Development of building bio-climatic design chart for high thermal mass strategy using adaptive comfort approach

Ph.D. Thesis

by

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September - 2017

Dedicated to my family

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CERTIFICATE

This is certified that the thesis entitled **“Development of building bio-climatic design chart for high thermal mass strategy using adaptive comfort approach”** is being submitted by **SANJAY** (ID-2013RCV9026), to the Malaviya National Institute of Technology, Jaipur for the award of the Degree of **Doctor of Philosophy** in Centre for Energy and Environment is a bonafide record of original research work carried out by him. He has worked under our guidance and supervision and has fulfilled the requirement for the submission of this thesis, which has reached the requisite standard.

The results contained in this thesis have not been submitted in part or full, to any other University or Institute for the award of any degree or diploma.

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DECLARATION

I hereby certify that the work which is presented in the thesis entitled **“Development of building bio-climatic design chart for high thermal mass strategy using adaptive comfort approach”** in partial fulfilment of the requirements for the award of Doctor of Philosophy, in the Centre for Energy and Environment, Malaviya National Institute of Technology, Jaipur, is an authentic record of my own work unless otherwise referenced or acknowledged. The thesis was completed under the supervision of **Prof. Jyotirmay Mathur**, Professor and **Dr. Sanjay Mathur**, Associate Professor & Head, Centre for Energy and Environment, Malaviya National Institute of Technology, Jaipur. The results presented in this thesis have not been submitted in part or full, to any other University or Institute for the award of any degree. I also certify that no part of this work has been copied or borrowed from anyone else. In case any type of plagiarism is found out, I will be solely and entirely responsible for it.

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LIST OF PUBLICATIONS

1. **Sanjay Kumar**, Priyam Tewari, Sanjay Mathur, Jyotirmay Mathur, **“**Development of mathematical correlations for indoor temperature from field observations of the performance of high thermal mass buildings in India**”, Building and Environment,** 122(2017): 324-342.
2. **Sanjay Kumar**, Jyotirmay Mathur, Sanjay Mathur, Manoj Kumar Singh, Vivian Loftness, **“**An adaptive approach to define thermal comfort zones on psychrometric chart for naturally ventilated buildings in composite climate of India**” Building and Environment** 109 (2016): 135-153.
3. **Sanjay Kumar**, Manoj Kumar Singh, Vivian Loftness, Jyotirmay Mathur, Sanjay Mathur, **“**Thermal Comfort Assessment and Characteristics of Occupant’s Behavior in Composite Climate of India**”, Energy for Sustainable Development**, 33 (2016): 108–121.
4. **Sanjay Kumar**, Jyotirmay Mathur, Sanjay Mathur, “Adaptive use of environmental controls for thermal comfort in composite climate of India” in proceedings of 9th International conference of **IAQVEC 2016**, Seoul, Korea.

ABSTRACT

About one-third of India's energy consumption is being used for space cooling and heating applications in built environment. This energy consumption trend will increase with the continued strong economic growth, on-going population explosion, increasing urbanization, living standard gains and change in lifestyles. So, the design of buildings, during its initial phase, plays a major role in making buildings comfortable and energy efficient. Given the importance of energy in today’s scenario, it is imperative and urgent to find some passive design solutions for buildings which consume less energy without sacrificing human comfort.

International comfort standards such as ISO 7730, ASHRAE Standard 55−2013, and EN 15251 are commonly being used for evaluating indoor environmental conditions for a defined activity and clothing insulation irrespective of climatic conditions and building types. Field studies of thermal comfort conducted all over the world for the different type of buildings and climates, had illustrated that indoor comfort conditions are dependent on local climatic conditions and order of thermal adaptations.

From ancient times, building envelopes with high thermal mass were found to be preferable as they dampen the amplitude of ambient temperature and help in creating the acceptable indoor environment. This has facilitated the increasing importance of the thermal mass in the hot and dry climates.

Building Bio-climatic Design Charts (BBCC) uses ASHRAE Standard 55 comfort zone for accessing indoor thermal comfort in buildings using different passive strategies for a local climate. The available building bio-climatic design charts for selection of an appropriate strategy to produce thermal comfort in buildings are based on some experimental studies carried out in few buildings for climates other than Indian climates. Therefore, a serious need was felt to develop a customized building bio-climatic design chart especially for one commonly used passive strategy viz. high thermal mass in naturally ventilated buildings for this climatic region of India. The present study selected composite climate of Jaipur, India, due to its diverse climatic conditions.

To fulfil the goals set in the present work, first of all, a thermal comfort field study was conducted in thirty-two naturally ventilated buildings, collecting a total of 2610 samples spread over a total period of five years (between 2011 and 2016), covering all seasons, age groups, clothing types, and building types. The present study analyzed the thermal sensations and preferences for different environmental parameters, thermal neutrality and the various thermal adaptations prevailing in naturally ventilated buildings for this region. This study also analyzed the occupant's adaptive behavior for the use of controls like the doors, windows, curtains and fans, etc.

On an annual basis, the mean comfort temperature, as predicted by Griffiths' method, was found to be 27.9˚C. The seasonal analysis revealed the mean comfort temperature bandwidth is about 6.6˚C as obtained through Griffiths' method. In the present study 40% of total observation, windows were found open. The proportion of window opening reaches to a maximum of 60% when mean indoor operative temperature peaks at 33.5˚C. The percentage of fans in use increased as the temperature increased, and it reached a maximum of 81% when the mean indoor operative temperatures peaked at 28.5˚C. Finally, equations for predicting fan use and window opening have been developed using the logistic regression method. The predicted data using these equations matched fairly with measured data.

The boundaries of ASHRAE Standard 55 comfort zones have been extended reflecting the results of this study for naturally ventilated buildings. The subjects are found comfortable at the temperature up to 32˚C and relative humidity of 20%−80% in still air conditions of 0−0.2 m/s. The comfort zones further extends up to 35˚C between the relative humidity of 20%−80% at the higher indoor air speed of 1.5 m/s. The comfortable votes (±1 thermal sensations) from extended database have been used to validate the proposed adaptive comfort zones.

Fully functional thermal mass residential and office buildings are monitored for one year to develop mathematical correlations for predicting indoor air temperatures in the monitored high mass buildings using multiple linear regression technique. Further statistical analysis based on R^2 value, 'F–statistics', and 't–statistics' has been carried out to determine the accuracy and

robustness of the obtained correlations. It is demonstrated in the present study that good agreement (R^2>0.90) existed between the measured data and the predicted data for similar building types.

Results of thermal monitoring are further used to develop a new bioclimatic boundary of ambient conditions for the use of high thermal mass in buildings on building bio-climatic design chart using defined comfort zones for this climatic zone of India. The boundaries extend up to an average monthly maximum temperature of about 38.4˚C and 37.4˚C for residential and office type thermal mass buildings, respectively. A bandwidth of more than 3˚C has been observed for different thermal mass levels and at high internal gains. The study further recommends analysing the potential of other passive strategies like direct evaporative cooling, natural ventilation, direct gain, etc. using these customised bio-climatic design charts in the different climatic zone of India to maximize indoor thermal comfort and minimize energy consumption.

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ABBREVIATIONS

Notation	Description
AC	Air Conditioned
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
AVS	Air Velocity Sensation Votes
AVP	Air Velocity Preferences
BBCC	Building Bio-Climatic Charts
BIS	Bureau of Indian Standards
CEN	European Committee for Standardization
DBT	Dry bulb temperature
DR	Draught
EN	European Nation
ET*	New Effective Temperature
HSI	Heat Stress Index
HP	Humidity Preferences
HSV	Humidity Sensation Votes
HVAC	Heating, Ventilation and Air-Conditioning
ISO	International Standard Organization
ISHRAE	Indian Society of Heating, Refrigerating and Air-Conditioning Engineers
ITS	Index of Thermal Stress
MM	Mixed Mode
NBC	National Building Code
NV	Naturally Ventilated
OT	Operative Temperature
PD	Percentage Dissatisfied
PMV	Predicted Mean Vote
PPD	Percentage of People Dissatisfied
SET*/SET	Standard Effective Temperature
TP	Temperature Preferences
TSI	Thermal Strain Index
TSI	Tropical Summer Index
TSV	Thermal Sensation Votes
WBT	Wet Bulb Temperature
WWR	Window to Wall Ratio

NOMENCLATURE

English Symbols

Notation	Description	Unit
A_D	Du Bois Body surface Area	m^2
A/A_I	Surface area of room/isothermal mass	m^2
Clo	Clothing Insulation (1 clo=0.155 m^2k/W)	Clo
f_{cl}	Ratio of the surface area of the clothed body to surface area of the nude body	unit less
G	Griffiths' coefficient	$^oC^{-1}$
$h_c/h_i/h_o$	Convective heat transfer coefficient	$W/m^2\,^oC$
I(t)	Solar Irradiance intensity	W/m^2
$I_{cl,tot}$	Total thermal resistance of the clothing assemble	m^2k/W
k	Thermal conductivity	$W/m\,^oC$
M/A_{Du}	Metabolic rate	kcal/hr. m^2
M_a	Mass of air in room	kg
η	Mechanical Efficiency	unit less
P_a	Partial vapor pressure	mm HG
p	Probability	unit less
RH	Relative humidity	%
R/r	Pearson's correlation coefficient	unit less
R^2	Coefficient of correlation	unit less
$T_a/T_i/t_a$	Indoor air temperature	^oC
T_g/GT	Globe temperature	^oC
T_c	Comfort temperature	^oC
$t_{mrt}/\ t_r$	Mean radiant temperature.	^oC
T_{mm}	Mean monthly outdoor air temperature	^oC
T_o	Outdoor air temperature	^oC
T_{op}	Operative temperature	^oC
T_{rm}	Running mean of outdoor air temperature	^oC
V_i/v	Indoor air speed	m s^{-1}
V_1	Volumetric efficiency	unit less
U	Overall heat transfer coefficient	W/m^2K
WBT	Wet bulb temperature	^oC

Greek Symbols

Notation	**Description**	**Unit**
ρ	Density of air	kg m^{-3}
c	Thermal conductivity	$W/m^2\ {}^oC$
ε	Emissivity	unit less
α_a	Absorptivity of absorber	unit less
α	Level of significance	unit less
ω	Angular frequency	s^{-1}
η_o/ η_i/ ach	Number of air change per hour	h^{-1}

CHAPTER 1
INTRODUCTION

Energy conservation is an important issue in era of global warming. About one-third of India's energy consumption is being used for space heating and cooling applications [1]. This energy consumption trend will increase with the continued strong economic growth, on-going population explosion, increasing urbanization, living standard gains and change in lifestyles [2]. The sectoral energy consumption in commercial and residential buildings of India is presented in Figure 1-1. Given the importance of energy for the existence of our society, it is imperative and urgent to find alternative sources to mitigate its widespread consumption and the consequent impact on the environment without sacrificing human comfort. Building occupants are usually affected by the following built environment seated comfort domains: ‘Thermal comfort,' ‘Visual comfort,' ‘Acoustic comfort,' and ‘Air quality.' Out of these four, thermal comfort has the strongest relationship with energy consumption in built environment.

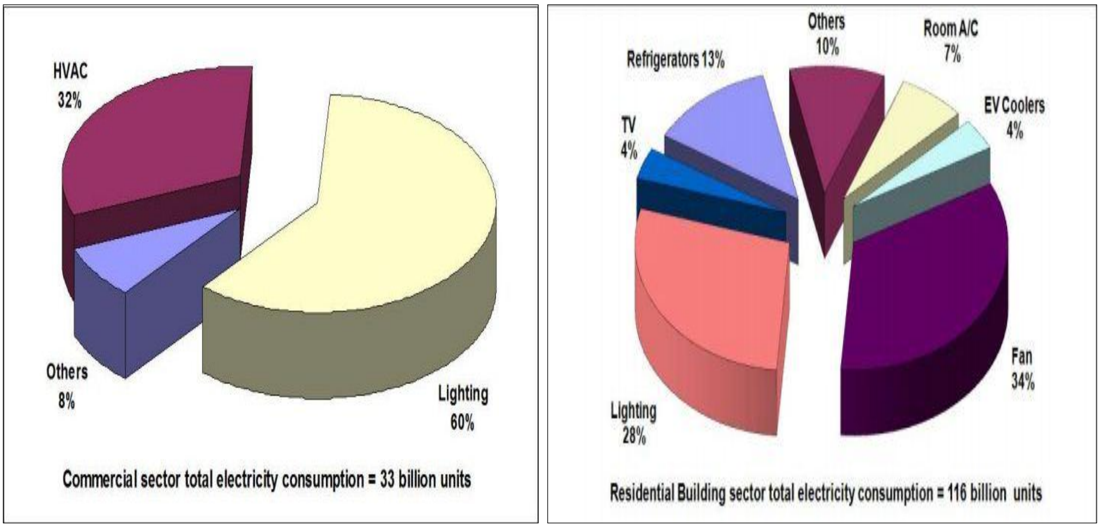


Figure 1-1 Energy consumption in building sector of India [3]

1.1 Thermal comfort

Thermal comfort is that “condition of mind which expresses satisfaction with the thermal environment” [4]. Thermal comfort analysis is one of the most useful methods of identifying thermal perceptions of occupants in a particular building space. International comfort standards such as ISO 7730 [**5**], ASHRAE Standard 55−2013 [**4**], and EN 15251 [**6**] are commonly being used for evaluating indoor environmental conditions for a defined activity and clothing irrespective of climatic conditions and building types.

1.2 Thermal adaptation

The fundamental assumption of the adaptive thermal comfort approach was expressed by Auliciem [**7**], Humphreys [**8**] and Nicol and Humphreys [**9**]. The adaptive principle states that ‘if a change occurs such as to produce discomfort, people react in ways that tend to restore their comfort' [**10**]. It implies that human beings have shown an amazing tendency to adopt the variable climatic conditions for making themselves thermally comfortable. The generic term “adaptation” might broadly be interpreted as the gradual diminution of the organism’s response to repeated environmental stimulation. The adaptive thermal comfort approach has been classified into three principal components such as psychological adaptation, physiological adaptation and behavioral adaptation [**11**]. Thermal comfort field study for more than 200 buildings globally with more than 21,000 subject responses revealed that thermal adaptation is usually attributed to habituation, acclimatization, and adjustments. Furthermore, adaptive thermal comfort practice is found to be context dependent, and different aspect of building services and climatic variations affects thermal comfort [**12**] [**13**]. In last past decade, researchers across all over the world conducted field studies of thermal comfort in both conditioned and unconditioned buildings and derived comfort conditions and models for different climatic conditions. The adaptive approach of thermal comfort evaluates the thermal neutrality conditions better than models associated with fixed environment variables.

