900	2

conduct these experiments and were also asked to fill it and also register their thermal sensation and indoor air quality and randomly 5 questionnaires were selected for carrying-out analysis. This process was continue till all the 70 graduate students, 2 staff and 3 research students were covered through this questionnaires. Out of 75 subjects, 72 were male and 3 were female. Table 3 represents comfort survey parameters.

The study was conducted during the month of April 2009. Since in April, the summer starts, so people wear light clothing. During the survey, the respondents were asked to vote on seven point ASHRAE thermal sensation scale about their perception regarding the existing thermal environment. On the thermal sensation scale -3 stands for cold, zero for neutral and +3 stands for hot thermal condition. For indoor air quality assessment, subjects were provided with to point scale to register their vote for acceptable and unacceptable indoor air quality. Corresponding temperature ($^{\circ}\text{C}$), relative humidity (%) and level of CO and CO₂ concentration were recorded simultaneously with respective votes. During the survey, all the respondents were interacted extensively. Interaction with the respondents also helped us in recording adaptive opportunities to make them comfortable in the indoor environment.

Table 3 Comfort survey parameters

Clothing level (clo)	0.3	
Metabolic rate (met)	1.2	
Number of subjects	75	
Location	Electronics Laboratory, IDDC, IIT Delhi	
Survey time	April 2009	
Respondent age (numbers)	<20 years	16
	>20-40 years	57
	>40 years	2
Respondent gender (numbers)	Male	72
	Female	3

adaptive signal processing. Adaptive systems are usually operates in a real time environment with stringent computational complexity, storage requirement and parameter variations due to the environment changes.

b. Clothing insulation

Clothing insulation measurement is a time consuming and a detailed process usually done in laboratory. For survey and field study, it is advisable to assume these values using table provided in ASHRAE 55-2004 and ISO 7730 standards. Researchers assume that the clothing value for the occupant based on season, climate and geographic region of the study. Clothing insulation has a good agreement with occupant heat balance to environment during sedentary activities (metabolic activity ranges 1.0 to 1.9). The most appropriate value for metabolic activity is 1.2 to get good result for PMV based calculation. Havenith *et al.* concluded that air movements around the human body has affect on clothing insulation [20]. Clothing insulation value given in ISO 9920 over estimates the actual insulation and do not fully reflects the effects of body posture, clothing material and dynamic heat transfer over the body. The clothing level today, in most of the thermal comfort study is still roughly estimated and these estimates fail to reflect the difference between people change in clothing and social and cultural constraints on clothing preferences. The importance of clothing value in PMV calculations is a source of concern because of its contribution to the discrepancies between predicted and actual thermal sensation. PMV analysis provides best results in predicting neutral temperatures for clothing insulation level in the range of 0.3 to 1.2.

c. Activity level

Activity level is one of the least well described parameters in PMV calculations. Activity level has a strong influence on human thermal sensation, comfort and indoor temperature preferences. Current database provide the information for an average person, so it fails to consider the differences between people and context and many times underestimates the actual *met* value. As *met* rate increases, activity of the person increases resulting change in relative air velocity between body surface and surroundings, change in body surface area exposed to air and change in evaporation rate from the exposed body surface area.

To validate the temperature profile, model of the laboratory is generated in TRNSYS 15.1. Thermo-physical properties of building materials listed in Table 2 are used as input for this analysis. The simulation of the model is carried out for the month of April 2009 by applying weather conditions in TMY (Typical Metrological Year) format. Figure 8 represents the simulation plot for the month under condition infiltration 1ACH (air change per hour) and ventilation 5ACH. From the simulation plot, it is observed that the maximum temperature in zone 2 is 39°C and minimum temperature is around 22°C. So there is a temperature swing of 17°C at ventilation 5ACH. At reducing ventilation rate, the minimum temperature rises to 26°C or temperature swing comes down from 17°C to 13°C. This TRNSYS model results are in good agreement with the experimental data.

During the subjective measurement each respondent is asked to fill the questionnaires followed by interaction with the respondent. This interaction helps us to record the preferences and expectation about the thermal environment leaving to behavioral adaptation. Before recording thermal sensation vote, the subject was advised to be in the same environment and to maintain the same activity level for around 20 minutes. This is done to maintain the uniformity and to minimize the error. The subjective responses are plotted in Figure 9 and 10. Figure 9 represents the acceptability of the thermal environment that 68% subjects feel '*hot*', 13.33% feel '*warm*', and 18.66% feel '*slightly warm*'. Figure 10 represents the acceptability for the indoor air quality in the laboratory, 53.33% of the users feel '*normal*', 26.66% feel '*bad*', 13.33% feel '*good*' and 6.66% feel '*very bad*'. Temperature and relative humidity are measured simultaneously at the time of voting. These measurements are done at three different heights (0.5m, 0.8m and 1.2m from the floor). Average of these three temperature and humidity values are used to calculate the PMV values. The clothing level and metabolic level values are used according to ISO7730.

