Original Article/Research

Seasonal evaluation of adaptive use of controls in multi-storied apartments: A field study in composite climate of north India

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Abstract

A Class II level field survey is conducted in five naturally ventilated multi-storied apartments in the composite climatic zone of north India. A total of 984 data-sets were collected for the whole year, involving over 82 subjects and 55 apartment units. This paper highlighted the season-wise behavioral change in the usage pattern of controls and the resultant thermal response of the subjects. It is observed that at extreme weather conditions, subjects are switching to ‘seasonal controls’ (i.e. fans, A/C’s and heaters/hot blowers) as oppose to the ‘designed controls’ (i.e. windows, balcony doors and blinds) or personal controls (i.e. changing ‘clo’ and ‘met’ levels). The study concludes that if designed controls are efficiently incorporated in the building the thermal perception of the residents and the resultant energy consumption can be improved.

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Keywords: Thermal comfort; Adaptive behavior; Control-use; Naturally ventilated apartments; Seasonal variation

1. Introduction

The fundamental assumption of adaptive model of thermal comfort is: ‘if a change occurs, such as to produce discomfort, people react in ways which tend to restore their comfort’ (Nicol and Humphreys, 2002). It embraces the notion that people play an important role in creating their own thermal preferences through the way they interact with the environment or modify their own behavior, or gradually adapt their expectations to match the thermal environment (Brager and de Dear, 1998). Adaptive behavior as a response to the thermal discomfort has a huge implication on the energy consumption of any building (Murakami et al., 2007 and Yang and Su, 1997). Steemers and Manchanda (2010), in their study, has justified this point with the detailed monitoring of 12 case studies (office buildings) in U.K. and India. The study proved that the key link variable between energy consumption and occupant’s happiness is the degree of control available on the adaptive opportunities. It is a well acknowledged fact that indoors with high adaptive opportunities are likely to prove more comfortable than one with the low...
opportunities (Zain et al., 2007). Brager and de Dear (1998) reported a link between personal control of environmental conditions (temperature and ventilation) and work performance. Raja et al. (2001) also inferred that the change in indoor temperature is about one-third of the outdoors when occupant controls the indoor. Therefore, it is necessary to understand and quantify the adaptive measures taken by the occupants so as to avoid any conflicts between user behavior, in terms of thermal expectations and the resultant energy consumption.

Previous studies (Raja et al., 2001; Rijal et al., 2008; Baker and Standeven, 1996; Peeters et al., 2009) have proved that the temperature (indoor/outdoor), among all other parameters, strongly influences the control use behavior of the respondents. It suggests that the seasonal variation has a huge repercussion on the way occupants perceive and respond to the environmental changes. Due to its geographical position India witnesses different climatic seasons in a year (Library of Congress-Federal Research Division) and is divided into six climatic zones (Nayak and Prajapati, 2006), with its maximum coverage falling under composite climate. This seasonal and climatic diversity makes it quite essential to revise the operational thermal comfort standards in India. On the contrary, National Building Code (NBC) follows a narrow comfort range for air-conditioned buildings (Indraganti, 2010a,b,c; BIS, 2005; Pellegrino et al., 2012) irrespective of the climatic zone it falls under.

Leen Peeters et al. (2009) has inferred that the adaptive measures in a residential building vary within a small time scale, which consequently affects the indoor environment. Residential buildings in India are, predominantly, naturally ventilated with the occasional use of heating and cooling appliances at extreme weather conditions. This makes the indoor conditions quite dynamic and unpredictable, which not only exhilarates the energy consumption but also affects thermal comfort. This paper has highlighted the findings of the field survey in Chandigarh and Roorkee (both falls under composite climatic zone as per classification given by NBC; BIS, 2005) with the main focus on the seasonal variations in the use of adaptive measures in naturally ventilated apartments. The most common means of controlling the indoor environment in summer, winter and monsoon are studied. Windows (W), blinds (BL), balcony door (BD) were found to be used at varying scale in all the seasons. The use of fan, air conditioner (A/C) and heater/blower is also explored. For analysis, ‘window open’, ‘door open’, ‘blind drawn’, ‘fan on’ and ‘A/C on’ were coded as ‘1’ and otherwise as ‘0’. The relative frequency of “open” and “close” events for each of the controls is calculated separately for indoor globe temperature (Tg). Objectives of the paper:

- To explore the adaptive approach in naturally ventilated buildings.
- To analyze the impact of seasonal changes on the thermal perception and control the use of occupants.

2. Materials and methods

Adaptive controls are employed by the subjects to restore comfort conditions and the decisions are partially based on outdoor/indoor temperatures (Raja et al., 2001) and partially on personal expectations (Brager and de Dear, 1998). People, consciously and sub-consciously, respond to discomfort either by changing activity (Indraganti, 2010b; Darby and White, 2005), clothing/posture (Indraganti, 2010b,c; Fishman and Pimbert, 1982 and Nicol and Raja, 1996) or thermal environment. In naturally ventilated buildings, the usual controls available to regulate the thermal environment are doors, windows, blinds, doors, however, fans, A/C’s and hot air blower have also been used in this study at extreme weather conditions of the year. Opening of doors or windows enhances natural ventilation, fans provide forced convective cooling and blinds/curtains reduce the heat gain from direct solar radiation as well as the glares (Raja et al., 2001).

Temperature (outdoor and indoor) is the key statistical variable in predicting the use of control. But studies have confirmed that it is the immediate environment that stimulates the instincts of the subject to use the available controls (Rijal et al., 2008). The relative frequency of the control-use during the survey period is plotted against indoor globe temperature (Tg) using regression analysis.