1.3 Using thermal mass for comfortable indoor conditions

In many hot countries, there is growing interest in utilizing passive and low-energy systems for cooling buildings, both residential and commercial. From ancient times, building envelopes with high thermal mass were found to be preferable as they dampen the amplitude of ambient temperature heat wave and help in creating an acceptable indoor environment [**14**] [**15**] [**16**]. This has facilitated the increasing importance of the thermal mass in hot and dry climates. In the hot and dry climate of India, from ancient time common practice is to build with heavy thermal mass, and experience shows that better thermal comfort conditions exist in massive structures than in light buildings. The traditional architectures are examples of a very close relationship with this climate specific conditions and adapted to the external environment through the adoption of passive strategies such as high thermal mass envelopes and natural cross ventilation [**17**] [**18**].

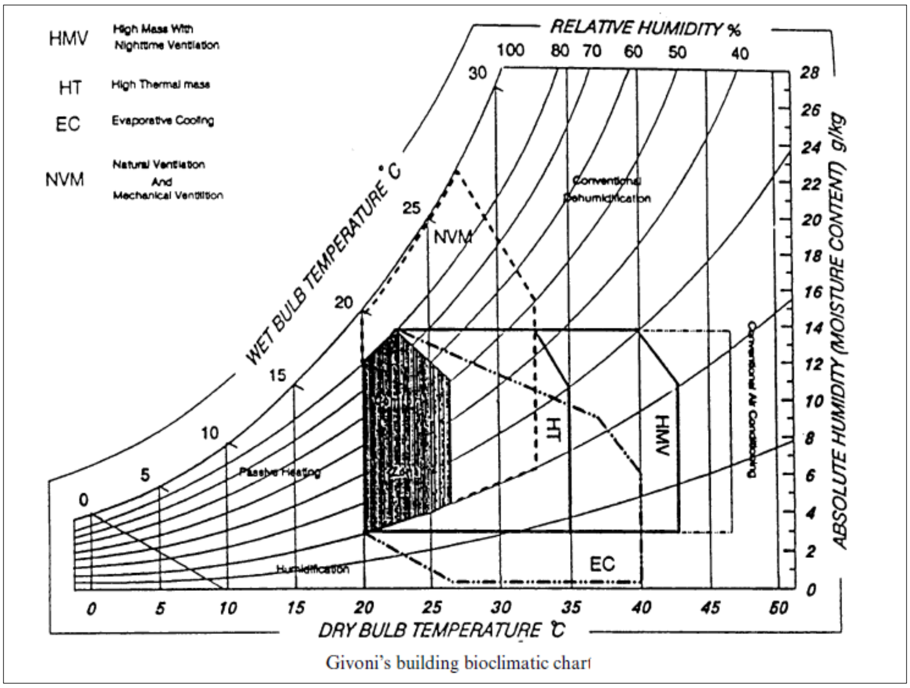
Thermal mass is defined as any building material having a high heat storage capacity that can be integrated into the structural fabric of the building to effectively utilize the passive solar energy for the purposes of heating and cooling. It is typically contained in walls, partitions, ceilings and floors of the building, constructed of material with high heat capacities, such as poured concrete, bricks, and tiles. The selection of a particular material to function as thermal mass depends on a variety of factors such as a high density (ρ), a high specific heat capacity (C_p), the ability to delay the time (Time lag) and decrement factor [**16**] [**19**].

1.4 Building bio-climatic design charts

Many pre-design tools and simplified techniques have been developed last few decades to help architects, engineers or building designers for considering human comfort requirement in pre-design stage. The bioclimatic building design is a practice most commonly defined as using climatic “resources” of a particular location with the help of building envelope elements to ensure comfortable indoor conditions [**20**]. Therefore, it is recommended to start the bioclimatic design with a regional “climate resources” analysis, which uses basic climatic data to determine best satisfactory passive solutions [**21**].

The Building Bio-climatic Design Charts (BBCC) indicates that whenever ambient conditions (temperature and humidity) fall within the designated limits of a passive design strategy, then the interior of a building intended to execute that strategy effectively will remain comfortable. Since its introduction, the bioclimatic charts have been continuously developed, updated, and presented in different forms across the world by several authors [**22**] [**23**] [**24**] [**14**].

However, the most commonly used bio-climatic design chart is one developed by Givoni [**25**] in year 1992 that is based on some experimental studies in Israel, California and other European countries (Figure 1-2). It has two principal components: indoor comfort zone based on ASHRAE Standard 55, which defines the combinations of temperature and humidity within which occupants will be comfortable, and boundaries of climatic conditions within which various building passive design strategies and natural cooling systems can provide comfort. Currently, many architects use these building bioclimatic design charts, developed in past few decade by various researchers, for identifying suitable passive measures.



Givoni's building bioclimatic chart

Figure 1-2 Building bio-climatic design chart [25**]**

1.5 Origin and objectives of present research

Research gaps based on the literature review revealed that current comfort standards do not correlate to the conditions specific to India due to the large variation in meteorological conditions and also due to social and cultural differences. Also, existing building bio-climatic design charts are not universally acceptable as these are also depend upon local meteorological conditions and building types. These charts are also widely used in India and other countries for potential passive solutions to a particular climate. However, from time to time researchers have identified the need for developing these charts considering Indian building typologies, climates and comfort preferences in Indian subjects.

These research gaps encouraged to perform a study for development of customized building bio-climatic design chart for high thermal mass used as passive design strategy in naturally ventilated buildings in the composite climatic zone of India. To fulfill this, two specific objectives has been set for current study which is as follows:

1. Development of an adaptive comfort zone especially for composite climate considering adaptive thermal comfort approach.
2. Develop a building bio-climatic chart for one widely used passive strategy – high thermal mass in buildings for composite climate of India.

1.6 Thesis organization

The entire thesis is summed up in seven chapters. Presented below are the highlights of the chapters.

Chapter 1 gives an overview of the introduction, problem statement, and outline of the tasks performed in the present research.

Chapter 2 focused on various methods and different approaches used for the quantification of the indoor thermal environment and thermal adaptations, existing comfort standards, thermal comfort studies across the world, building bio-climatic charts, the historical development of building bio-climatic design charts, design tools, thermal mass in building construction, etc. Lastly, this Chapter finds out research gaps and defines study goals.

Chapter 3 Research methodology adopted for the present study is described in this chapter. The chapter includes the approaches used for assessment of thermal adaptations in naturally ventilated buildings and then defining the adaptive comfort zones for composite climate of India. Lastly, the methods used in present study for defining the climatic boundary for high thermal mass through BBCC approach are described.

Chapter 4 This chapter discussed the results of thermal comfort and adaptation in naturally ventilated buildings for composite climate of India. The Chapter also summarized the assessment of thermal sensations, preferences for indoor variables, thermal neutrality using Linear Regression techniques and Griffths'

Method and use of adaptive controls for comfort by occupants in naturally ventilated buildings. Further, Logistic regression is carried out to predict the opening behaviour of controls and compared with the findings of other studies in different climates.

Chapter 5 This chapter discussed the methods used for defining the comfort zones on standard psychrometric chart considering region-specific adaptations, comfort expectations, and the role of higher air velocities in naturally ventilated buildings. The comfort zones are defined by airspeed ranges and validated with field study data.

Chapter 6 focused on the methodology adopted for developing building bio-climatic design chart for the use of high thermal mass in buildings. Long term thermal monitoring has been carried out for thermal performance analysis of residential and office buildings. Mathematical correlations are developed to predict indoor conditions. The comfort zones defined in Chapter 5 are used to define the climatic limit of ambient temperature for the use of high thermal mass in buildings for office and residential buildings. Further, a simulation study was also carried out to investigate the effect of thermal mass and internal gains on developed boundaries through sensitivity analysis.

Chapter 7 This chapter summarize the findings and conclusions and future work coming out present study.

CHAPTER 2
LITERATURE REVIEW

2.1 Preamble

The science of comfort is the precise specification of conditions under which most of the occupants accept their environment and feel satisfied with surroundings. Since the residents spend most of their times in offices and homes, therefore, evaluation of the indoor comfort or occupants overall satisfaction for their thermal environment becomes essential. Thermal comfort is an example of a “complex adaptive system − a multitude of interacting environmental and non-environmental variables” [**9**]. Various studies on adaptive comfort across the world in last decade have revealed that buildings designed with climatic considerations and different socio-cultural expectations provide an acceptable thermal environment for building occupants.

In many hot countries, and also in countries with a temperate climate having hot summers, there is growing interest in utilizing passive and low-energy systems for cooling buildings, both residential and commercial [**26**] [**27**]. Cooling of buildings by passive and low energy systems can be provided through the utilization of several natural heat sinks like the ambient air, the upper atmosphere, and the under-surface soil. To design comfortable buildings, many architects or building designers use simplified analyses and synthesis techniques. Currently, many designers use the building bioclimatic design chart for the assessment of human comfort potential in built environment by various passive strategies for a particular climate [**28**].

It is established in the literature that building envelopes with high thermal mass were found to be preferable where diurnal swing are more than 10˚C [**15**] [**26**] [**29**]. This has facilitated the increasing importance of the thermal mass in hot and dry climates where there is a much large diurnal swing. In the hot and dry climate of India, from ancient times common practice has been to design the buildings with high thermal mass construction, and experience shows that better thermal comfort conditions exist in high thermal mass structures than in low thermal mass buildings [**15**].

This chapter has been focused on various methods and different approaches used for the quantification of the indoor thermal environment and thermal adaptations, existing comfort standards, thermal comfort studies across the world, building bio-climatic charts, the historical development of building bio-climatic chart, design tools, thermal mass in the construction of buildings, etc. The review of the literature related to this research is organized under following three sections:

1. Thermal adaptations and comfort
2. Use of thermal mass in buildings
3. Building bio-climatic chart (BBCC)

2.2 Thermal comfort indices

Thermal comfort indices describe criteria for assessing the human thermal satisfaction for the particular thermal environment. In last decade various indices have been developed by different researchers across the world. These environmental indices can be divided into two categories: a) Analytical, b) Empirical. A few such indices are reviewed briefly in the following section.

2.2.1 Analytical indices

A few analytical indices are discussed briefly below.

- **Thermal strain index (TSI)**

This index was developed partly by observation, partly by analyzing the heat transfer mechanisms [**30**]. This index consists of a set of parallel strain lines on the standard psychrometric chart. At high levels of strain these are almost parallel with the wet bulb temperature lines, while at low levels they are vertical, coinciding with the dry bulb temperature lines.

- **Predicted 4- hour sweat rate**

The scale was established by analyzing many different combinations of air temperature, humidity, air movement, mean radiant temperature, metabolic rate and the amount of clothing worn, producing the same sweat rate, thus presumably the same physiological stress. The primary objective to develop this index was to determine the physical stress induced the sweat rate, pulse or internal body temperature. This index was well suited for the condition with high-temperature ranges but found less suitable for low temperature ranges up to 28˚C. Givoni [**31**] later found that this index underestimates the cooling effect of air movement at high humidity ratio.

- **Heat stress index (HSI)**

It is defined as the ratio of evaporative cooling required ($\mathbf{E_{req}}$) for maintaining heat balance, to the maximum evaporative cooling ($\mathbf{E_{max}}$) possible under the existing conditions [**32**]. The range of the scale is thought to be reliable for still air between 27˚C and 35˚C, 30%−80% RH. It overestimates the effect of air speed at low and high humidity ratio at medium to high temperatures. Also, it is not suitable for the comfort limits defined as zones or below it and it overestimates the effect of thermal stress.

$$\mathbf{HSI} = \left(\frac{\mathbf{E_{req}}}{\mathbf{E_{max}}}\right) \times \mathbf{100} \qquad (\mathbf{2.1})$$

- **Index of thermal stress (ITS)**

This index is the calculated cooling rate produced by sweating, which would maintain thermal equilibrium under the given conditions [**31**]. The calculation is based on a refined biophysical model of the man-environment thermal system. It includes a very typical mathematical relation, allowing for clothing insulation and ‘sitting with back to the sun and standing with back to the sun’ in desert areas. Its usefulness extends from comfortable to overheated conditions, as far as physiological adjustments are (or would be) able to maintain a thermal equilibrium.

- **Predicted Mean Vote (PMV) and Percentage of People Dissatisfied (PPD)**

That comfort equation is based on the empirical relations that were developed by Fanger [**33**] from the database he collected during climatic chamber experiments conducted on European subjects. The resulting equation described thermal comfort as the imbalance between the actual heat flow from the body in a given thermal environment and the heat flow required for optimum (i.e.

neutral) comfort for a particular activity. PMV is expressed regarding the ASHRAE comfort scale which is used to represent the percentage of peoples that would vote (dis)comfort and became known as the ‘‘Predicted Mean Vote’’ (PMV) index. The PMV was then incorporated into the ‘‘Predicted Percentage of Dissatisfied’’ (PPD) index. This heat balance model considers four environmental parameters, i.e. temperature, mean radiant temperature, relative humidity and air velocity, and two personal variables, i.e. activity and clothing insulation. The calculation method of PMV and PPD has been described by equations (2.2) to (2.4) as suggested by Fanger [**33**]. Fanger’s PMV-PPD model on thermal comfort has been a pathbreaking contribution to the theory of thermal comfort and the evaluation of indoor thermal environments in buildings. Figure 2-1 presents the graphic relation between PMV-PPD indices.

$$\begin{aligned}\mathbf{PMV} = {} & \left(\mathbf{0.352e}^{-0.042\left(\frac{\mathbf{M}}{\mathbf{A_{Du}}}\right)} + \mathbf{0.032}\right)\Big[\frac{\mathbf{M}}{\mathbf{A_{Dn}}}(\mathbf{1}-\boldsymbol{n}) \\ & - \mathbf{0.35}\left[\mathbf{43} - \mathbf{0.061}\frac{\mathbf{M}}{\mathbf{A_{Du}}}(\mathbf{1}-\boldsymbol{n}) - \mathbf{P_a}\right] - \mathbf{0.42}\left[\frac{\mathbf{M}}{\mathbf{A_{Du}}}(\mathbf{1}-\boldsymbol{n}) - \mathbf{50}\right] \\ & - \mathbf{0.0023}\frac{\mathbf{M}}{\mathbf{A_{Du}}}(\mathbf{44} - \mathbf{P_a}) \\ & - \mathbf{0.0014}\frac{\mathbf{M}}{\mathbf{A_{Du}}}(\mathbf{34} - \mathbf{t_a}) - \mathbf{3.4.10^{-8}f_{cl}}[(\mathbf{t_{cl}}+\mathbf{273})^{\mathbf{4}} - (\mathbf{t_{mrt}} + \mathbf{273})^{\mathbf{4}}] \\ & - \mathbf{f_{cl}h_c}(\mathbf{t_{cl}} - \mathbf{ta})\Big]\end{aligned} \tag{2.2}$$

t_{cl} corresponds to mean temperature of the outer surface of clothed body (˚C) and it is determined using equation (2.3)

$$\mathbf{t_{cl}} = \mathbf{35.7} - \mathbf{0.032}\frac{\mathbf{M}}{\mathbf{A_{Du}}}(\mathbf{1}-\mathbf{n}) - \mathbf{0.18I_{cl}}[\mathbf{3.4.10^{-8}f_{cl}}[(\mathbf{t_{cl}}+\mathbf{273})^{\mathbf{4}} - (\mathbf{t_{mrt}}+\mathbf{273})^{\mathbf{4}}] + \mathbf{f_{cl}h_c}(\mathbf{t_{cl}} - \mathbf{t_a}) \tag{2.3}$$