Three PMV values for same environmental conditions are calculated by three different techniques. One by subjective response method on ASHRAE 7 point sensation scale, second by mathematically calculating according to ISO7730 calculation procedure and the third one PMV based thermal comfort smart sensor. All these the three values for 75 subjects plotted in Figure 11. From the figure 11, it is observed that the PMV values from the smart sensor and the value calculated by using ISO7730 calculation procedure are

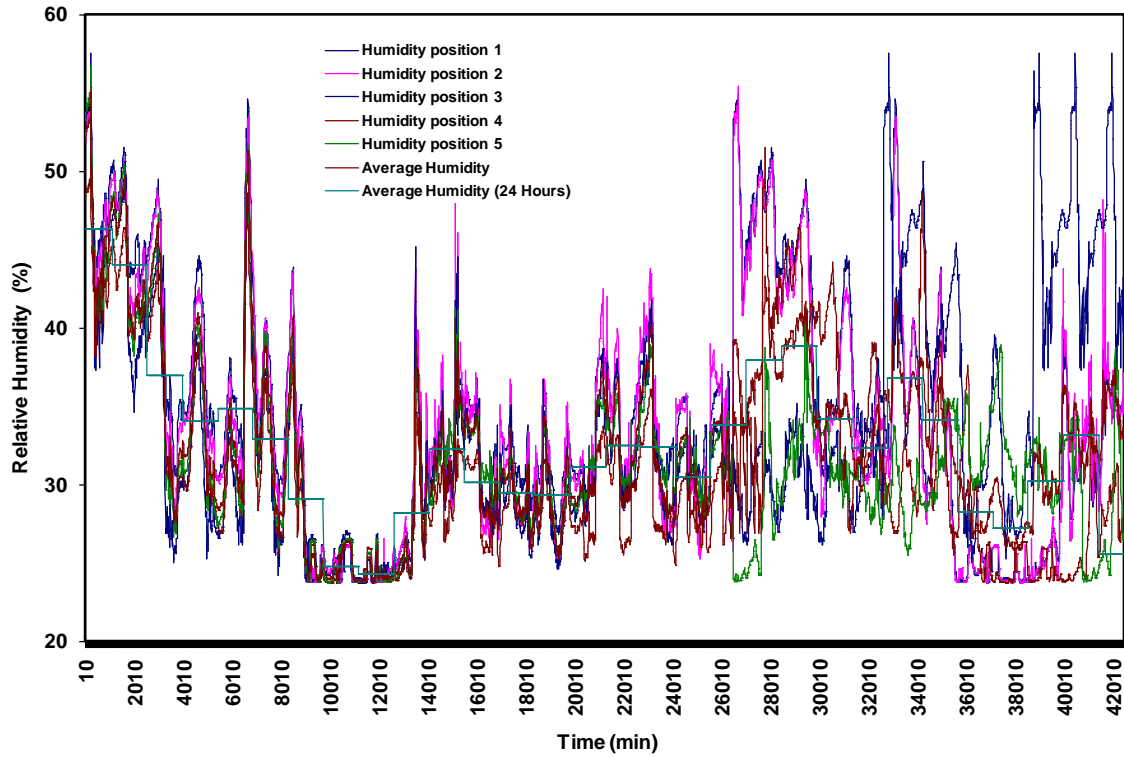


Figure 6 Humidity profile at different locations at Zone 2

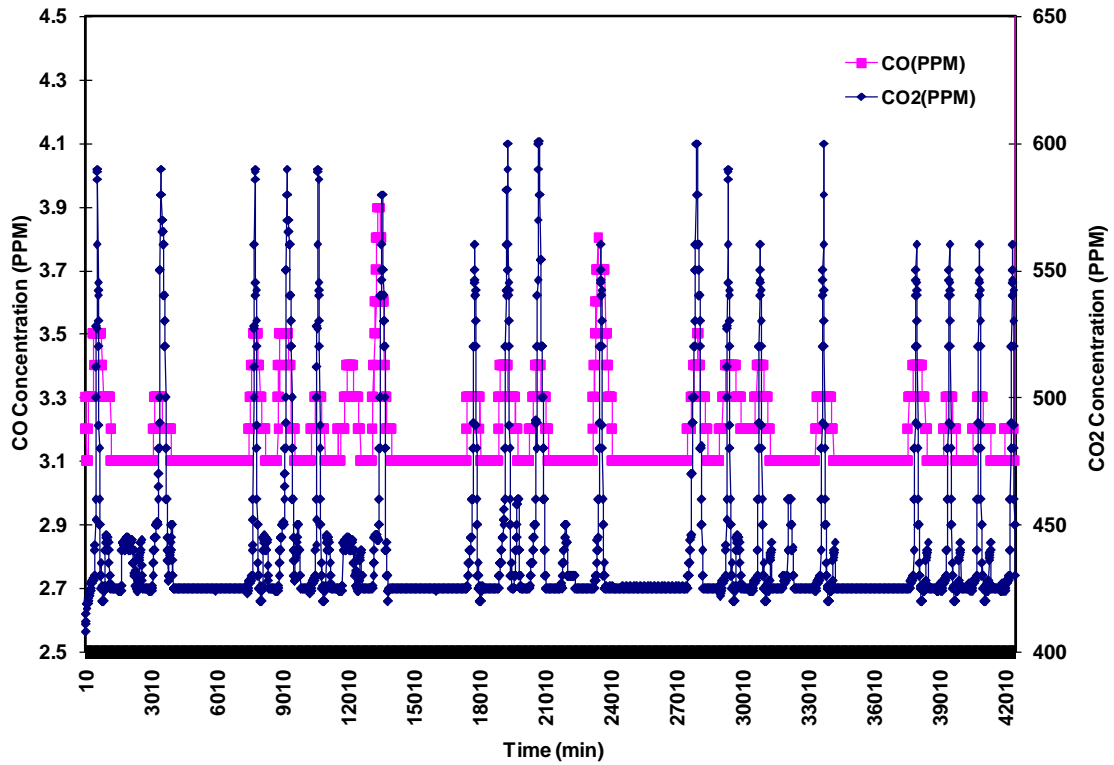


Figure 7 CO and CO₂ profiles at Zone 2

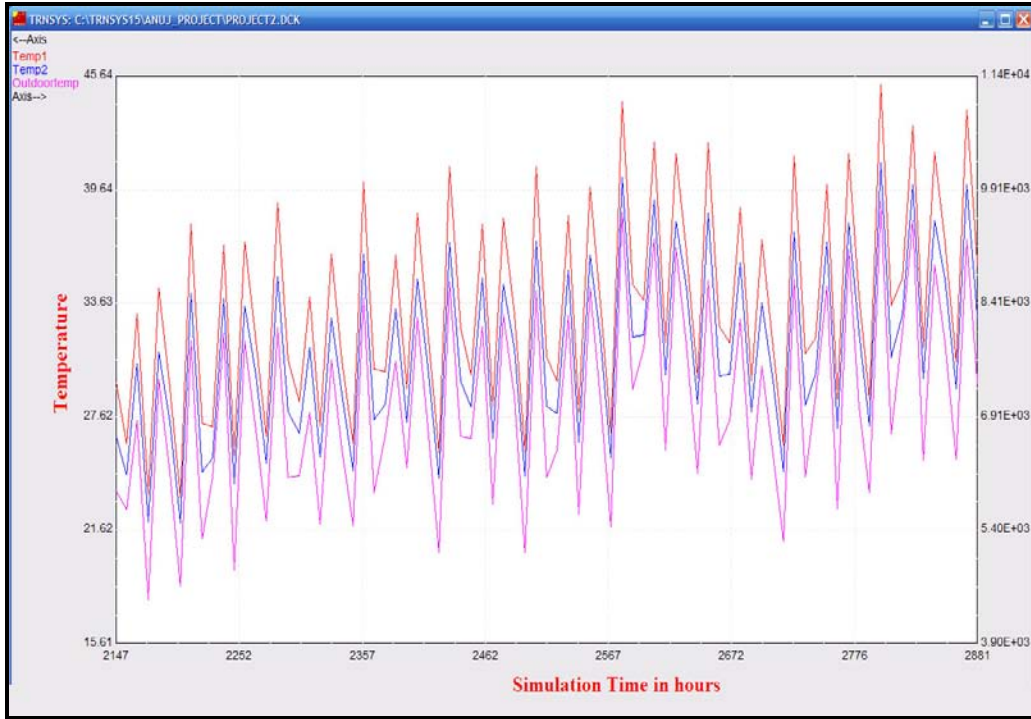