2.1. Survey

A field survey is conducted for the year of 2012 in five naturally ventilated (NV) multi-storied apartments. The aim of the survey was to establish the temperature, which people find comfortable in a composite climate of north India. The selection of the case studies was solely made on the basis of factors like climate zone, building type, income group, no. of floors, floor areas/dwelling unit (DU) and most importantly clearance from the concerned authorities i.e. President of the societies and approval from the occupants of the buildings to be surveyed. Two buildings i.e. Hill View Apartments (HV) and Canal View Apartments (CV) are located in Roorkee and three buildings i.e. Grow-more Society (GMR) and Bhaimata Das Society (BMD) and Trishla (TR) are located in Chandigarh. As per climate classification proposed by Bansal and Minke (Nayak and Prajapati, 2006), Chandigarh and Roorkee both fall under composite climatic zone.

Survey sheet included interviewee’s demographic information, comfort vote on seven point ASHRAE’s thermal sensation scale or ‘TSV’ (−3 to +3), the preference vote on a five-point thermal preference scale or ‘TP’ (−2 to +2), clothing worn, activity level, adaptive use of environmental controls at the time of voting. Besides this, questions related to the tenure of stay, number of family members, household appliances and the hourly consumptions of fans, A/C’s, heater/blowers etc. are also included in the questionnaire. The questions were put in English and were explained in regional languages, when required.
The details of the questionnaire are given in Appendix. MH 3350- Thermo Hygrometer is used to measure air temperature or ‘Ta’ (using sensor ‘TFS0100E’) and indoor globe temperatures (Tg) using sensor ‘TYP101’, whose probe was inserted in a black-painted table tennis ball (about 40 mm diameter). Handheld Digital Vane Thermo Anemometer (Type 93460) is used to measure air movement (Av). All measurements were made close to the respondent at 1.1 m level, refer Fig. 1a. The mean outdoor temperature ($T_{om}$) was taken from the meteorological data of each city. Table 1a and Table 1b give the summary of the annual outdoor and indoor environmental conditions for the surveyed period.

The participant’s metabolic rate (met) and clothing insulation (clo) were estimated using numerical ‘met’ and ‘clo’ values for typical activities/clothing as specified in ASHRAE Standard 55. During the survey, the annual ‘clo’ level ranged between 0.3 and 2.2 clo. The metabolic level or ‘met’ also ranged between 0.7 met (sleeping/resting) to 2.0 met (standing working) in this survey. Fig. 1b shows the typical winter and summer clothing of males and females in north India. It is imperative to note that, owning to the cultural diversities, the clothing patterns of people in India vary dramatically from region to region. In north India, females mostly wear ‘salwar-kameez’, whereas, men prefer shirt/T-shirt/‘kurta’ with trousers/shorts/pajamas’ in summers. In winter period, insulation layers of sweater/jacket/shawl, caps, muffler and other woolen wears’ are most commonly used. Clothing patterns are progressively changing, particularly, among youngsters as they are inclined toward the western outfits. This has affected the use of clothing as an adaptive measure and, consequently, the resultant thermal responses.

The usage pattern of doors, windows, blinds is recorded as ‘closed’/‘opened’ and ‘on’/‘off’ for fans, A/C’s, heaters. The relative frequency of ‘closed/open’ and ‘on/off’ events are averaged for each temperature bin (round off value of recorded indoor globe temperature), separately. During the survey, the layers of clothing ensembles are ticked (refer Appendix) and later ASHRAE’s checklist is referred for ‘clo’ estimation. The summation of each clothing layer gives ‘clo’ level of the subject for each occasion when the questionnaire is being conducted. As the apartment unit and the subject are same throughout the survey, the main focus is to analyze how the adaptive use of controls (doors, windows, blinds etc.) and ‘clo’ and ‘met’ level changes for the varying indoor environmental conditions.

### Table 1a
Annual summary outdoor environmental conditions for the surveyed period.

<table>
<thead>
<tr>
<th></th>
<th>Chandigarh</th>
<th>Roorkee</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Toutside</td>
<td>RH (%)</td>
</tr>
<tr>
<td>Mean</td>
<td>24.1</td>
<td>58.7</td>
</tr>
<tr>
<td>Min</td>
<td>7.5</td>
<td>29.0</td>
</tr>
<tr>
<td>Max</td>
<td>41.5</td>
<td>98.0</td>
</tr>
<tr>
<td>StDev</td>
<td>6.7</td>
<td>14.7</td>
</tr>
</tbody>
</table>

Toutside: outside temperature.
RH: relative humidity.

### Table 1b
Annual summary of indoor environmental conditions for the surveyed period.

<table>
<thead>
<tr>
<th></th>
<th>Chandigarh</th>
<th>Roorkee</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ta</td>
<td>RH</td>
</tr>
<tr>
<td>Mean</td>
<td>26.1</td>
<td>52.6</td>
</tr>
<tr>
<td>Min</td>
<td>14.2</td>
<td>23.6</td>
</tr>
<tr>
<td>Max</td>
<td>35.9</td>
<td>84.8</td>
</tr>
<tr>
<td>StDev</td>
<td>6.8</td>
<td>13.1</td>
</tr>
</tbody>
</table>

Mean: mean indoor temperature; TMin : minimum indoor temperature; TMax: maximum indoor temperature; StDev : standard deviation.