It is traditional assumption that PMV within a band of ±0.5 (corresponding to 90% acceptability) and ±0.85 (corresponding to 80% acceptability) is to be considered comfortable and beyond this limit, occupants suffer thermal dissatisfaction either due to warmness or coolness. Predicted percentage of dissatisfied (PPD) ranges from 5%−80% and can be deduced from equation (2.4)

$$\mathbf{PPD} = \mathbf{100} - \mathbf{95.exp}\left(-\mathbf{0.03353.PMV^4} - \mathbf{0.2179.PMV^2}\right) \tag{2.4}$$

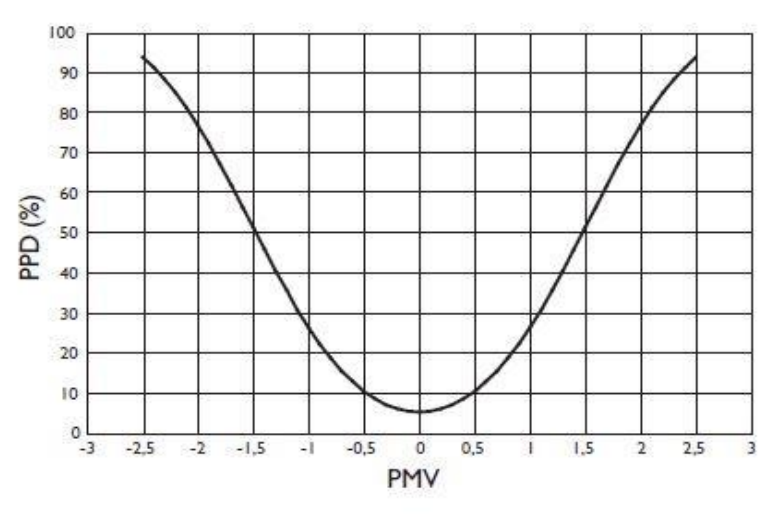


Figure 2-1 Percentage Predicted Dissatisfied as function of Predicted Mean Vote (PMV) [33**]**

However, heat balance model included physical and behavioural adaptations in the form of clothing thus addressing the issue of contextual nature of comfort to some extent. But still more important factors such as psychological, physiological and socio-cultural aspects of occupant comfort in different types of buildings and climates were left out [**34**] [**35**] [**36**]. In general, PMV model works well in a built environment with HVAC systems. For naturally ventilated (or free-running) buildings, however, the indoor temperature considered most comfortable increases significantly in warmer climates and decreases in colder climate regions [**37**] [**38**]. In non-air-conditioned buildings in warm climates, people may sense the warmth as being less severe than that predicted by the PMV model due mainly to low expectations.

2.2.2 Empirical indices

A few empirical indices are reviewed in the present section.

- **Operative Temperature (OT)**

The empirical index was firstly introduced in late 1937 by Gagge [**39**], as a result of work similar to Bedford's. It is defined as the temperature of a uniform, isothermal "black" enclosure in which man would exchange heat by radiation and convection at the same rate as in the given non-uniform environment. ASHRAE Standard 55 now suggests that a simple averaging gives acceptable results:

$$\mathbf{OT} = \frac{\mathbf{MRT + DBT}}{\mathbf{2}} \qquad (\mathbf{2.5})$$

- **Effective temperature (ET)**

Developed by Houghten and Yagloglou [**40**], defined as the temperature of a still, in the absence of radiation, produce the same effect as the atmosphere in question. It thus combines the effect of dry air temperature and humidity. It has been found later that ET overestimates the influence of humidity under both cool and comfortable conditions.

- **New Effective Temperature (ET*) and Standard Effective Temperature (SET*)**

New Effective temperature (ET*) was first developed by Gagge in 1971 [**41**] using the ‘two-node model’ from the study of climate chambers. It is defined as the temperature (DBT) of a uniform enclosure at 50% relative humidity, having the same net heat exchange by radiation, convection, and evaporation as the environment in question. Effective Temperature can be calculated using equation (2.6) as also presented in ASHRAE Handbook of Fundamental [**42**].

$$\mathbf{ET^{*} = t_{op} + \; wi_{m}LR\left(P_{a} - 0.5P_{ET*,s}\right)} \qquad (\mathbf{2.6})$$

where, ET* corresponds to Effective Temperature (˚C), t_{op} represents operative temperature (˚C), w corresponds to respiratory water loss, i_m refers to permeability index, L represents to thermal load on body (W/m^2), R corresponds to the thermal resistance (m^2-K/W), Pa refers to the water vapour pressure (kPa) and PET*,S represents saturated vapor pressure, in psi, at ET*.

SET* has been interpreted by Gagge et al. [**43**] as a subset of ET* under standardized conditions: clothing standardized for given activities. According to ASHRAE Standard 55-2013, SET* is defined as the equivalent air temperature of an isothermal environment at 50% RH, less than 0.1 m/s airspeed and $t_r = t_a$, in which a subject wearing clothing standardized for the activity concerned, has the same heat stress (skin temperature) and thermoregulatory strain (skin wittedness) as in the actual environment. This is the most commonly used index.

- **Tropical Summer Index (TSI)**

It is an empirical index developed by Sharma and Ali [**44**] through elaborate field studies on office subjects in northern India to determine the comfort condition for hot dry and warm –humid conditions. Thermal comfort field study has been carried out on acclimatized young Indian males during the summer season for three consecutive years. They have made a simultaneous observation of the thermal sensations and the prevailing environmental conditions of 18 subjects. Tropical Summer Index (TSI) was obtained through multiple regression of comfort sensation along with the environmental variables; it is defined as “the temperature of the still air, at 50% relative humidity, which causes the same thermal sensation as the given environmental condition. Equation (2.7) shows the mathematical relationship obtained between various variables.

$$\mathbf{TSI = WBT \times 0.3 + GT \times 0.75 - 2\sqrt{v}} \qquad (\mathbf{2.7})$$

Where TSI is Tropical summer index, WBT is wet bulb temperature (˚C), GT is indoor globe temperature (˚C), v is indoor average air speed (m/s). The study also observed higher comfort bandwidth (25˚C−30˚C) than ASHRAE 55 standard and higher mean comfort temperature such as 27.5˚C for hot and warm climatic conditions. Figure 2-2 shows the Tropical Summer Index (TSI) for still air condition. This index is simple to use and gives reasonable predictions for hot- dry climates of India [**12**]. The simple mathematical relation is adopted by the National Building of India [**45**].

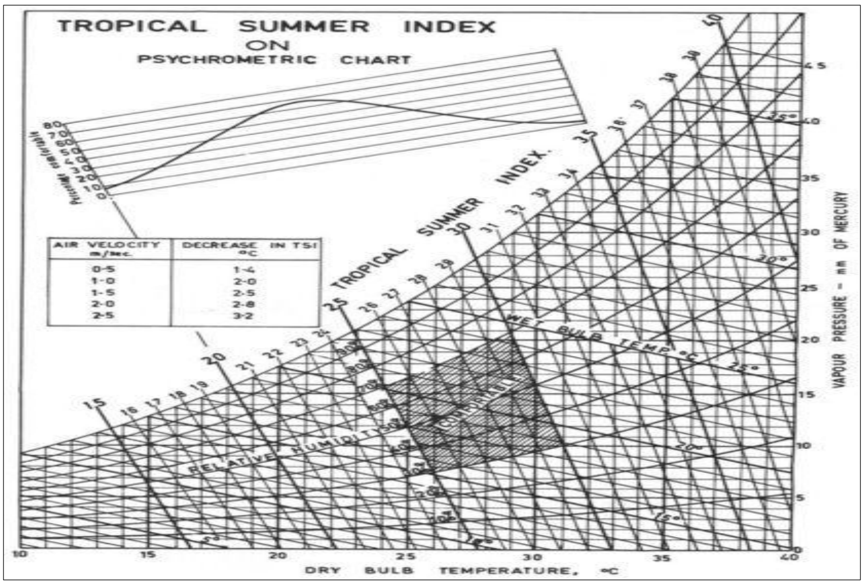


Figure 2-2 Tropical Summer Index for still air condition [44]

2.3 Thermal comfort standards

International comfort standards such as ISO 7730 [**5**], ASHRAE Standard 55–2013 [**4**], and EN 15251 [**6**] are commonly being used for evaluating indoor environmental conditions for a defined activity and clothing irrespective of climatic conditions and building types. The current thermal comfort standards followed worldwide are set by ASHRAE Standard 55-2013, which are primarily based on climatic chamber studies based empirical relations called PMV/ PPD models intending to cover the air conditioned buildings.

2.3.1 ISO 7730 (2005): Ergonomics of thermal environment–Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria

The ISO standard offers greater flexibility as it offers a standard method rather than the standard environment. The ISO 7730 [**5**] mainly used in Europe and applies for moderate thermal conditions. ISO 7730 grouped the thermal environment into three different categories, i.e., Category –A, Category −B, and Category –C as presented in Table 2.1. The ISO 7730 recommends a PPD of 10% for local thermal discomfort. The standard describes the calculation of the PMV and PPD indices for thermal comfort and also for local discomfort. The standard defines the local clothing habits for indoor comfort and does not provide any method for clothing ensembles. This standard also provides an acceptable indoor environment that can be extended by incorporating the behavioral adjustment such as the use of window/door or control of room air speed using graphical method (Figure 2-3). ISO 7730 is well suited for evaluating indoor environmental conditions for moderate climatic conditions.

Table 2.1 Categories of thermal environment [5]

	Thermal state of the body as a whole		Local discomfort			
				PD (%) caused by		
Category	**PPD (%)**	**PMV**	**DR (%)**	**Vertical air temperature difference**	**Warm or cool floor**	**Radiant asymmetry**
A	< 6	-0.2 <PMV <0.2	< 10	< 3	< 10	< 5
B	< 10	-0.5 < PMV < +0.5	< 20	< 5	< 10	< 5
C	< 15	-0.7 < PMV < +0.7	< 30	< 10	< 15	< 10

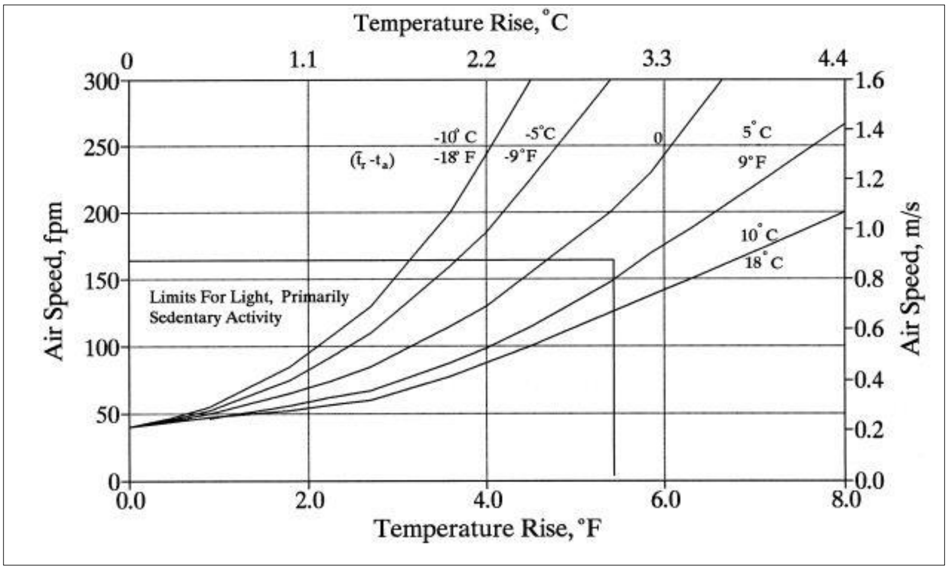
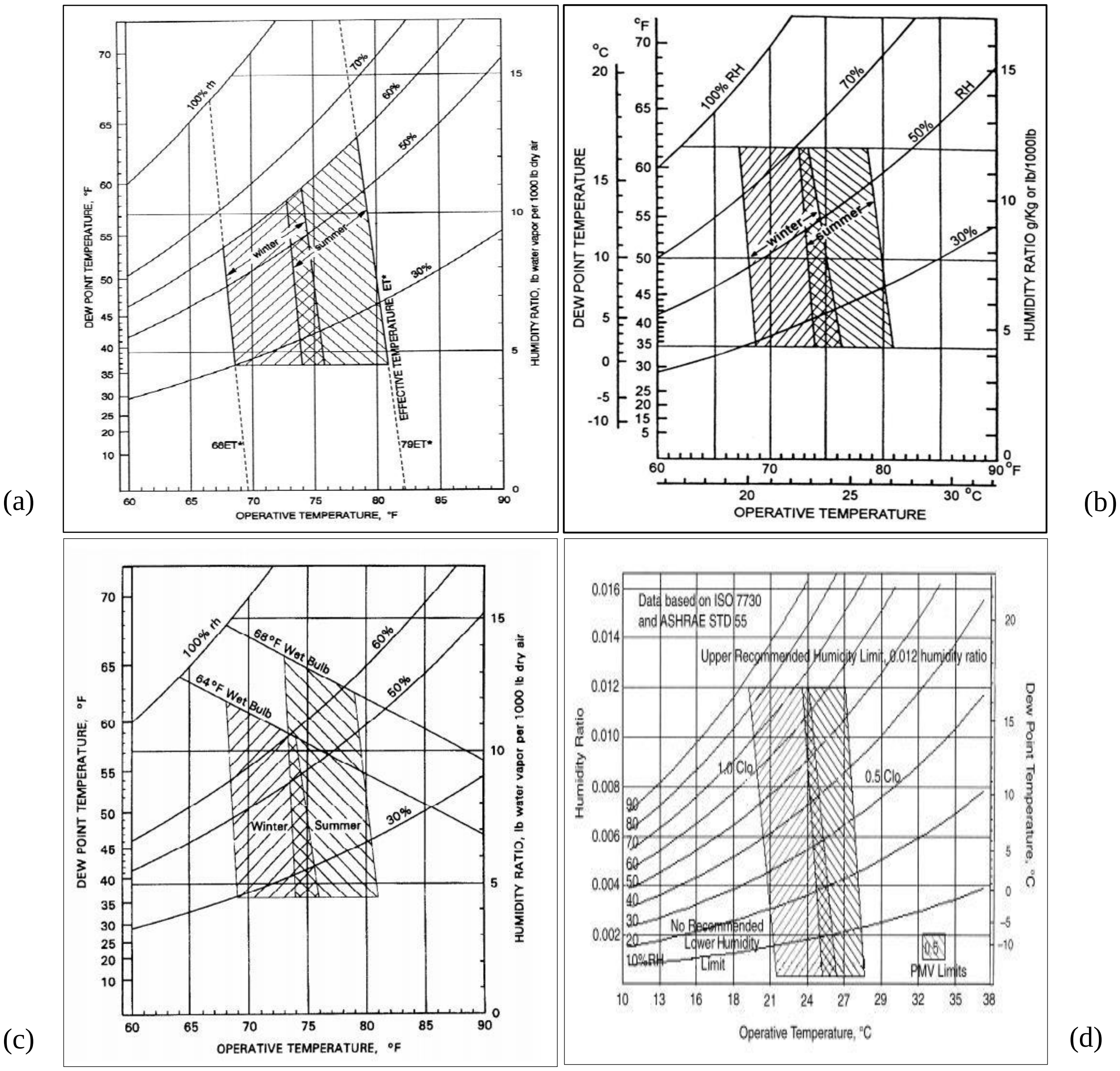