Figure 8 Temperature profile in pre-summer from TRNSYS simulation

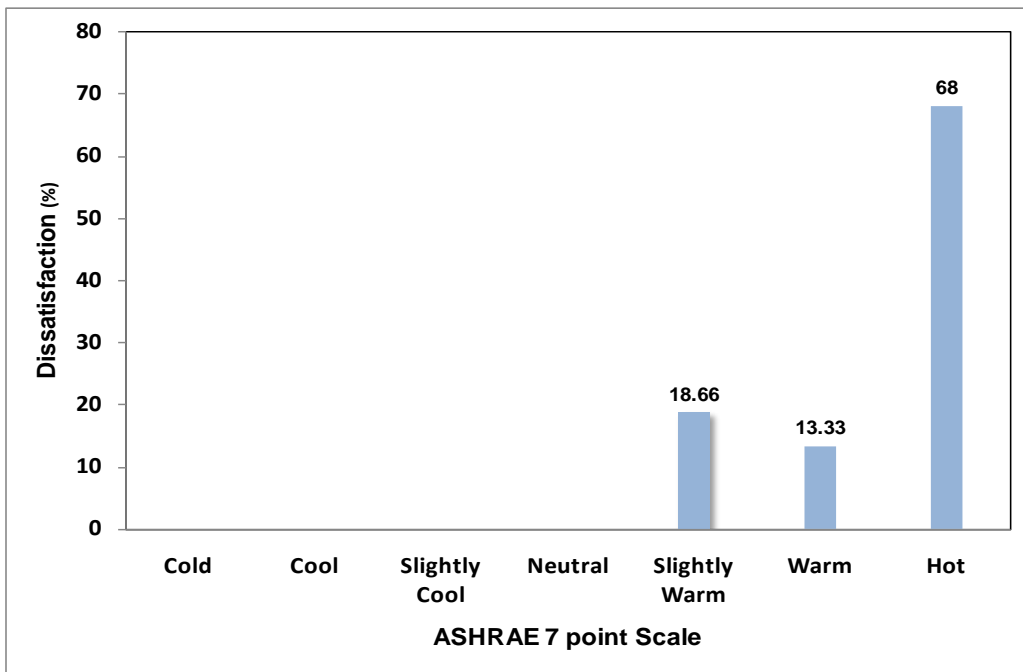


Figure 9 Subjective judgments about acceptability of the thermal environment

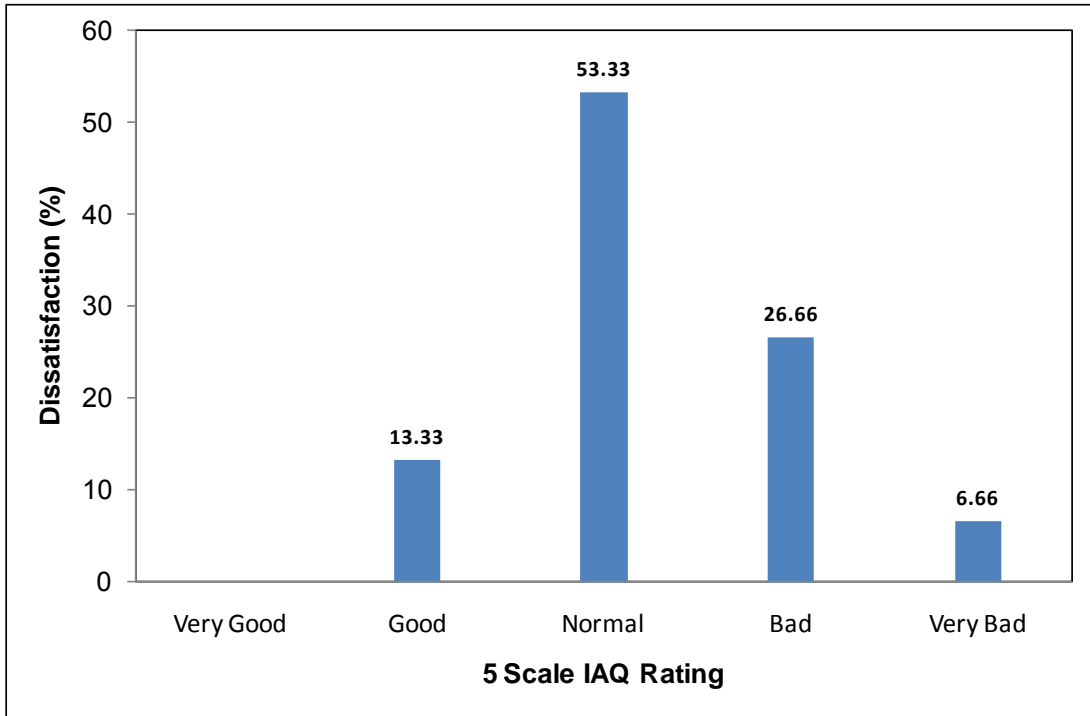


Figure 10 Subjective judgments about the acceptability of the IAQ

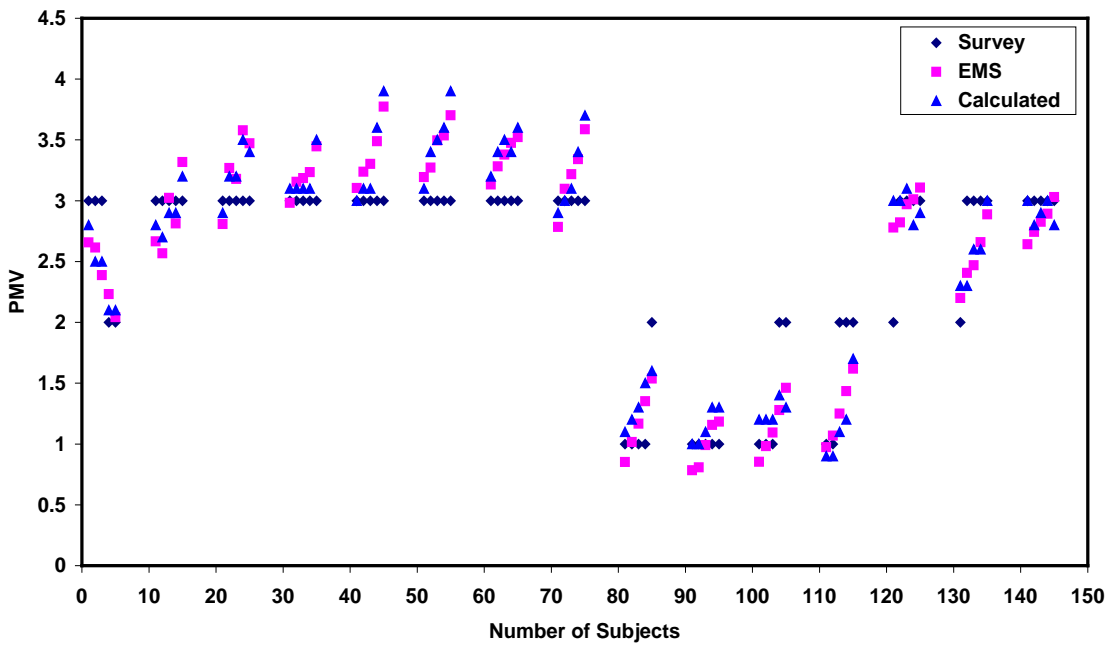


Figure 11 Comparative PMV values from three different methods

VIII. CONCLUSIONS

Thermal comfort in built environment is maintained by regulating temperature of indoor air at pre-determined value which may not be necessary to make indoor environment comfortable with respect to occupant. Without proper determination of the desired indoor air condition to HVAC system, it may not be feasible to provide occupants with thermal comfort and acceptable air quality simultaneously. This makes HVAC system highly energy intensive since thermal comfort conditions for the occupant is dynamic in nature and is influenced by outdoor conditions. So it has become necessary to do real time assessment for comfort conditions for energy savings. To address this issue an approach towards development of PMV based thermal comfort smart sensor for indoor thermal environment assessment is proposed. Monitoring of four physical parameters, temperature, relative humidity, CO₂ and CO has done for one month using this monitoring unit. Selection of sensors were done based on adequate sensitivity, fast response time, high stability, long life, low cost, low dependency on humidity, low power consumption, and compact size. Calculation of PMV has done by three different methods viz. survey, using ISO 7730 calculation procedure and through the prototype monitoring system. Results shows that values calculated by ISO 7730 and proposed monitoring system are close but deviate to that of survey. This deviation is mainly due to adaptive nature of occupants, which is very difficult to define and derive mathematically. But this problem can be overcome by carrying out large experiments spreading over year and applying these data for the training of neural network. This work reveals the possibility of development of PMV based thermal comfort smart sensor.

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