### 2.2. Subject sample

A longitudinal survey was conducted to investigate the thermal perception of occupants residing in multi-storied apartments. About 29 males (~35%) and 53 females (~65%) participated in the survey. The age group varied from 8 to 80 years; having 11 young subjects ($\leq$7–17 years), 54 middle age subjects ($\leq$20–50 years) and 18 old age subjects ($\geq$50 years). The average age of male and female subjects is 39.24 years and 39.77 years, respectively. They were all healthy Indian nationals, living in the surveyed flats for a period of a year or more. All of them were assumed to be naturally acclimated to the respective places i.e. Roorkee and Chandigarh. Table 2 give the detailed summary of the surveyed subjects.

On the first visit, occupants were deliberately explained about the research and the survey to be conducted. Subjects were hesitant and sceptical with the frequent visits in a day, so it was decided to conduct interview once a month for all the subjects. In order to investigate the individual changes between the seasons, only those subjects are included who participated in all the twelve months. So, finally 82 residents of 55 different apartment units are surveyed from five different buildings for 12 months. This study collected a data-set of 984 in total.

### 3. Results and discussion

#### 3.1. Seasonal thermal Evaluation

Thermal sensation votes (TSV), thermal preference votes (TP) and thermal acceptance votes votes have shown some interesting voting patterns. In summer and monsoon period, majority of the subjects voted for ‘neutral’ or ‘0’ on ‘TSV’ or thermal sensation scale but still 40–50% preferred
for ‘slightly cool’ on ‘TP’ or thermal preference scale. It is also observed that relatively high percentage of subjects found indoors acceptable even when the comfort votes were low. Lower expectations, difference in the psychological attitudes and health issues could be the possible explanation (Brager and de Dear, 1998; Indraganti, 2010b). ‘Tg’ or indoor globe temperature and ‘TSV’ or thermal sensation votes have shown a moderate correlation coefficient (0.44) in winters as compared to summer (0.85) and monsoon period (0.77). The regression slope (indicating thermal sensitivity) is observed to be higher in summer (0.23/°C) and monsoon period (0.31/°C) and lower for the winter period (0.15/°C). It suggests that mean thermal sensation changed one unit for every 6.7 °C of globe temperature in the winter period, 4.4 °C in summer and 3.2 °C in monsoon period. The comfort range (+1,0,−1) of the subjects is calculated using linear regression of ‘Tg’ with ‘TSV’. A neutral temperature of 26.06 °C is obtained with a significant regression coefficient of 0.77. The broader comfort band (22.5–30.6 °C), as obtained in the study, suggests that residents are well adapted to their thermal environment as opposed to what is recommended by the National Building Code (NBC). The Eq. (1) derived is as follows:

![Figure 1a. Subject during interview with an instrument setup at 1.1 m level.](image1)

![Figure 1b. Typical winter clothing & summer clothing of male and female subjects.](image2)

<table>
<thead>
<tr>
<th>Apartment</th>
<th>No. of Subjects</th>
<th>Weight (kg)</th>
<th>Height (mt)</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Male Female</td>
<td>Males</td>
<td>Females</td>
<td>Males Female</td>
</tr>
<tr>
<td>GMR</td>
<td>10 10</td>
<td>67.3 12.3</td>
<td>63.8 10.9</td>
<td>1.7 0.1 1.6 0.1</td>
</tr>
<tr>
<td>TR</td>
<td>5 10</td>
<td>59.2 17.9</td>
<td>59.7 7.9</td>
<td>1.6 0.2 1.6 0.1</td>
</tr>
<tr>
<td>BMD</td>
<td>4 9</td>
<td>63.3 8.2</td>
<td>64.8 11.9</td>
<td>1.7 0.1 1.6 0.1</td>
</tr>
<tr>
<td>HV</td>
<td>5 10</td>
<td>61.4 14.3</td>
<td>68.9 11.5</td>
<td>1.7 0.1 1.6 0.1</td>
</tr>
<tr>
<td>CV</td>
<td>5 14</td>
<td>59.6 20.2</td>
<td>59.4 11.2</td>
<td>1.6 0.2 1.6 0.1</td>
</tr>
<tr>
<td>TOTAL</td>
<td>29 53</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
where $T_{SV}$ is thermal sensation votes and $T_g$ is globe temperature.

3.1. Griffith’s neutral temperature

Studies (Rijal et al., 2010; Oseland, 1994; Nicol et al., 1999) have suggested that simple regression analysis for estimating comfort temperature is not a very reliable approach, especially when the adaptive behavior of the occupants is active. In this study also, neutral temperature ($T_n$) turned out to be superfluous ($−1.5^\circ \text{C}, 8.2^\circ \text{C}, −11^\circ \text{C}$ etc.) for some subjects. It is observed that subjects having very poor correlation between ‘$T_g$’ and ‘$T_{SV}$’ (winter period showing more of such values as compared to the other two seasons) are the ones with these erratic values. It is imperative to note that this poor ‘$T_{SV}−T_g$’ correlation indicates the adaptive use of controls to adjust the thermal environment of the surroundings.

Therefore, Griffith’s method, as suggested by Nicol et al. (1999) is used to calculate neutral temperature for each subject using mean comfort vote and the mean temperatures as follows:

$$T_{nG} = T_{gm} + (0 − T_{Sm})/a$$

Where $T_{nG}$: neutral temperature by Griffith’s method, $T_{gm}$: mean globe temperature when votes are recorded, 0: “neutral” thermal sensation vote, $T_{Sm}$: mean thermal sensation vote and ‘$a$’: regression coefficient.