Figure 2-3 Acceptable range of operative temperature and air speed for comfort using Graphical method [5]

2.3.2 ASHRAE Standard 55−2013

Thermal comfort is that "condition of mind which expresses satisfaction with the thermal environment" [**4**]. Because there are significant variations, both physiologically and psychologically, from person to person, it's hard to satisfy everyone in space.

The ASHRAE comfort zone is usually drawn on a standard psychrometric chart. The comfort zone defines the indoor operative temperature and humidity for a sedentary person at defined clothing level. The shape of the ASHRAE Standard 55 comfort zone on the standard psychrometric chart has evolved over time. The first thermal comfort standard had been introduced in 1966 followed by subsequent revision produced in 1981, 1992, 2004, 2010 and 2013 as illustrated in Figure 2-4.



(e)

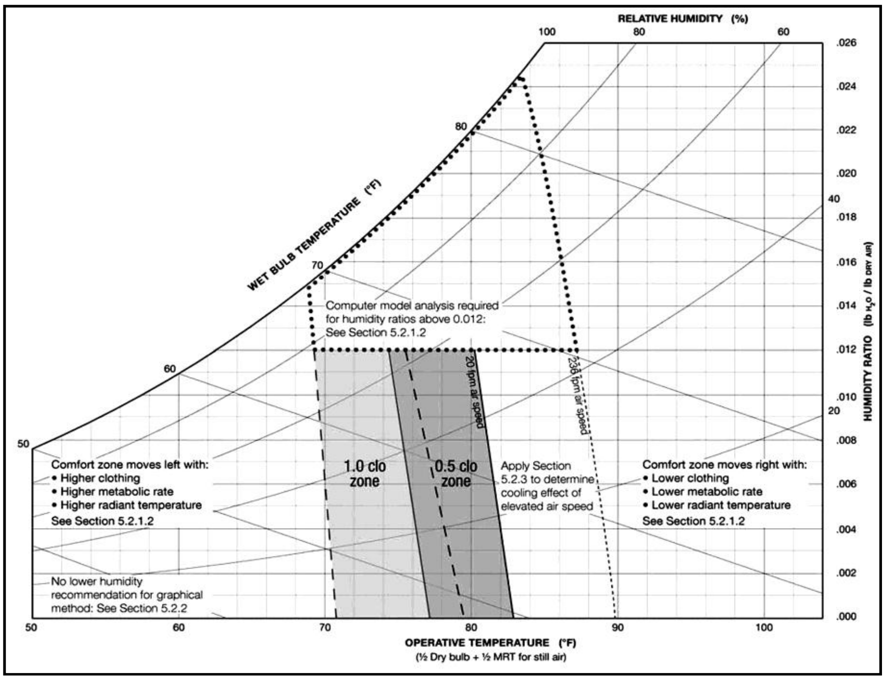


Figure 2-4 Acceptable comfort limits for ASHRAE Standard 55 (a) 1981, (b) 1992and 1995, (c) 2004; (d) 2010 and (e) 2013

In 2004, ASHRAE published the new version of the Standard 55 [**46**]. This version of ASHRAE Standard introduced significant changes. Unlike the previous versions, the ASHRAE Standard 55−2004 had defined no lower humidity limit (Figure 2-4 (d)). These is because of the influence of the humidity level, as related to thermal comfort, is relatively small and still questioned in the research community. ASHRAE Standard 55−2004 Addendum d, e, f, and g modified some of the issues and discuss the effective use of air speed to cool the people as a way to improve indoor comfort conditions. In a further revision to these addenda, ASHRAE Standard 55−2010 [**47**] [**48**] included a new method for expressing and selecting air speed limits using Standard Effective Temperature (SET*) concept. The notable contribution was the introduction of the adaptive model, which was based on field studies across the world to support natural ventilation designs for more sustainable, energy efficient and occupant’s friendly designs as shown in Figure 2-5.

Currently, ASHRAE Standard 55−2013 [**4**] defines an acceptable comfort zone on a psychrometric chart, specifying boundaries of operative temperature and humidity for sedentary activity (1−1.3 met) and defined clothing (0.5−1clo). This standard is not limited to any specific building type. Figure 2-4 (e) demonstrates the acceptable operative temperature ranges for summer

(23.6˚C−27.9˚C) and winter season (19.6˚C−25.7˚C) at defined activity (1−1.3 met), clothing (0.5−1 clo) and humidity conditions for which majority of occupants (at least 80% of the occupants) feels thermally comfortable.

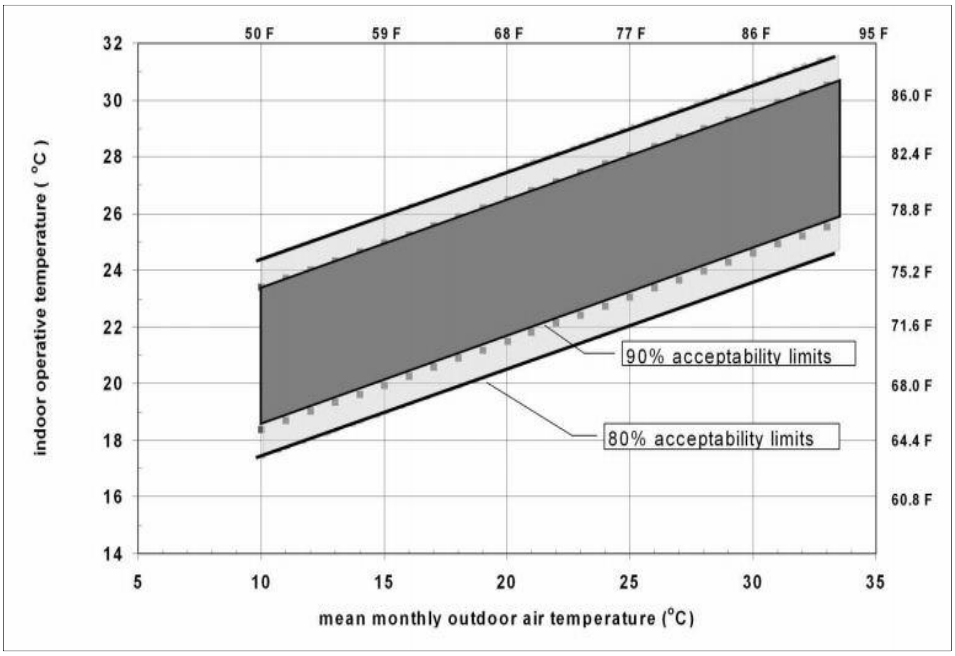


Figure 2-5 Acceptable operative temperatures for naturally ventilated spaces as per [46]

The PMV model used in ASHRAE Standard 55−2013, while suggesting thermal comfort zone, considers the air velocity up to 0.2 m/s whereas, the Graphical Elevated Air Velocity method and the Standard Effective Temperature (SET*) method allows the use of high air velocities to offset in indoor temperature for comfort improvement. ASHRAE Standard 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 blowing due to ceiling or pedestal fans to the sedentary occupants doing light office work. Figure 2-6 shows the SET* method used for improvement in comfort temperature at elevated air speed for different clothing and an activity of 1.2 met as defined in ASHRAE Standard 55−2013.

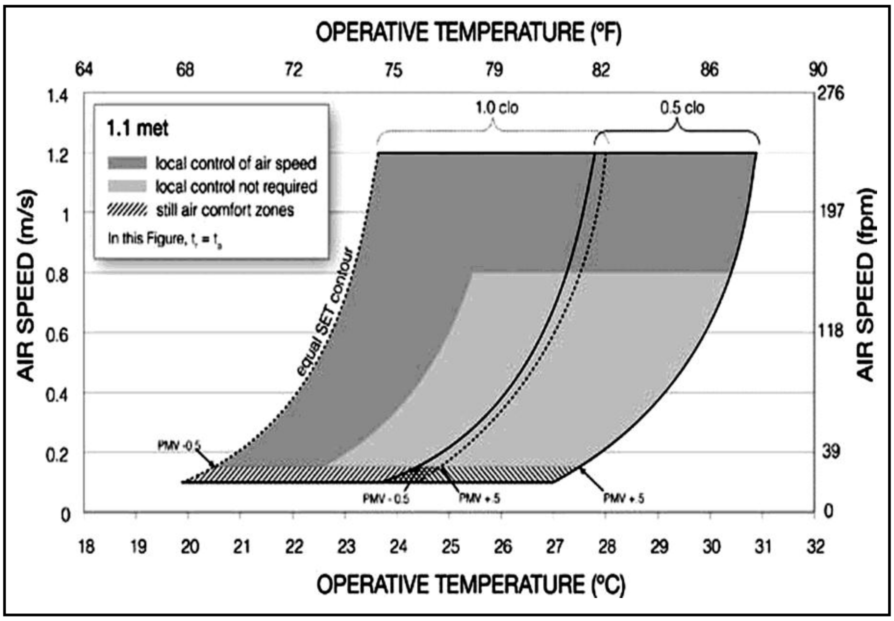


Figure 2-6 Acceptable range of operative temperature and air speed for comfort using SET* method [4]

2.3.3 EN 15251 (2007): Indoor environmental input parameters for design and assessment of energy performance of buildings – addressing indoor air quality, thermal environment, lighting and acoustics

The standard exclusively deals with the energy efficiency of buildings. This standard is applicable mainly in non-industrial buildings where the criteria for indoor environment are set by human occupancy and where the production or process does not have a major impact on indoor environment. The standard is thus applicable to the following building types: single family houses, apartment buildings, offices, educational buildings, hospitals, hotels and restaurants, sports facilities, wholesale and retail trade service buildings **[pp 6, 6]** and does not specify method to design comfortable climate.. The standard also reveals that indoor environment and occupant's expectation influence energy consumption of buildings. Nicol and Wilson [**49**] explained that this standard helps building designers/architects to optimize the building energy consumption, considering thermal, air quality, acoustic and visual comfort. Furthermore, Nicol and Humphreys [**10**] [**50**] carried out field studies of thermal comfort under SCATs (Smart Controls and Thermal Comfort) research project that involved European countries and office buildings only.

2.3.4 Indian comfort guidelines: National Building Code

National Building Code (NBC), 2005 [**45**] was developed by the Bureau of Indian Standards (BIS), and it prescribes the guidelines for buildings construction, indoor environment and building operation for creating a healthy environment. The code considered TSI index (Tropical Summer Index) [**44**] for comfort calculation and defined the comfort bandwidth between 21˚C–23˚C for winter and 23˚C–26˚C for summer irrespective of the climatic zone and building types. However various studies conducted in this tropical region suggested that these limits have to be revised considering this region specific climatic conditions and adaptations [**51**] [**52**] [**53**] [**54**].

2.4 Thermal adaptations

The generic term "adaptation" might broadly be interpreted as the gradual diminution of the organism's response to repeated environmental stimulation [**55**]. The adaptive thermal comfort approach has been classified into three principal components such as psychological adaptation, physiological adaptation and behavioral adaptation [**55**]. Figure 2-7 illustrates the three elements of thermal adaptation to indoor environments.

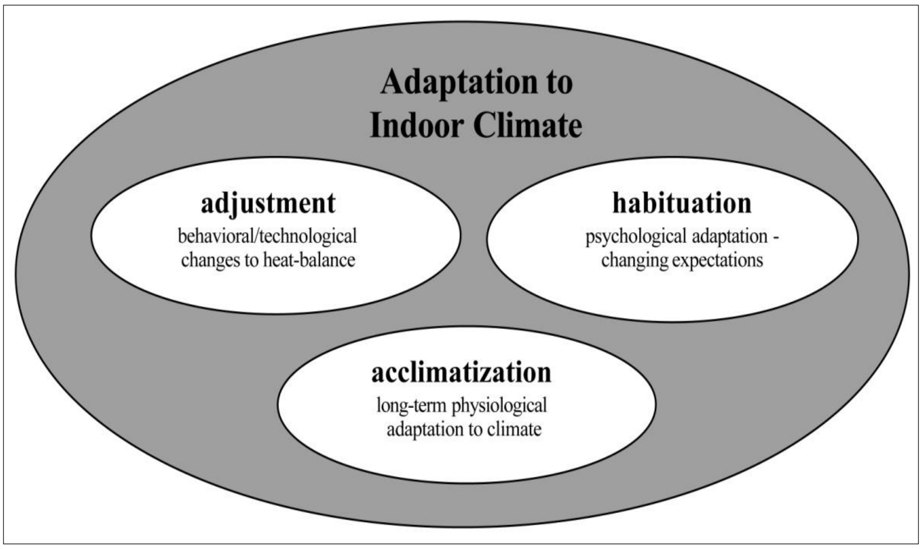


Figure 2-7 Three components of thermal adaptation to indoor environment [55**]**

- **Physiological adaptations**

Physiological adaptation loop would include all of the changes in the physiological responses resulting from exposure to thermal environmental factors. This would lead to a gradual decrease in the strain induced by such exposure. Physiological adaptations are categorized into two subcategories:

- Genetic adaptations: adjustments that have become part of the genetic heritage of an individual or group of people.
- Acclimatization: changes in the physiological thermoregulation system over a period of days or weeks or months for particular environmental conditions.

The factors such as internal body and skin temperature, vasodilatation and vasoconstriction, sweating, etc. help to maintain the body heat balance during variable temperature conditions. Due to repeated exposure of warm environment subject acclimatized and felt comfortable in higher temperature conditions. The repeated exposure reduces the increase in heart rate and rises in core temperature [**7**] [**56**]. Auliciems [**7**] mentioned that perception of warmth is solely the function of thermal stimulus-physiological response and proposed an adaptive model of thermal perception. Furthermore, it has been revised by de Dear et al. [**11**] as shown in Figure 2-8.

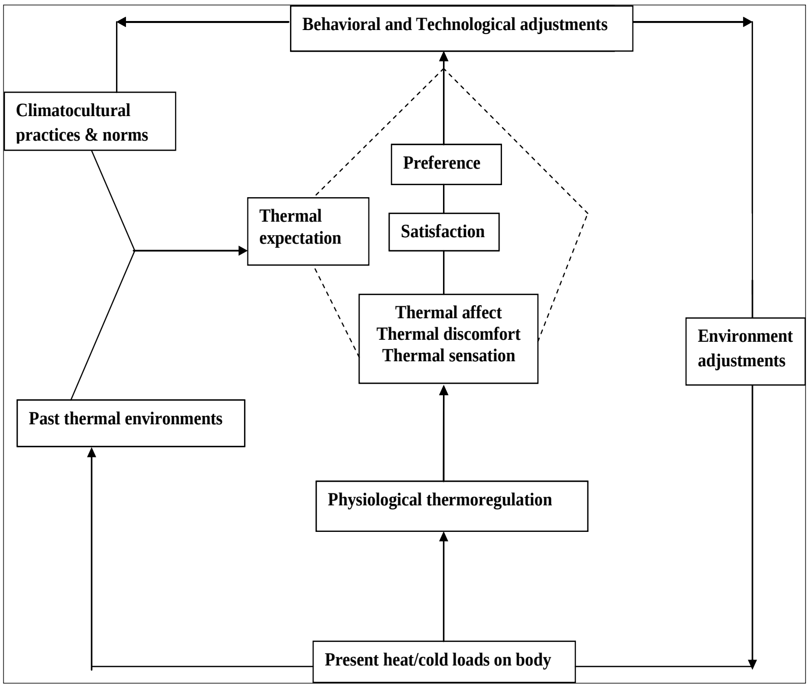


Figure 2-8 The adaptive model of thermal perception [11**]**

- **Psychological adaptations**

Psychological adaptation encompasses the effects of cognitive and cultural variables and describes the extent to which habituation and expectation alter thermal perceptions of individuals [**55**]. Several authors have also addressed the issue of psychological adaptation [**57**] [**58**] [**59**] [**60**]. Research on psychological adaptation reveals that humans are adaptive in nature and after a time span becomes habitual to the living environment. Psychological parameters have been studied extensively, but their effect is not yet quantified numerically [**61**].

- **Behavioral adaptations**

Heat balance of the thermal body is affected to the highest degree by behavioural adjustments, including personal, cultural and technological adaptations [**55**]. Behavioural adaptation refers to cultural alterations such as changes in activity, clothing, and posture, drinking-eating or moving to different locations. The technological aspect includes adjustments to opening/closing of windows/doors/ shades, switch on/off the mechanical system and use of a fan or change fan speed transforms thermal background. Behavioural use of controls is interconnected with the physiology/psychology of the body and physics of the buildings [**62**]. Several researchers during different field studies explained the role of behavioral adaptations on comfort in naturally ventilated buildings [**63**] [**64**] [**65**] [**66**] [**67**] [**68**].

- **Use of personal/environmental controls**

Naturally conditioned buildings offer adaptive control opportunities such as alterations to window, door, ventilators, and switch on/off the fan and change fan speeds. Occupant tries to restore the state of thermal balance by altering these controls. Several researchers have concluded that personal control of operable windows and other controls improved the local thermal conditions and occupants comfort [**62**] [**69**] [**70**] [**64**] [**66**] [**71**] [**72**] [**73**] [**74**].

People open windows/blinds/curtains/fans in response to increasing indoor and outdoor air temperature. The window opening reduces the indoor temperature through cross ventilation, while blinds and curtains cut down the direct solar radiation penetration and glare to the occupied space [**62**] [**70**] [**72**].Many non-thermal factors influenced the window or door opening behaviour, like privacy, safety, and noise social cultural aspects, attitudinal impediments or behavioural aspects [**65**] [**75**].

- **Clothing adaptations**

Clothing is an important behavioural adaptation to achieve thermal monotony at temperature especially in hot and warm climates [**76**]. Relative humidity and discomfort caused by clothing are closely related [**11**] [**67**] [**77**].The contact between the skin and inner clothing predicts the subjective thermal sensation of occupants about clothing comfort. Several researchers have found good correlations between clothing insulation (clo) value and outdoor and indoor temperature [**11**] [**13**] [**54**] [**71**] [**78**] [**79**] [**80**]. Nicol et al. [**71**] revealed a strong correlation between mean numbers of clothing garments worn and mean indoor and outdoor temperatures. Indraganti [**51**], Singh et al. [**36**] and Sanyogita et al. [**81**] also observed the similar findings for clothing adaptations in naturally ventilated office and residential buildings for Indian climatic conditions. Clothing adaptation was found to be one of the principle opportunities to overcome seasonal thermal discomfort.

2.5 Field measurement protocols

Field studies for thermal comfort are conducted under a particular study protocol as per the research questions. A field study of thermal comfort is classified into three categories, namely Class-I, Class-II, and Class-III based on the standard of the instrumentation used for recording the indoor environmental variables [**55**].

- **Class-I protocol**

Field experiments in which all the sensors and the procedures are in 100% compliance with the specifications proposed by ASHRAE Standard 55–1992 [**82**] and ISO 7730 [**5**]. Under this procedure, measurement is carried out at three different heights with laboratory-grade instruments including omnidirectional anemometry capable of turbulence intensity assessment.

- **Class-II protocol**

In this method, field experiments in which all indoor physical environmental variables (room temperature, mean radiant temperature, air velocity, relative humidity, clothing insulation, activity) necessary for the calculation of comfort indices (PMV-PPD, SET*, etc.) are collected at the same time and place where thermal questionnaires are administered. Measurements of environmental variables are recorded at the height of 1.1 m from the ground. Class-II protocol as per ASHRAE 55−2013, has been used in the various studies [**11**] [**10**] [**12**] [**51**] [**38**] [**83**], which signifies measurement of indoor thermal environment variables using laboratory grade instruments compatible with ISO 7730 standard along with recording of subjective variable like clothing ensembles and activity level during ‘Right Now’ questionnaire. Class-II protocol has been mostly used in field studies due to these mentioned advantages over other Protocols and hence used in the present field study.

- **Class-III protocol**

Field studies are carried out based on simple measurements of a limited indoor variable like indoor air temperature and possibly the relative humidity. Measurement is performed at one level above the floor.

2.5.1 Type of survey methods

Two types of questionnaire-based survey methods are commonly used in field studies of thermal comfort, namely; longitudinal survey and transverse survey method. Questions related to the indoor thermal environment are asked to subjects during the study along with measurement of thermal environmental variables around the subject.

- **Longitudinal survey method**

In longitudinal survey method, thermal responses are collected from few buildings having and limited subjects/ occupants repeatedly on a daily basis. Building Use Studies (BUS) also corresponds to the longitudinal survey method. The main disadvantage of longitudinal studies is that only a small number of people are used, and so there is a risk of sample bias as explained by McCartney and Nicol [**84**] and Raja et al. [**67**].

- **Transverse survey method**

Transverse survey method is used for collecting a much larger number of subject samples from the greater number of buildings as compared to longitudinal studies. This method provides good cross-section environmental conditions as reported by Raja et al. [**67**]. In this approach, thermal responses are collected based on right now thermal environmental conditions. The questionnaire in this method carries more details than longitudinal survey, and it is also called cross-sectional survey method. Since the transverse survey method provides a good cross-section of environmental conditions and subjects than longitudinal surveys; it has been used in the present research.

2.6 Methods for assessment of neutrality/comfort temperature

The comfort or neutral temperature can be defined as “the indoor operative temperature at which an average subject will vote comfortable (or neutral) on the ASHRAE seven-point scale” [**51**]. 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 [**10**]. ASHRAE Standard 55-2013 suggested a seven-point thermal sensation scale that is used to evaluate thermal sensation of the individual subject to particular indoor climatic conditions.

Owing to individual differences, it is impossible to specify a thermal environment that will satisfy everybody. Thus, it is not possible to specify the environments known to be acceptable for all the occupants [**85**]. The ISO standard 7730, for example, recommends that the PPD should be lower than 20 percent, i.e. PMV within the range -1 to $+1$ can be considered as comfortable. Also, the traditional assumption is that people voting within the central three categories of the thermal sensation scale (±1) are comfortable.

Linear regression analysis is performed between thermal sensation votes and corresponding room temperatures or globe temperature to determine the neutral/comfort temperature of the study group [**10**] [**11**] [**70**] [**53**] [**86**]. The slope of the regression model is also indicative of adaptation of the subjects to indoor conditions encountered. Lower the regression slope more the adaptations of a population to its climatic conditions encountered.

Some researchers have pointed out the problem in applying the regression method in the presence of adaptive behaviour. It has been found that the presence of behavioural adaptation in the data tends to artificially lower the regression coefficients and therefore the estimates of the comfort temperature [**10**,**13**] [**71**] [**87**] [**88**] [**89**] [**75**]. Also, the mean comfort vote which is much different from the neutrality, may also adversely affect the predictive power of the resultant regression equation.

Griffith [**90**] suggested a way in which the comfort temperature is calculated from a small sample of data eliminating the thermal adaptations of subjects. To estimate the comfort temperature, he had assumed the 0.33 regression slope for 7 points thermal sensation scale. Griffith assumed this value to test the reliability of climate chamber estimates of neutrality in the field study since value thus obtained is less controversial due to no adaptation effects there. Griffiths' comfort temperature is calculated using equation (2.8)

$$\mathbf{T_C = T_g + \frac{0 - TSV}{G}} \qquad (\mathbf{2.8})$$

The value of Griffiths' coefficient can be calculated from the field surveys, and it represents the maximum rate of change of comfort votes with indoor air temperature or thermal indices [**37**]. Humphreys showed regarding standard deviation in operative temperature that it is safe to assume the value of Griffiths' coefficient greater than 0.4 [**13**]. Humphreys et al. [**91**] and other studies [**51**] [**75**] [**89**] [**92**] across the world found that Griffiths' coefficient was about 0.5 in field study.

2.6.1 Thermal acceptability

Thermal acceptability is quite a controversial construct of thermal comfort because it can be assessed different art scale and depends on various psychological factors, expectations levels, etc. [**93**]. ASHRAE Standard 55-2013 recommends two acceptability limits: 90% and 80%. Thermal acceptability of 90% signifies that 90% of subjects are thermally satisfied (10% feels thermal dissatisfaction) at particular environmental conditions [**4**]. This criterion is used to design indoor environment within a narrower comfort bandwidth or when intensive information is available about the indoor environment. However, 90% acceptability is rarely obtained. Thermal acceptability of 80% (20% subjects are thermally dissatisfied) criterion is used when less information of indoor environment is available [**94**] [**95**].

2.7 Adaptive thermal comfort studies

An alternative to conventional comfort theory (heat balance approach) termed as ‘adaptive theory’ of comfort embraces the idea that occupant acts as an active agent interacting with the person-environment system approach via multiple feedback loops. Occupants play an important role as an active agent in creating their thermal environment. Nicol and Humphreys [**9**] defined adaptive comfort approach; “if a self-regulating control system is working to secure thermal comfort, then the whole system, in any case, tends towards its optimum”. This area has recently regained momentum due to increasing concerns over the human impact on energy and the environment.

Nicol and Humphreys in 1972 [**9**] put forth the concept of the adaptive model which challenged the steady state comfort theory. Supported by field study findings, many researchers have been critically questioning the assumption of universality, arguing that it ignores the psychological dimensions of adaptation, social and cultural aspects of an occupant. 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 [**11**]. Currently, the adaptive model is widely accepted as an efficient tool for predicting indoor comfort conditions for naturally ventilated buildings. The energy saving potential in the building will be enormous by switching over to these adaptive comfort standards. After that, various studies on adaptive comfort across the world in last decade have revealed that occupants in naturally ventilated buildings are more flexible towards variations in outdoor environmental conditions. Occupants use several adaptive uses of environmental controls to make their indoor environment thermally comfortable [**11**] [**62**] [**69**] [**70**] [**64**] [**92**].

One of the main inventions of an adaptive approach to thermal comfort is to express correlation between comfort temperature and the mean outdoor dry bulb temperature. Auliciems and Szokolay [**96**], Brager and de Dear [**55**] [**97**], de Dear and Brager [**98**], and Nicol [**12**] emphasizes that building should be designed considering adaptive comfort options through field study. Field studies such as Humphreys [**8**], Auliciems [**57**], Humphreys [**99**], Humphreys and Nicol [**100**], de Dear et al. [**11**], Nicol [**12**], Feriadi and Wong [**101**], Wang et al. [**102**], Indraganti [**51**] [**75**], Singh et al. [**36**], Dhaka et al. [**53**] and Kumar et al. [**54**] [**103**] have been performed in different buildings located in various climates to quantify the different thermal adaptations in naturally ventilated buildings.

2.7.1 Thermal comfort studies for cold climate

One of the earliest studies for the guidelines of thermal comfort is based on the Smart Control and Thermal Comfort project (SCATs), commissioned by the European Commission. In this project, 26 European buildings in France, Greece, Portugal, Sweden and the UK were surveyed for three years covering free-running, conditioned and mixed-mode buildings [**13**]. Based on the survey, different adaptive algorithms for each participating country were developed as shown in Table 2.2.