In this study, four different coefficients are used to estimate the Griffith’s neutral temperatures or ‘$T_{nG}$’ using Eq. (2). First one, as obtained by Indraganti (2010a) in her Hyderabad study (0.31), other two coefficients from Nicol’s Pakistan study (0.25 and 0.33) (Nicol et al., 1999) and finally the one obtained in this study (0.21). $T_{nG1}$, $T_{nG2}$, $T_{nG3}$ and $T_{nG4}$ are the Griffith’s neutral temperatures obtained using regression coefficients 0.31, 0.25, 0.33 and 0.21, respectively.

The difference in $T_n$ is observed to be increasing as the subjects are voting away from ‘0’ whereas the difference is receding as the $T_{Sm}$ value is close to ‘0’. The difference between $T_{nG1}$ and $T_{nG2}$ and $T_{nG3}$ is observed to be smaller for monsoon and summer period (within a range of 0–3.0) as compared to the winter period (from 0.6 to 4.8). The proportion of ‘neutral’ votes is higher in summer and monsoon period and, thus, explains the smaller difference. This seasonal variation in comfort temperature can further be related to usage pattern of various controls, consequently affecting the thermal sensation of the subject. On further analysis, top exposed floors (TF) are observed to have higher Griffith’s neutral temperatures than the lower floors (LF). This difference is more pronounced in the monsoon period, as more subjects have voted for neutrality in the ‘LF’ (0.5%) as compared to ‘TF’ (0.3%). The results are in alignment with the one obtained by Indraganti (2010a).

3.2. Adaptive use of controls

‘Adaptation’ is interpreted as a gradual diminution of the organism’s response to the recurring environmental stimulation (de Dear et al., 1997). In the study, it is observed that the behavioral adaptations of the subjects have considerably varied for summer, winter and monsoon period, in response to the recurrent seasonal changes. The adaptive use of controls is broadly evaluated under the following three categories

- In-built Controls/Designed controls.
- Seasonal Controls/Energy Intensive controls.
- Personal Controls.

In the study, the usage pattern of doors, windows, blinds (in-built controls) is recorded as either ‘closed/opened’ and ‘on/off’ for fans, A/C’s, heaters (seasonal controls)

3.2.1. In-built Controls/Designed controls

Balcony doors, windows, blinds, external doors etc. are the in-built features of the building which are adaptively used by the occupants to control the indoor thermal environment. To analyze the behavioral change in the use of ‘in-built controls’ or ‘designed controls’, ‘$T_g$’ is regressed with the proportional use of ‘BD’, ‘W’ and ‘BL’. External doors are found to have a weak correlation with the variables and, thus, not included in the study.

3.2.1.1. Windows. Windows are widely used as an adaptive adjustment to control the indoor thermal environment of buildings. It is observed that the relative frequency of opened windows crossed 40% as the indoor globe temperature ranges between 20 °C and 34 °C, whereas only 20% of the windows are recorded to be opened during extreme outdoor temperatures in winter and summer period, refer Fig. 2a. The relative frequency of window-use continues to rise as the indoor globe temperature has increase but it has lowered as the outdoor temperature is at its lowest or highest point. Simulation results (Singh et al., 2014) have shown that solar gain and loss through exterior window glazing is significant in summer and winter period, respectively (refer Fig. 2b). It should be noted that, in winters, to maintain the indoor warmth, closing of doors and windows is the easiest, effective and economically viable control to isolate the indoors from the outdoor chills, while in summer, alternate controls like fans and A/C’s are more effective and are excessively used by the subjects to control the indoor environmental conditions and ventilation rates. This explains the restricted window opening behavior of the subjects in extreme summer and winter period.

Fig. 2c shows that windows are mostly closed in all the seasons. Factors like ‘dust’ and ‘loo/fog’ have hampered the use of the windows, regardless of its effectiveness to regulate the natural ventilation, refer Fig. 2d. A significant proportion of occupants have voted ‘dust’ and ‘loo/fog’ for not opening the doors and windows. Window has, thus,
not only helped in regulating the natural ventilation but also acted as a key barrier to the contextual adversities. The adaptive use of windows, surely, needs to be considered while designing the buildings, so as to provide ample opportunities to the occupants to restore the indoor comfort conditions.

3.2.1.2 Balcony doors. Balcony doors are observed to be used in a wider range of temperatures. Fig. 3a shows that seasonal distribution of votes for BD-use is uniform as compared to any other control. The proportion of ‘BD-use’ gently rises from 40% at 19 °C to 80% at 32 °C. Fig. 3b shows the seasonal changes in ‘BD-use’ when
plotted against ‘Tg’, with a maximum usage in the monsoon months (BD-monsoon). Also, the ‘BD-use’ is observed to be higher when the ‘Tg’ is within the comfort band, i.e. indoor temperature ranging between 22.5 and 30.6 °C. Most subjects reasonably expressed their preference for open doors and windows, not just for the allowance of cross ventilation but because it gives the feeling of ‘freshness’ and ‘openness’. The expectations in terms of ‘freshness’ and ‘openness’ with the opening of windows and doors have considerably played a very important role in the thermal responses and the comfort preferences. It is imperative to note that out of the annual total responses (984), 419 responded to be not using the balcony spaces and still ‘BD’ is the most preferred control in all the seasons. Balcony spaces, with shaded buffer space provide better options for cross ventilation over windows, as also
3.2.1.3. Blinds. Indoorglobe temperature (i.e. ‘Tg’) and out-
door temperature has strongly correlated in the study
(0.96), which implies that any change in the outdoors has
a direct or indirect influence on the indoor environment.
Fig. 4a shows that the usage pattern of blinds is varying
with change in indoor globe temperature. During peak
summer and winter periods, ‘BL’ is preferred to be drawn
in order to maintain a barrier between extreme outdoor
conditions and to restore the indoor comfort levels. In win-
ters, the mean outdoor temperature in Chandigarh and
Roorkee drops to around 5–7°C. Blinds in combination
with the heater/hot blowers has acted as a good insulator
and helped in reducing heat loss through windows. Simi-
larly, in summer period, outdoor temperature rises up to
41°C and blinds are preferred to be drawn in combination
with the closed doors and windows (and/or air condition-
ers ‘on’) to keep the ‘too’ and glare out. Fig. 4b shows
the seasonal distribution of BL-use.