Table 2.2 Adaptive comfort models for cold countries [104]

Country	**Adaptive control algorithm**	
	$T_{rm} \leq 10$ ˚C	**$T_{rm} \geq 10$ ˚C**
All	22.9 ˚C	$0.30\ T_{rm} + 19.39$
France	$0.049\ T_{rm} + 22.85$	$0.206\ T_{rm} + 21.42$
Portugal	$0.38T_{rm} + 18.12$	$0.381\ T_{rm} + 18.12$
Sweden	$0.051\ T_{rm} + 22.83$	$0.051T_{rm} + 22.83$
UK	$0.104\ T_{rm} + 22.85$	$0.168T_{rm} + 21.63$

T_{rm}: Running mean outdoor air temperature

Field studies of thermal comfort such as Nicol and Humphrey [**10**], Brager and de Dear [**11**] , Fanger [**33**], Mc Cartney and Nicol [**84**], Gossauer and Wagner [**105**], Schweiker et al. [**60**] [**106**], Baker and Stevedan [**107**] have been carried out for naturally ventilated office buildings in cold climates. The studies revealed the thermal neutralities and various adaptation opportunities available to these natural ventilated spaces for thermal comfort and reduction in energy consumption in these buildings. A study performed by Bouden and Ghrab [**79**] for Tunisia revealed that more than 80% of subjects accepted temperatures between 16˚C and 26.5˚C.

2.7.2 Thermal comfort studies for hot and warm climate

Adaptation effects subject's perception, and thereby comfort temperature varies from one building to another and also varies from one climate to another. A field study conducted by Nicol and Roaf [**71**] at Pakistan demonstrated high neutral temperature during the summer period. Sharma and Ali's [**44**] research focused on naturally ventilated buildings in Roorkee in North India. Heidari and Sharples [**108**] carried out a field study in Iran and found the neutral temperature of 28.4˚C during the hot summer in the short-term study and 26.7˚C for the long-term study. Tablada et al. [**109**] studied subjects from the warm-humid climate of Malaysia and reported that subjects felt neutral at 28.5˚C, whereas, field study carried out by Feriadi and Wang [**101**] for residential buildings of hot and humid climate reported the neutral temperature higher than 29˚C. Zhang et al. [**102**] carried out thermal comfort studies to evaluate the indoor comfort in non-climate controlled buildings located in different climates. The studies observed a broad range of acceptable indoor environment such as 22.1˚C −28.7˚C in hot-humid climatic conditions. Nguyen et al. [**110**] collected subject responses from hot and humid climates of South-East Asia and found the neutral temperature of 27.9˚C in free-running buildings. People living in free-running buildings in hot and warm climate countries are tolerant to higher temperature limits than recommended by comfort standards. These discrepancies in temperature show that comfort is context dependent and field study needs to be carried out in buildings lying in different climates.

2.7.3 Thermal comfort: Indian subcontinent studies

Among the studies conducted in past one decade from the Indian sub-continent focused mainly on: (1) residential apartment buildings in Hyderabad [**51**], [**80**]; (2) vernacular housing in the north-east region [**36**] [**111**], (4) students dormitories/ laboratory [**112**] (5) hostels and residential buildings [**54**] [**53**] [**83**] [**113**] and (6) office buildings [**75**] [**81**] (7) Railway terminal [**114**]. The National Building Code of India, 2005 specifies a narrow comfort temperature range between 21˚C–23˚C in winter and 23-26˚C for summer for all types of buildings. A summary of such studies with their climatic region and building typologies are presented in Table 2.3.

Table 2.3 Summary details of recent studies conducted in tropical country, India [103]

Authors	**Climate zone**	**Year/ Seasons**	**Building Type**	**Mode**	**Neutral Temperature**	**Comfort bandwidth**
Sharma & Ali	Composite	1986/All Seasons	Residential	NV	27.5˚C	25˚C —30˚C
Indraganti	Composite	2010/ All Seasons	Residential	NV	29.23˚C	26˚C—32.5˚C
Singh et al.	Warm & Humid	2010/ All Seasons	Residential	NV	26.0˚C	22.8˚C —29.1˚C
	Cool & Humid	2010/ All Seasons	Residential	NV	24˚C	21.1˚C —27.6˚C
	Cold & Cloudy,	2010/ All Seasons	Residential	NV	22˚C	18.9˚C—26.2˚C
Mishra	Composite	2014/ Summer season	Students dormitories/ Laboratory	NV	26.6˚C	19.4˚C—33.7˚C
Dhaka et al.	Composite	2015/ All Seasons	Residential and Students dormitories	NV	27.2˚C	16.7˚C—34.8˚C
Kumar et al.	Composite	2016/All Seasons	Residential and Students dormitories	NV	27.9˚C	25.2˚C—30.6˚C
Indraganti et al.	Composite	2014/ All Seasons	Offices	NV	26.4˚C	22.4˚C—30.2˚C
	Composite	2014/ All Seasons	Offices	AC	26.3˚C	18˚C—34˚C
Manu et al.	All climatic zones	2015/ All Seasons	Offices	NV	-	19.6˚C—28.5˚C
	All climatic zones	2015/ All Seasons	Offices	MM and AC	-	21.5˚C—28.7˚C

NV: Naturally ventilated; MM: Mixed mode, AC: Air conditioned

A similar type of thermal comfort study [**115**] for warm and humid climatic in India reported that traditional buildings are very efficient and provide indoor conditions comfortable for building occupants round the year irrespective of seasonal fluctuations. Researchers have revealed that the occupants of naturally ventilated buildings in this tropical sub-continent are tolerant to a higher temperature.

It has been found that most of the studies conducted in India so far had data collection from one particular building type and a limited region, including a study conducted by Sharma and Ali [**44**], Indraganti [**70**] and Singh et al. [**86**] that is in residential buildings. Even the recent work IMAC [**81**], in which only office buildings have been considered, and there is no data for four critical months, it is not sufficient to be considered as true representation of thermal comfort in the entire country. Application of results from these studies on other building types needs additional investigation, data collection or at least validation.

2.8 Thermal mass as passive strategy in unconditioned buildings

In many hot and developing countries, and also in countries with a temperate climate having hot summers, there is growing interested in utilizing passive and low-energy systems for cooling buildings, both residential and commercial [**15**] [**29**] [**26**]. To reduce indoor air temperature and cooling load peaks, and to transfer the load to a later time in the day, it is possible to store heat in the material of the outer envelope and the interior mass of the building [**116**]. The storage material is the construction mass of the building itself, which is referred to as thermal mass. It is typically contained in walls, partitions, ceilings and floors of the building, constructed of a material with high heat capacities, such as poured concrete, bricks, and tiles. The thermal mass of the building could have a positive effect on the indoor conditions during the summer and winter periods. When a building is naturally ventilated, thermal mass can be used to regulate indoor air temperatures [**117**].

Givoni and Vecchia [**118**] presented formulae for predicting daily maximum, average and minimum indoor temperature of occupied buildings in Pala, California, with very limited climate data. Kruger and Givoni [**119**] [**120**] reported long-term monitoring work of outdoor temperature measurement at seven houses in Curitiba, Brazil and they had generated such formulas for the occupied houses with good correlation coefficients. Kruger and Givoni [**121**] have reported long-term thermal monitoring of an occupied passive solar apartment in an arid environment also with mathematical formulas predicting its indoor temperature. Table 2.4 shows the results of some studies carried out to develop a correlation for occupied and unoccupied buildings, especially for high mass buildings in different climates. One of the advantages of using these relationships is to predict the indoor conditions for buildings in different climates provided buildings should have similar construction details and management [**111**]. Also, these correlations incorporate some behavioral adaptive actions taken by occupants in different seasons or conditions in naturally ventilated buildings to make their living conditions comfortable which is otherwise so challenging and complex phenomenon to include in simulation tools [**27**] [**120**]. However, these correlations are proposed with limited statistical analysis, relying on the correlation of coefficients (R^2) during generation and validation of correlations from measured data (Table 2.4). Furthermore, very few studies have validated these correlations to other typologies for similar construction type and in different climates.

Table 2.4 Excerpts from previous studies done to develop correlations for indoor temperatures in buldings

Reference	Country/ Climate type	Season or Monitoring period	Building typology type	Correlations/Predictive formulae	R^2, F-Statistic, t-statistics	Validation to other typologies
J. Drysdale [**122**]	Australia Semi-arid	–	High mass /unoccupied	$\mathbf{T_{max-in}(°F) = T_{max-out} - 0.009W(T_{max-out} - 68)}$	N.A.	N.A.
Raychaudhary & Choudhary [**123**]	India Tropical	–	High mass /unoccupied	$\mathbf{T_{max-in}(°F) = T_{max-out} - 0.004W(T_{max-out} - 60)}$	N.A.	N.A.
Givoni [**124**]	Israel/ Arid	2- Years	High mass & Low mass / Unoccupied	**Closed all time :** $\mathbf{T_{max-in} = T_{max-out} - 0.31(T_{max-out} - T_{min-out}) + 1.6}$ **Open all time:** $\mathbf{T_{max-in} = GT_{avg} - 0.5(T_{avg} - GT_{avg} + 4}$	R^2 ≥0.8 F-Statistic=N.A. t–Statistic = N.A.	N.A.
Givoni & Vecchia [**125**]	Brazil/ Tropical	20 Days (Sept & Oct)	High mass / Occupied	$\mathbf{T_{max-in} = 1.16 * PT_{avg} + 1.2(T_{avg} - PT_{avg}) + 2.7}$ $\mathbf{T_{min-in} = 1.33 * PT_{min} + 1.2(T_{min} - PGT_{min}) - 0.2}$	R^2 ≥0.90 F-Statistic=N.A. t–Stastic = N.A.	N.A.
Cheng et al. [**126**]	China/Hot-Humid	1- year (Summer & Winter)	High mass & Low mass/ Unoccupied	$\mathbf{T_{max-in} = T_{max} + (2.63\alpha - 0.30) * (T_{max-out} - PT_{max-out}) + (18.9\alpha - 2.93)}$ $\mathbf{T_{max-in} = T_{max} + (0.40\alpha - 0.18 * (T_{avg} - PT_{avg}) + 5.82\alpha - 0.15}$	R^2= N.A. F-Statistic=N.A. t–Statistic = N.A.	N.A.

Kruger & Givoni [**120**]	Brazil/ Tropical	42 days (Summer & Winter)	High mass & Low mass /Occupied	**High mass:** $T_{max-in} = 0.87 * PT_{avg} + 0.6(T_{avg} - PT_{avg}) + 7.6$ $T_{min-in} = PT_{min} + 0.69 * (T_{min} - PT_{min}) + 6.5$ **Low mass:** $T_{max-in} = 0.87 * PT_{avg} + 0.8(T_{avg} - PT_{avg}) - 0.126 * T_{avg} + 0.7 * PT_{avg} + 5.3$ $T_{min-in} = PT_{min} + 0.75 * (T_{min} - PT_{min}) - 0.116 * T_{min}$	$R^2 \geq 0.97$ F-Statistic=N.A. t–Statistic = N.A.	Yes
Kruger & Givoni [**121**]	Brazil/ Tropical	9 Months (Summer & Winter season)	High mass/ Occupied	**Winter:** $T_{max-in} = 13.14 + 0.05 * T_{max} - 0.012T_{avg} + 0.015 * PT_{avg} + 0.31 * RnAvg + 0.029 * S_{wg} + Occup$ $T_{min-in} = 13.12 + 0.30 * T_{min} + 0.27 * T_{drop}$ **Summer:** $T_{max-in} = 11.8 + 0.048 * T_{max} + 0.017T_{avg} + 0.015 * PT_{avg} + 0.34 * RnAvg + 0.133 * S_{wg}$ $T_{min-in} = 15.76 + 0.36 * T_{min} + 0.128 * T_{drop}$	$R^2= \geq 0.9$ F-Statistic=N.A. t–Statistic = N.A.	Yes
D Ogoli [**127**]	Kenya/ Tropical & Semi Arid	2 months	High mass	$T_{max-in}(°F) = T_{max-out} - 0.488(T_{max-out} - T_{min-out}) + 2.44$	$R^2 \geq 0.63$ F-Statistic=N.A. t–Stastic = N.A.	N.A.
Singh et al. [**111**]	Northeast India/ Warm-humid & Cold -cloudy	1-year (Summer & Winter)	Low Mass/ Occupied	**Vernacular house (Warm & Humid):** $T_{max-in} = 1.2 + 0.20 * T_{max} + 0.28T_{avg} + 0.52 * PT_{avg} - 0.44 * V$ $T_{min-in} = 1.9 + 0.74 * T_{min} + 0.18 * T_{drop} + 0.18 * PT_{avg} + 0.14 * V$ **Vernacular house (Cold & Cloudy):** $T_{max-in} = 1.3 + 0.13 * T_{max} + 0.85 * T_{avg} + 0.25 * S_{wg} + 3 * Ill$ $T_{min-in} = 2.2 + 1.0 * T_{min} + 0.11 * T_{drop}$	$R^2 > 0.90$ F-Statistic=N.A. t–Stastic = N.A.	Yes

T_{max-in}: Indoor maximum temperature (˚C); T_{min-in}: Indoor minimum temperature (˚C); T_{max}: Outddor maximum temperature(˚C), T_{avg}: Outdoor average temperature(˚C); PT_{avg}: Outdoor period average temperature(˚C); RnAvg : Averge running mean temperature(˚C); S_{wg}: Outdoor swing(˚C); T_{drop}: Drop in minimum temperature(˚C); etc.

2.8.1 Thermal analysis: Transient behaviour of thermal mass in buildings

To find the amount of heat fluxes through thermal mass inside the buildings, various researchers have used the one-dimensional transient heat conduction equation for thermal performance investigation [**128**] [**129**] [**130**] [**131**] [**132**]. The one-dimensional heat transfer equation used to calculate the heat fluxes through the wall, and roofs are depicted in equation (2.9) [**17**] [**133**]

$$\mathbf{k\frac{\partial^2 T}{\partial^2 x} = \rho c_p \frac{\partial T}{\partial x}} \qquad (2.9)$$

To solve this transient equation, two boundary conditions and one initial condition are needed. At the inner and outer surface, the boundary conditions are given by equations (2.10) and (2.11)

$$\mathbf{k\left(\frac{\partial T}{\partial x}\right)_{x=0} = h_i\left[T_{x=0(t)} - T_i\right]} \qquad (2.10)$$

$$\mathbf{k\left(\frac{\partial T}{\partial x}\right)_{x=L} = h_o\left[T_{sa(t)} - T_{x=L(t)}\right]} \qquad (2.11)$$

The ‘‘sol–air temperature’’, $T_{sa(t)}$, includes the effects of the solar radiation combined with outside air temperature and changes periodically. The general equation for sol-air temperature can be taken as follows:

$$\mathbf{T_{sa(t)=} \frac{\alpha I(t)}{h_o} + T_a - \frac{\varepsilon \Delta R}{h_o}} \qquad (2.12)$$

In a steady-state condition, the solution of equation (2.13) can be expressed as

$$\mathbf{T_{(x,t)} = T_x + \sum T_n \exp(in\omega t)} \qquad (2.13)$$

Equating time independent and dependent parts of both sides of above equation and after algebraic simplification,

$$\mathbf{T_{(x,t)} = A_x + B + \sum [C_x \exp(\beta x) + D\exp(-\beta x)]\exp(in\omega t)]} \qquad (2.14)$$

where, A, B, C and D are constants and can be determined by using the energy balance equations for each case by separating real and imaginary part, and β can be calculated as expressed in equation (2.15)

$$\boldsymbol{\beta} = \left[\frac{\boldsymbol{\omega\rho c}}{\mathbf{2k}}\right]^{\mathbf{1/2}} \qquad (\mathbf{2.15})$$

Heat is also gained or lost in a building through heat conduction through the building envelope, thermal radiation through windows, doors, isothermal mass and ventilation through openings and infiltration/exfiltration through leakages. The energy balance equations for heat fluxes through these are described below.