3.2.2. Personal controls

Clothing level or activity level, drinking tea or cold
drink, changing posture etc. are some of the personal con-
trols. In the present study, clothing level ‘clo’ and meta-
bolic level/met’ are analyzed for evaluating the personal
controls.

3.2.2.1. Clothing. Clothing adjustment is one of the most
common adaptive behavior that covers a wide range of
temperature. The regression analysis depicted in Fig. 5a,
suggests that the indoor temperature is an important deter-
minant of clothing as an adaptive control. Studies have
also reported that building occupants modify their clothing
several times a day in naturally ventilated buildings (Baker
and Standeven, 1996; Morgan and de Dear, 2003). But in
residential buildings, people know what kind of thermal
environment to expect and easily avail the adaptive oppor-
tunities, resulting in minimal clothing adjustments over a
day (Mishra and Ramgopal, 2013). The annual ‘clo’ vari-
ability observed during the survey ranged from 0.3 to 2.2
‘clo’, Tg have exhibited a strong correlation with the ‘clo’
level \( r = -0.84 \) and \( r = -0.6 \), respectively), whereas, rela-
tive humidity (RH) has weakly correlated \( r = 0.2 \), refer
Table 3a. The results obtained in this study are in align-
ment with the one established by Heidari and Sharples
(2002). Below is the derived regression Eq. (3) with:
\[
\text{clo} = 2.05 - 0.05 \times Tg
\]
\( R^2 = 0.7 \)

where ‘clo’ is clothing level and ‘Tg’ is globe temperature (in
°C)

Seasonal variations in the clothing adjustments have
shown a strong linear dependence on ‘Tg’ in summer
\( r = -0.7 \) and winter \( r = -0.7 \) period and weak correla-
tion in the monsoon period \( r = -0.3 \), refer Table 3b.
With the increase in temperature, ‘clo’ level decreases till
it reaches a minimal acceptable limit. Beyond this level
no further changes are observed due to socio-cultural con-
straints, termed as ‘adaptive saturation’ (Mishra and
Ramgopal, 2013). As the minimal acceptable ‘clo’ level
has already been crossed in summer time, occupants opt
for easier and more effective controls to enhance the con-
vective cooling (i.e. fans, A/C, windows, doors etc.) in
the monsoon period. With the increase in temperature
and humidity level in the monsoon period, subjects have
voted on the higher side in the TSV scale which is believed
to be affecting the clothing preferences of the occupants.

When ‘clo’ level is regressed with the ‘Av’, a moderately
strong correlation is established in the summer period
\( r = -0.5 \) as compared to winter \( r = 0.2 \) and monsoon
\( r = -0.2 \) period, refer Table 3b. The reduced ‘clo’ level
with the increased air velocity suggests that clothing adjust-
ment is an effective control measure in the summer period
(Fig. 5b). Also, that it tends to work well when the ventila-
tion rates (through fans, doors and windows) are
adaptively used by subjects.

![Figure 4a. Seasonal variation of blind use as function of Tg.](image)
3.2.2.2. Metabolic activity. Metabolic activity has shown no correlation with any of the physical variables or with the comfort votes of the subjects, similar results were drawn by Nicol (Indraganti, 2010d). Indraganti (2010d) has reported that people lower down their metabolic rate as an adaptive measure in response to the discomfort on the warmer side. In this study no such observations are made as the monthly survey, with one time visit to the subjects, could not reveal any significant variations. Seasonal analysis has not revealed any significant correlation with any of the physical variables. Although, clothing has shown a fairly negative correlation (−0.2) with ‘met’ in the summer period, refer Table 4a. Similar observation was made by Indraganti (2010d) in Hyderabad study. This implies that with the increase in temperature, subjects prefer to keep their clothing to low (within acceptable limits) if they are involved in heavy activities or vice versa. The gender-wise analysis of ‘met’ rates has clearly shown that female subjects are more involved in heavy activities as compared to the male subjects. Almost 33% of the female subjects were observed to be involved in heavy activities as opposed to only 8% male subjects (Table 4b). This difference in the metabolic activities, to some extent, has affected the thermal comfort perception of the two genders.

The current methods for evaluating the ‘met’ level are debatable as the factors like psychological stress, transient effects of earlier activities, or the vigor with which a given activity is performed (Brager and de Dear, 1998) are not fully considered. A detailed research with prior focus on the relevance of physical environmental variables on daily metabolic activities can help to fill these voids.

Table 3a
Correlation of clo with variables.

<table>
<thead>
<tr>
<th>clo: Av</th>
<th>clo: RH</th>
<th>clo: Tg</th>
<th>clo: TSV</th>
<th>clo: met</th>
</tr>
</thead>
<tbody>
<tr>
<td>−.60</td>
<td>0.2</td>
<td>−.84</td>
<td>−.72</td>
<td>−.02</td>
</tr>
</tbody>
</table>

Table 3b
Seasonal variation in correlation of ‘clo’ with variables.