The rate of heat flux entering the room through window/opening can be expressed as

$$\mathbf{Q_G = (I(t) - U_g(T_R - T_a)} \qquad (\mathbf{2.16})$$

The rate of heat flux entering inside or outside the room through door material can be expressed as:

$$\mathbf{Q_D = h_D\,(T_R - T_a)} \qquad (\mathbf{2.17})$$

Internal thermal mass such as furniture and purposed built internal concrete partitions does not expose to ambient temperature directly which introduces the concept of isothermal mass or internal mass. The energy balances for isothermal/internal mass can be expressed as

$$\mathbf{Q_i = h_i A_I (T_R - T_I) = M_I C_I \frac{dT}{dt}} \qquad (\mathbf{2.18})$$

Time lag and decrement factor are essential characteristics to determine the heat storage capabilities of any materials [**16**], [**127**], [**131**]. Time lag and decrement factors for different building materials have been investigated numerically by Asan [**16**]. One-dimensional transient heat conduction equation was solved using the Crank–Nicolson scheme under convection boundary condition. Twenty-six different building materials for eight different thicknesses of each material and the effects of thickness and the type of material on time lag and decrement factor were investigated. Ogoli [**127**] showed that materials with high thermal mass increase the time lag and reduce indoor temperature fluctuations leading to low decrement factors.

2.8.2 Studies on effect of thermal mass in buildings

The building envelope should provide the necessary thermal comfort for the occupants as well as reduce energy consumption requirements for cooling and heating. For the material to effectively store heat, it must exhibit a proper density, high thermal capacity, and a high thermal conductivity value.

Optimization of thermal mass levels depends on building material properties, building orientation for its location and distribution, thermal insulation, ventilation, climatic conditions and use of auxiliary cooling systems, and occupancy patterns [**14**] [**15**] [**116**] [**134**].

Pearlmutter and Meir [**135**] have compared indoor temperatures in two residential buildings, a factory-built lightweight structure and a traditional high-mass building, both of similar size and heat loss coefficients, but differing in their thermal mass. The high thermal mass building shows the better performance in both closed and open mode in comparison to the lightweight building.

Balaras [**15**] showed that proper use of thermal mass could increase indoor comfort level and reduce peak load in regions with large diurnal temperature swings. Givoni [**124**] carried out an experimental study, where buildings with different thermal mass levels were monitored under different ventilation and shading conditions during the summer in Pala, South California in the USA. That study evaluated the effect of thermal mass in lowering the daytime indoor temperatures.

Shaviv et al. [**134**] calculated the influence of thermal mass and night ventilation on the maximum indoor temperature in summer using an hourly simulation model ENERGY. The results obtained show that, in the hot, humid climate of Israel, it is possible to achieve a reduction of 3˚C–6˚C in a massively constructed building without conventional cooling unit.

Al-Sanea [**132**] [**136**] developed and applied a computer model, based on the finite-volume implicit procedure, to evaluate dynamic thermal characteristics of building walls. Dynamic wall R-values were calculated which accounted for effects of heat storage, wall orientation, long-wave radiation exchange, as well as nominal convection and conduction resistances.

Cheng et al. [**137**] carried out an experimental study in a hot and humid climate of Hong Kong and investigated the effect of colour and building thermal mass. The results show that walls with high mass and lighter outside surface colour could reduce maximum indoor temperature substantially. The study also considers the effect of orientation on the effectiveness of thermal mass and concluded that thermal mass suppressed the difference due to orientation.

A study by Kontoleon and Bikas [**138**] showed that solar absorptivity had a major effect on time lag and decrement factor of insulated walls during the cooling period by employing a dynamic thermal-network model. Results showed that maximum time lag was obtained with two insulation layers; one placed on outside surface and the other at the middle, while minimum decrement factor was achieved by placing the insulation layers on outer and inner surfaces.

Coupling natural ventilation and thermal mass are used for better thermal comfort inside the buildings and also lower the capital, operational, and maintenance costs for building sustainability [**117**]. The quantitative effect of convective cooling was studied extensively by Givoni at the Institute for Desert Research of Ben-Gurion University in Israel [**27**]. Based on his experimental studies, it was observed the drop in the daytime indoor temperature of a high-mass building below the outdoor maximum by night ventilation is roughly proportional to the outdoor temperature range.

The analysis of night ventilation for office buildings during summer period is performed, and results showed a reduction of diurnal variation from 1.5˚C–2˚C, resulting in a significant comfort improvement for the occupants [**139**].

The suitability of night ventilation for office buildings with lightweight construction located in cold climates is analysed [**140**]. Through simulation based approaches using Energy Plus, the indoor thermal environment and the energy consumption in typical office buildings in northern China are studied. The most important factors influencing night ventilation performance such as ventilation rates, ventilation duration, building mass and climatic conditions were evaluated. With night ventilation rate of 10ach^{-1}, the mean radiant temperature of the indoor surface decreased by up to 3.9˚C.

Kubota et al. [**141**] studied the effectiveness of night ventilation technique for residential buildings in a hot-humid climate of Malaysia. The effects of different natural ventilation strategies on the indoor thermal environment for Malaysian terraced houses are evaluated based on the results of a full-scale field experiment.

Specific monitoring studies in real buildings or test cells are reported in the various literature and assessed the effect of night ventilation [**134**] [**124**] [**142**] [**143**] [**144**]. Most of the studies conclude that the use of night ventilation in free floating buildings may decrease the next day peak indoor temperature up to 3˚C. In parallel, when applied in air conditioned buildings, a considerable reduction of the peak cooling may be expected.

The effect of building thermal storage on the peak cooling load has been evaluated during an experiment with a large office building in Jacksonville, Florida [**145**]. Diurnal heat capacity calculations were used in analysing the experimental results. The results showed an 18% reduction in cooling energy supplied during the daytime.

The theoretical performance of six configurations of insulation placement in massive walls using Program DOE2.1E was critically examined. The energy consumption of a ranch house in six climatic regions of the United States was simulated. The study concluded that walls with exterior insulation perform best, leading to the energy requirements for heating and cooling [**146**].

Kalogirou et al. [**147**] examined the effects of the heating and cooling load resulting from the use of building thermal mass in Cyprus using TRANSYS simulation program. The results of the study showed that there was a reduction in the heating load requirement of the zone by about 47% while at same time a partial increment in cooling load.

The influence of the thermal inertia of external walls on the energy performance of well-insulated buildings was analysed. The study results showed that the wall system with the highest energy performance had a proper combination of dynamic thermal transmittance and thermal admittance values [**148**].

Masoso and Grobler [**149**] also found that annual cooling load decreases with increasing interior temperature and becomes negative when the interior set point temperature increases beyond a set value (25.7˚C).

The use of wall insulation in residential villas in Dubai was investigated using simulation study and found that proper insulation of the exterior wall can result in an energy savings of 30% [**150**].

Insulation could help improve the thermal performance of walls based on the results of both experimental and simulation studies on the comparative energy and economic performance of walls used to enclose air-conditioned spaces [**151**]. In a similar study, conducted by Guo et al. [**152**], the energy-saving effect of coating exterior walls with heat-reflective insulation studied and found a clear saving in energy with this insulation in Hangzhou.

Most of the studies focused on the thermal performance of the insulated wall and examined energy consumption using simulation methods, and only a few of these studies investigated the effects of the indoor thermal environment.

2.8.3 Thermal mass studies in India

In India also numbers of studies are being carried out on the thermal performance of architecture.

Sodha et al. [**129**] [**153**] and Seth et al. [**130**] investigated optimum locations/distribution of insulation/air gap and thermal mass layers in building walls and roofs for best load levelling. The periodic heat transfer equation analysis has been carried out for optimum placement of an air gap in a stratified hollow concrete slab subjected to periodic solar radiation and atmospheric air.

Chand et al. [**154**] presented the results of ventilation survey carried out in a few typical airy buildings located in hot dry and hot humid zones of India. The airy environment in buildings is attributable to the design parameters, like proper orientation, elevated location, large facade area, proper plan form, centrally located wind shaft, and a series connection of openings.

Tiwari et al. [**17**] carried out a comparison of passive cooling techniques of a non-air-conditioned apartment for Delhi climate. The results revealed that the evaporative cooling was the best option to reduce the incoming heat flux through the roof and the air cavity also reduced the incoming flux entering through walls.

Singh et al. [**111**] carried out a field study and presented the result of long-term monitoring of two vernacular houses selected one in warm and humid and other in cold and cloudy climate of north-eastern India. The predicted formulae were developed based on the monitoring period, and the correlation coefficient (R^2 value) is found to be above 0.96 for all developed correlations.

Dili et al. [**115**] reported the effectiveness of passive control methods in Kerala vernacular architecture for the comfortable indoor environment in summer and winter months.

Kumar and Suman [**155**] carried out an analysis of the impact of the thermal insulation materials in buildings enabling effective energy savings through the use of Energy Conservation Building Code (ECBC), India. The results showed that 50 mm thick Elastospray with conventional roof and wall satisfied the ECBC requirements whereas, other insulation materials require higher thickness to fulfil the recommended values.

Dhaka et al. [**156**] concluded the effect of envelope measures on thermal environmental conditions of a naturally ventilated building block in a composite climate of India. This study found that envelope with ECBC specifications offers 60% hours under comfort state which were not comfortable with conventionally practice envelope specifications of India.

Chandel et al. [**157**] studied the performance of passive solar building constructed in western Himalaya’s and found that energy consumption of the building can be reduced if passive solar features are appropriately considered in the building. In an another review study by same authors a case study of building regulations of Hamirpur town with composite climate, located in north western Himalayan state of Himachal Pradesh, India was carried out to identify implementation problems for energy regulations [**158**].

Chandel et al. [**159**] conducted a thermal comfort field study for passive solar building in Mandi town, Himachal Pradesh. The impact of passive solar features on heating, cooling and energy savings was evaluated using e-Quest simulation software. The space heating, cooling and mechanical ventilation loads and total annual energy consumption were found to be reduced due to passive solar design features in the building.

2.9 Evaluation of different Building Bio-climatic design chart (BBCC)

“Bioclimatic” design is the phase that is used to define potential building design strategies for a particular climate that utilize their natural energy resources and minimize conventional energy utilization in buildings making them energy efficient and more comfortable [**20**]. Although the bioclimatic chart was introduced decades ago and it was a popular tool, it was, unexpectedly, rarely used. However, the use of bioclimatic analysis approach, in general, has significantly increased in the last years. A detailed review of these design tools used by various researchers in different climates and buildings and their evaluation is discussed in subsequent sections.

2.9.1 Historical development of building bio-climatic chart

In 1963, Olgyay [**22**] developed the first bioclimatic chart based on outdoor conditions as shown in Figure 2-9. The charts have various zones corresponding to human thermal comfort and have been prepared based on ambient temperature, humidity, mean radiant temperature, wind speed, solar radiation and evaporative cooling. Though, it was a significant finding in the process of building design but has some limitations. The chart was suggested for lightweight buildings in humid regions. Later Givoni [**14**] found that the Olgyay’s chart is inappropriate for use in hot and dry areas where the indoor and ambient conditions are varied significantly especially for massive construction buildings.

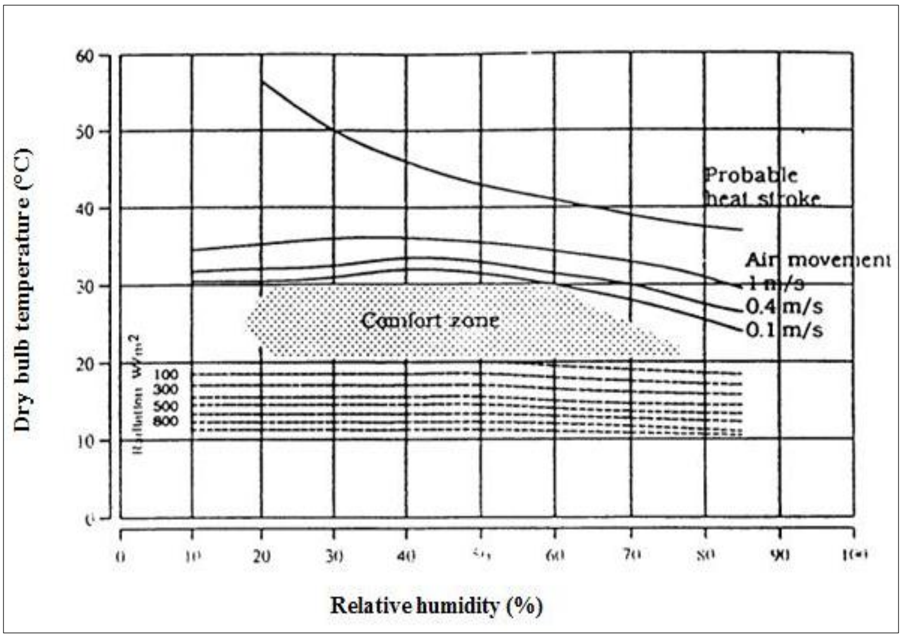


Figure 2-9 Olgyay bioclimatic chart [22**]**

To address the limitation of "Olgyay bioclimatic chart," Givoni [**25**] proposed a new series of bioclimatic chart known as "Givoni's bioclimatic chart" (Figure 2-10). Givoni's bio-climatic charts were developed from the experimental investigation based research in Europe, the USA, and Israel, using residential buildings with low internal heat gains [**14**]. They have two key components: envelopes which define the temperature and humidity within which occupants will be comfortable and 'boundaries of climatic conditions within which various building design strategies and natural cooling systems can provide comfort [**160**].