<table>
<thead>
<tr>
<th>clo: Av</th>
<th>clo: RH</th>
<th>clo: Tg</th>
<th>clo: TSV</th>
<th>clo: met</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>0.2</td>
<td>−0.7</td>
<td>−0.5</td>
<td>0.0</td>
</tr>
<tr>
<td>Summer</td>
<td>−0.5</td>
<td>0.0</td>
<td>−0.7</td>
<td>−0.6</td>
</tr>
<tr>
<td>Monsoon</td>
<td>−0.2</td>
<td>−0.2</td>
<td>−0.3</td>
<td>−0.2</td>
</tr>
</tbody>
</table>

3.2.2.2. Metabolic activity. Metabolic activity has shown no correlation with any of the physical variables or with the comfort votes of the subjects, similar results were drawn by Nicol (Indraganti, 2010d). Indraganti (2010d) has reported that people lower down their metabolic rate as an adaptive measure in response to the discomfort on the warmer side. In this study no such observations are made as the monthly survey, with one time visit to the subjects, could not reveal any significant variations. Seasonal analysis has not revealed any significant correlation with any of the physical variables. Although, clothing has shown a fairly negative correlation (−0.2) with ‘met’ in the summer period, refer Table 4a. Similar observation was made by Indraganti (2010d) in Hyderabad study. This implies that with the increase in temperature, subjects prefer to keep their clothing to low (within acceptable limits) if they are involved in heavy activities or vice versa. The gender-wise analysis of ‘met’ rates has clearly shown that female subjects are more involved in heavy activities as compared to the male subjects. Almost 33% of the female subjects were observed to be involved in heavy activities as opposed to only 8% male subjects (Table 4b). This difference in the metabolic activities, to some extent, has affected the thermal comfort perception of the two genders.

The current methods for evaluating the ‘met’ level are debatable as the factors like psychological stress, transient effects of earlier activities, or the vigor with which a given activity is performed (Brager and de Dear, 1998) are not fully considered. A detailed research with prior focus on the relevance of physical environmental variables on daily metabolic activities can help to fill these voids.
3.2.3. Seasonal controls

Most of the surveyed subjects are observed to be leveraging on the electrical controls (Indraganti, 2010c) for instant relief from the discomfort. Rapid urbanization has increased the disposable income (Lall et al., 2010) and also the dependence on energy intensive controls. It is evident that the cooling load is predominant in composite climate and reports show that almost 48% of the energy is expended on ventilation controls in residential buildings in India (Indraganti, 2010c and BEE, 2007). It is also observed that when the weather is at the extremities, subjects are switching to the energy intensive controls (i.e. fans, A/C’s and heaters/hot blowers) termed as ‘seasonal controls’, in the study, as oppose to the use of ‘designed controls’. The proportional use of fans or ‘F’, A/C’s and heaters/hot blowers were observed to be adaptively used as the indoor/outdoor temperature shifted from the comfort range, refer Fig. 6a.

3.2.3.1. Fans. The overall proportional use of the fan or ‘F’ is comparatively low as compared to ‘W’, ‘BD’ and ‘BL’, but has shown a strong regression coefficient, $r^2 = 0.91$, when plotted against ‘Tg’, refer Fig. 6a.

A notable observation is the increased air velocities when subjects voted ‘slightly warm’ or ‘hot’ on ‘TSV’ scale (Fig. 6b). The hourly consumption of fans, with the maximum usage (approx. 21 h) in June ($T_{om} = 32.4^\circ C$), July ($T_{om} = 30.3^\circ C$) and August ($T_{om} = 28.4^\circ C$), also exhibited a strong relationship with outdoor ($r^2 = 0.8$) and indoor temperature ($r^2 = 0.9$). This suggests that subjects are controlling the air flow using mechanical ventilation (fans, evaporative coolers etc.) or natural ventilation (door, windows etc.) to combat the thermal discomfort, similar to the results of previous studies (Raja et al., 2001; Rijal et al., 2008). A marked rise is observed in the proportional use of fans between 23 $^\circ C$ (approx. 20% usage) and 29 $^\circ C$ (approx. 80% usage), with practically all the fans running above 31 $^\circ C$, similar to the results obtained by Nicol et al. (1999).

3.2.3.2. Air conditioner (A/C). The statistical summary of the proportion of air-conditioner usage is very similar to fans (Fig. 6a). It exhibited a strong relationship to indoor and outdoor temperatures ($r^2 = 0.89$ and $r^2 = 0.85$ respectively) and has shown maximum hourly usage in the month

![Figure 5b. Linear regression of 'clo' with air velocity (Av).](image)

Table 4a
Seasonal variation in correlation of ‘met’ with different variables.

<table>
<thead>
<tr>
<th></th>
<th>met:Tg</th>
<th>met:TSV</th>
<th>met:Av</th>
<th>met:clo</th>
<th>met:RH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>-0.01</td>
<td>-0.09</td>
<td>0.04</td>
<td>0.02</td>
<td>-0.02</td>
</tr>
<tr>
<td>Summer</td>
<td>0.04</td>
<td>0.08</td>
<td>0.03</td>
<td>-0.18</td>
<td>-0.04</td>
</tr>
<tr>
<td>Monsoon</td>
<td>-0.06</td>
<td>0.01</td>
<td>-0.07</td>
<td>-0.08</td>
<td>-0.02</td>
</tr>
</tbody>
</table>

Table 4b
Gender-wise distribution of subjects involved in light and heavy activities.

<table>
<thead>
<tr>
<th>Activity</th>
<th>met</th>
<th>Female (%)</th>
<th>Male (%)</th>
<th>Female (%)</th>
<th>Male (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Activities</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sleeping</td>
<td>0.7</td>
<td>6</td>
<td>4</td>
<td>67</td>
<td>92</td>
</tr>
<tr>
<td>Sitting (Passive work)</td>
<td>0.8</td>
<td>33</td>
<td>40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sitting (Active work)</td>
<td>1</td>
<td>23</td>
<td>40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standing relaxed</td>
<td>1.2</td>
<td>5</td>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heavy Activities</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Walking about</td>
<td>1.7</td>
<td>2</td>
<td>2</td>
<td>33</td>
<td>8</td>
</tr>
<tr>
<td>Cooking</td>
<td>1.6</td>
<td>23</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>House cleaning</td>
<td>2</td>
<td>8</td>
<td>2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
of June with mean outdoor temperature of 32.4 °C. A significant rise is observed in the proportional use of A/C’s from 20% at 27 °C to 80% at 33 °C, Fig. 6a. As mentioned in a paper by Mishra and Ramgopal (2013), choice of adaptive adjustments by occupants is governed by three criteria: ease of use, effectiveness, and economy – the three E’s. It is observed that although fans were being used 24/7 (all day long or almost 24 h for all the days of the week) but the usage of A/C’s is only limited to the hours when subjects are either resting or sleeping (i.e. in the afternoon or at the night time). Subjects were observed to be deliberately pushing their comfort limits to the extent it is bearable, in order to control their electricity expenditures. As explained by Brager and De Dear (1998), “thermal perception of subjects is beyond the physics of the body’s heat balance, such as climatic setting, social conditioning, economic considerations and other contextual factors”. In this study, subjects were found to be more conscious about the electricity expenditure, and this has directly affected the A/C usage even during the peak discomfort hours.

3.2.3.3. Heater/hot blowers. Heater/hot blowers have also revealed a strong relationship with indoor/outdoor temperatures. As expected, heaters/hot blower’s usage increased with descending temperature. At 17 °C almost 80% of the subjects are using heaters/hot blowers and as the temperature increased its usage also drops down to 20% at 21 °C (Fig. 6a.).

Fans, A/C’s and heaters work instantly at the discomfort hours and accentuate the feeling of degree of control of the subjects. With this feeling of control on the indoor conditions the thermal perception of the occupants is elated, which explains the high regression coefficient of seasonal controls as opposed to the designed controls.

3.3. TSV in response to seasonal control-use

Thermal expectations of the people tend to shift gradually with the change in season. This is evident from the difference in the neutral temperature for summer, winter and monsoon period, as shown in Table 5. This difference in the thermal sensation, as explained before, is attributed to the adaptive measures employed by the subjects to restore the comfort conditions. Therefore, thermal sensation votes (TSV) of the subjects are evaluated in response to the adaptive use of the windows, balcony doors, blinds, fans, A/C’s and heaters/blowers.

‘W’-use is observed to be not used extensively as compared to the other controls but has shown a strong regression coefficient with the mean thermal sensation votes (‘TSm’), \( R^2 = 0.64 \). Fig. 7a, illustrates that the proportional use of ‘W’ is maximum (i.e. above 50%) when the subjects voted ‘slightly warmer’ on the ‘TSV’ scale in all

<table>
<thead>
<tr>
<th>Season</th>
<th>( T_{om} )</th>
<th>( T_{gm} )</th>
<th>( T_{m} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>15.6</td>
<td>18.6</td>
<td>26.3</td>
</tr>
<tr>
<td>Summer</td>
<td>28.8</td>
<td>30.1</td>
<td>25.4</td>
</tr>
<tr>
<td>Monsoon</td>
<td>28.6</td>
<td>30.8</td>
<td>27.7</td>
</tr>
<tr>
<td>ALL</td>
<td>24.3</td>
<td>26.5</td>
<td>26.6</td>
</tr>
</tbody>
</table>

Table 5

‘Neutral temperature – Winter, Summer and Monsoon’.
the surveyed buildings (GMR, BMD, TR, HV and CV). When the proportional use of ‘BD’ is regressed with ‘TSm’, up to 80% voted between ‘0’ (or ‘neutral’) and ‘1’ (or ‘slightly warm’) on ‘TSV’ scale (Fig. 7b). Comparing Figs. 7a and b, it is clear that maximum subjects preferred balcony doors over windows in response to the warm sensation. As discussed in the previous section, the shaded balconies have lowered the ambient temperature whereas windows are directly exposed to the solar gains.
‘BL’-drawn is observed to be minimum when subjects voted ‘neutral’ and observed a maximum rise as the ‘TSV’ shifted to either side of the neutrality i.e. feeling ‘slightly warm’ or ‘hot’ and ‘slightly cool’ or ‘cold’ (Fig. 7c). More than 80% of the blinds were open when the globe temperature ranged between 19 °C and 29 °C (Fig. 4). The minimum use of ‘BL’-drawn around ‘neutral’ votes confirms the adaptive behavior of the subjects as a response to only extreme outdoor conditions. The correlation coefficient of ‘TSV’ with clothing insulation was significantly negative in winter and summer period (−0.5 and −0.6) and moderately correlated (−0.2) in the monsoon period, refer Table 3b. The variability in ‘clo’ level increased as subjects voted for discomfort on a ‘TSV’ scale (i.e. −3, −2, 2 and 3). As shown in Fig. 7d, less variation is observed in ‘clo’ level when subjects voted on the warm side of the ‘TSV’ scale (i.e. from 1 to 3) as compared to when subjects voted on the cooler side of ‘TSV’ scale, similar observations are drawn by Schiavon and Lee (2013). This implies that subjects use clothing as an adaptive measure in response to the uncomfortable environmental conditions.

The results have clearly shown the significance of seasonal variability of various physical and contextual parameters on the adaptive behavior of the subjects. In a country like India, this has far more implications on the overall energy demand of naturally ventilated buildings, considering the comfort tolerance of the natives to a wider range of temperatures. And, thus, it is not only essential but inevitable to efficiently design the building controls (i.e. ‘in-built controls’ or ‘designed controls’) in order to minimize the dependence on ‘seasonal controls’ or ‘energy intensive’ controls.

4. Conclusion

Class II protocol is employed in the longitudinal survey collecting a data-set of 984 from 82 subjects. A comfort temperature of 26.1 °C is obtained, with a comfort band of 22.5–30.6 °C, using linear regression analysis. The findings reveal that the residents are very well adapted to their thermal environment and could achieve comfort at a broader temperature range, as opposed to what recommended by the Indian Standards.

‘Tg’ and ‘TSV’ have shown a poor correlation coefficient (.44) in winter as compared to summer (.85) and monsoon (.77). The thermal sensitivity of subjects is also observed to be higher in summer and monsoon period as compared to the winter period. Balcony doors have been widely used in the study in spite of negligible use of balcony spaces. Subjects preferred to open it (in all seasons) not just for cross ventilation but to get the feeling of ‘freshness’ and openness’. It is also observed that maximum subjects preferred balcony doors over windows in response to the warm sensation. ‘BL’-drawn is observed to be minimum when subjects voted ‘neutral’ and observed a maximum rise as the ‘TSV’ shifted to either side of the neutrality. It is also inferred that clo adjustment is an effective control measure in the summer period when the air movement (forced or natural) is controlled by the subjects. Metabolic activity has shown no correlation with any of the physical variables or with the comfort votes of the subjects. But, gender-wise analysis of ‘met’ rates has shown some clear differences for male and female subjects. The statistical summary of seasonal controls (i.e. fan, A/C and heater) has shown a strong dependence on Tg.

Finally, the study concludes that no matter how strong the statistical results sound, the ground situation of any domestic building is very dynamic in many terms and, thus, requires a systematic analysis. It is strongly suggested that the efficient design of the building controls (i.e. ‘in-built controls’) can help in minimizing the dependence on ‘seasonal controls’ and the overall energy consumption.
ENERGY ASSESSMENT OF APARTMENT BUILDINGS IN COMPOSITE CLIMATIC REGIONS OF NORTH INDIA
Shaliza Singh, Research Scholar, I.I.T Roorkee
QUESTIONNAIRE SURVEY

LONGITUDINAL SURVEY

<table>
<thead>
<tr>
<th>Time:</th>
<th>Building Name:</th>
<th>No. of DU /Floor:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date:</td>
<td>Flat no.:</td>
<td></td>
</tr>
</tbody>
</table>

Name: Age: Weight: Height: Sex:

What is your approximate monthly electricity bill?

CLOTHING: Tick as appropriate:

<table>
<thead>
<tr>
<th></th>
<th>Summer</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undergarments</td>
<td></td>
<td>Cotton salwar kameez</td>
</tr>
<tr>
<td>Upholestry</td>
<td></td>
<td>Woolen Salwar Kameez</td>
</tr>
<tr>
<td>Cotton Sari + petticoat+blouse</td>
<td></td>
<td>Jacket</td>
</tr>
<tr>
<td>Sari (polyester) + petticoat+ blouse</td>
<td></td>
<td>Sweater</td>
</tr>
<tr>
<td>Cotton Salwar Suit</td>
<td></td>
<td>Long gown</td>
</tr>
<tr>
<td>Trouser (thin)</td>
<td></td>
<td>Trousers/Long skirt</td>
</tr>
<tr>
<td>Walking Shorts</td>
<td></td>
<td>Long sleeves shirt</td>
</tr>
<tr>
<td>Long sleeves shirt</td>
<td></td>
<td>Short sleeves shirt</td>
</tr>
<tr>
<td>Short sleeves shirt</td>
<td></td>
<td>Hand Glubs</td>
</tr>
<tr>
<td>Sleeveless/scoop neck top</td>
<td></td>
<td>Shoes</td>
</tr>
<tr>
<td>T-shirt</td>
<td></td>
<td>Sandals</td>
</tr>
<tr>
<td>Skirt (thin)</td>
<td></td>
<td>Socks</td>
</tr>
<tr>
<td>Light Dress, short sleeves</td>
<td></td>
<td>Shawl</td>
</tr>
<tr>
<td>Short sleeves pajamas (thin)</td>
<td></td>
<td>Warmer</td>
</tr>
<tr>
<td>Shoes</td>
<td></td>
<td>Cotton sari</td>
</tr>
<tr>
<td>Sandals</td>
<td></td>
<td>Blouse</td>
</tr>
<tr>
<td>Socks (calf length)</td>
<td></td>
<td>Others (specify) ..........</td>
</tr>
</tbody>
</table>

FEELING: At present I feel:

- Hot
- Warm
- Slightly warm
- Neutral
- Slightly cool
- Cool
- Cold

PREFERENCE: I would prefer to be:

- Much warmer
- A bit warmer
- No change
- A bit cooler
- Much cooler

ACTIVITY in the last 15 mins:

- Sleeping
- Sitting (Passive work)
- Sitting (active work)
- Standing relaxed
- Standing working
- Walking indoors
- Walking outdoors
### References


de Dear, R., Brager, G.S., Cooper, D. Developing an adaptive model of thermal comfort and preference (ASHRAE RP-884). Sydney, NSW 2109 Australia: Macquarie Research Ltd., Macquarie University; 1997 [Center for Environmental Design Research, University of California, Berkeley, CA 94720, USA].