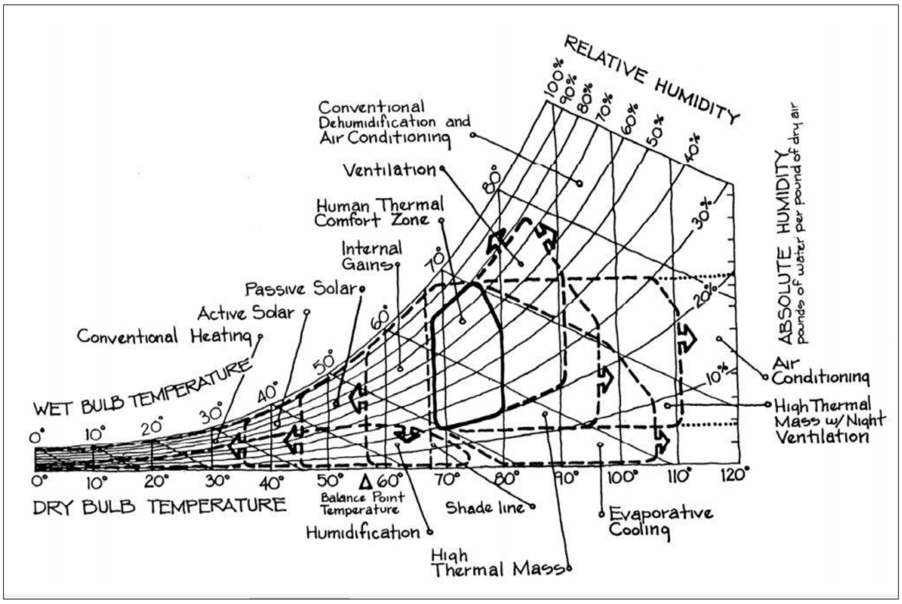


Figure 2-10 Givoni's building bio-climatic chart [25**]**

Later Milne and Givoni [**24**] carried out experimental studies on different buildings and combined the various design strategies in the Givoni's BBCC to meet the indoor comfort based on outdoor conditions. This chart can be effectively used to determine the passive cooling strategies according to building outdoor climatic conditions.

Szokolay [**161**] [**162**] combined the previous standards of the bioclimatic design concept and introduced a systematic procedure of climatic analysis by utilizing the standard effective temperature (SET) of the ASHRAE Standard 55 in defining the human thermal comfort zone. The work established the "Control Potential Zone" (CPZ) of the passive cooling techniques based on a more accurate recent research. The climate lines are then overlaid on the same bioclimatic chart which makes the analysis process more comprehensive and less time-consuming.

Arens et al. [**163**] concluded that bandwidth of thermal comfort is evaluated through the psychrometric/bioclimatic chart and it has to be extended on particular climate.

Lomas et al. [**160**] used BBCC of Givoni [**14**], to test whether passive downdraught evaporative cooling with night ventilation could yield thermal comfort in an office building in Southern Europe. New boundaries, defining the climatic applicability for thermal comfort for direct evaporative cooling in offices, with differing levels of internal heat gain, were proposed. For each one, a band of climatic conditions, within which comfort is sometimes achieved and sometimes not, is also indicated.

Sopa Visitask, [**20**] developed different design strategies for a thermostatically controlled House in 5 different climatic zones (mainly for Houston) by testing and validating Givoni–Milne BBCC with DOE-2 simulation work and hence deduced that Givoni-Milne charts are not universal but depend upon local climatic conditions prevail there.

Evan [**164**] developed a new visual analysis tool to select and verify different bioclimatic strategies according to climate conditions and requirements for thermal comfort. The Comfort Triangles tool relates outdoor daily temperature variations with the modification of thermal performance achieved indoors.

2.9.2 Other pre-design and simulation tools for passive strategy

Over the past 50 years, literally hundreds of building energy programs has been developed. Building performance simulation techniques can be supportive when integrated early in the design process. The historical series of pre-design tools include "Building Bio-climatic Design Charts" by Olgyay [**22**], Givoni [**14**,**25**,**29**], Givoni–Milne [**24**], Szokolay [**161**] [**165**], Mahoney tables [**166**], and Evan's design triangles [**164**], etc. Several other software pre-design tools that are very useful include: "Climate Consultant," "Autodesk© Ecotect Analysis," "The Weather Tool," and "Shaded Fenestration Design," "ENERGY-10", "HEED," etc. Overviews for some of the online tools used for pre-design and energy efficient buildings are discussed in subsequent sections.

- **Mahoney's Table**

Mahoney [**166**] proposed a climate analysis sequence consisting of four steps carried out by filling up four tables. Department of Development and Tropical Studies of the Architectural Association in London developed this methodology. It is named after architect Carl Mahoney. The main advantages of Mahoney tables are the simplicity and low input requirements. However, it is not meant to support detailed prescriptive-based or performance-based recommendations. In addition to this, comfort limits established in this method are mostly aimed at tropical climate, being less accurate in colder climates.

Mahoney Table 1 dealt with recording basic and widely available monthly climatic data of temperature, humidity, and rainfall. Mahoney Table 2 part I dealt with defining adaptive comfort limits, based on annual mean temperature and average monthly humidity. Mahoney Tables 3 and four help in the selection of design recommendations for the sketch design and detail design stage respectively [**166**].

Hosni [**167**] considered procedures of Mahoney method to identify a set of possible alternate architectural responses corresponding to a defined set of climatic conditions existing in the selected locations of Egypt. Ogunsote and Prucnal-Ogunsote, [**168**] arrived at combinations of building design strategies recommended using Mahoney Tables method, to define climatic zones for architectural design in Nigeria.

Pawar et al. [**169**] described a procedure devised using Geographical Information System (GIS) to delineate thermal comfort boundaries using Mahoney's Table for responsive building design strategies in India. The selected strategies in 8 groups are superimposed together to identify 62 "Thermal Comfort Design Zones" with a unique combination of building design strategies.

- **Climate Consultant**

The University of California developed climate consultant with the support of California Energy Commission. Climate Consultant is based on theoretical work of Givoni [**29**] and Milne [**24**] for their field experiments of residential buildings. Climate Consultant consists of a standard psychrometric chart, and specific zones represent different design strategies on this chart (Figure 2-11).

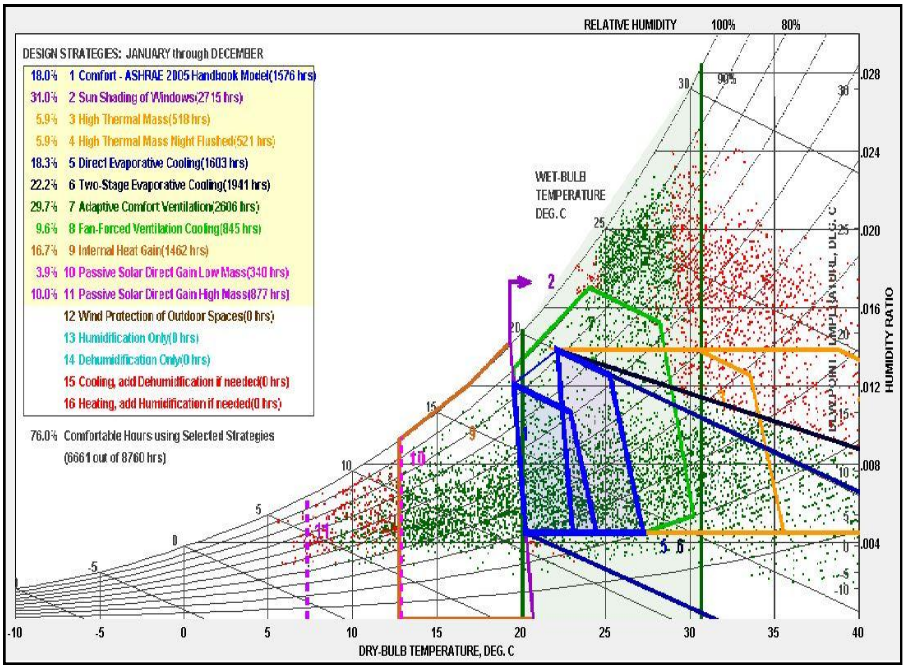


Figure 2-11 Various passive measures and their effect on comfort (Climate Consultant© v6)

- **Auto desk© Ecotect Analysis**

Auto desk© Ecotect Analysis is a complete building design and environmental analysis tool that through simulation and analysis functions predict how a building design will operate and perform. Ecotect is a highly visual architectural design and analysis tool. Its main advantage is a focus on feedback at the earliest stages of the building design process.

- **ENERGY-10**

Energy-10 was intended to facilitate the analysis of buildings at the beginning of the design process with a focus on providing a comprehensive tool suited to the design-team environment for smaller buildings. It is most suitable for smaller, simpler, commercial and residential buildings.

- **Home Energy Efficient Design (HEED)**

The objective of HEED is to combine a single-zone simulation engine with a user-friendly interface. It is intended for use at the very beginning of the design process when most of the decisions are made that ultimately impact the energy performance of envelope-dominated buildings.

The design of solar house/structure requires a detailed understanding of the complex relationship among architectural textures, human behaviours, culture and climatic factor. Initial simulations help the building designers and architects to make the building design more environment friendly and energy efficient. A design procedure for making of the buildings with minimum energy consumption while maintaining thermal comfort by means of various simulation programs is shown in Figure 2-12.

However, each simulation tool has its own limitations in both pre-design and execution stages of buildings which are summarized below:

i. The programs require a great knowledge and expertise from its users, and require a long learning process.
ii. Weather input data for selected locations for prediction of thermal performance behavior of buildings are limited. This may affects the actual performance of buildings and passive design alternatives available to the buildings.

iii. The choice of simulation program might change depending on the usability and applicability of the program to model the buildings.

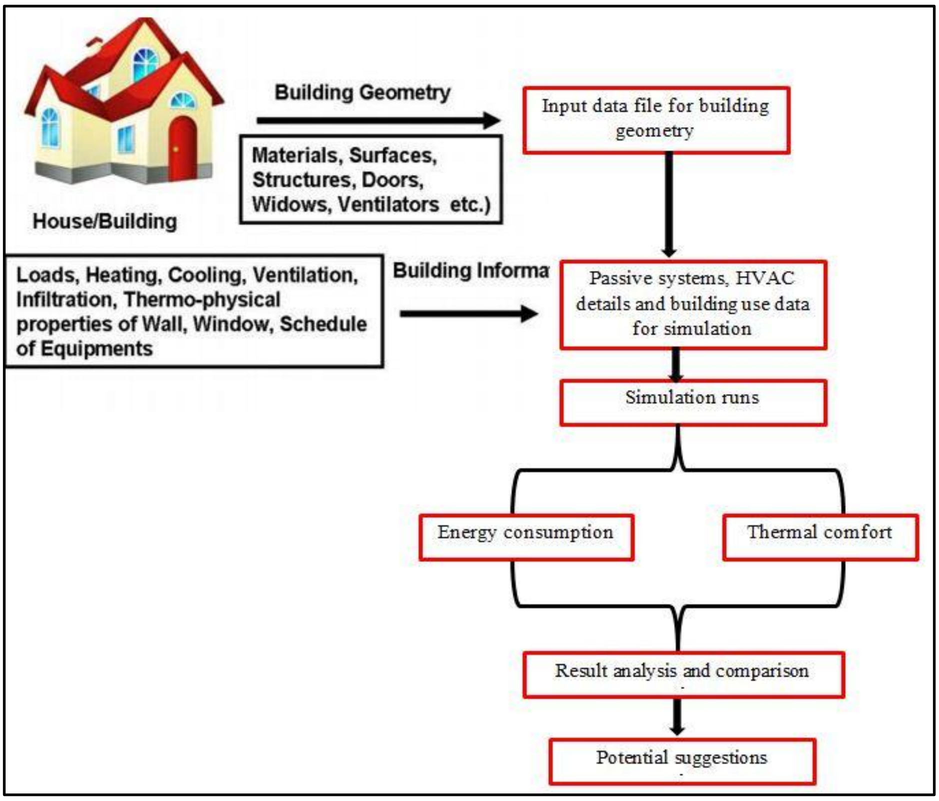


Figure 2-12 Systematic approach for building design using simulation programs

2.10 Summary and research gaps

Field studies of thermal comfort conducted all over the world for the different type of buildings and climates had illustrated that indoor comfort conditions are dependent on local climatic conditions and adaptations. Due to unavailability of the country and climate specific standard, developing nations use the comfort standards such as ISO 7730 [**5**], ASHRAE Standard 55–2013 [**4**], and EN 15251 [**6**] for the evaluation of indoor thermal conditions. It has been investigated through literature study that some problems exist; when these comfort standards are used to evaluate the indoor conditions in naturally ventilated buildings especially in tropical countries like India. The comfort zones defined on existing psychrometric chart partially account for the acclimatization, comfort expectations and behavioural adaptation of the inhabitants in such countries. Also, Building Bio-climatic design charts (BBCC) uses ASHRAE Standard 55 comfort zone for accessing indoor thermal comfort in buildings using different passive strategies for a local climate. However, it has been investigated that these building bioclimatic design’s environmentally friendly approaches with these conventional comfort standards are inconsistent. Based on the literature review followings research gaps are identified:

- International comfort standards do not correlate to the conditions specific to India due to the large variation in meteorological conditions and also due to social and cultural differences; this is a gap in research.
- Thermal comfort research is in its nascent stage in India, although not new, however very few studies have been carried out for a wide diversity of Indian conditions.
- It has been investigated through many literatures that building bio-climatic design charts are not universal in its approach and depends upon local meteorological conditions and building types.
- Also available bio-climatic charts for a selection of an appropriate strategy for producing thermal comfort in buildings are based on climates other than Indian climates. No study has been carried out for appropriateness of these charts in Indian climatic conditions.

Based on literature gaps identified above following objectives are proposed for present study.

- Development of an adaptive comfort zone especially for composite climate considering adaptive thermal comfort approach.
- Develop a bio-climatic chart for one widely used passive strategy viz. high thermal mass in buildings for composite climate of India.

CHAPTER 3
RESEARCH METHODOLOGY

3.1 Preamble

The first objective of the present study is to define the comfort boundaries for indoors on the psychrometric chart based on adaptive comfort approach considering climate specific adaptations, the role of air speed and thermal preferences of the occupants in naturally ventilated buildings. The second objective is to develop the climatic boundary for the outdoor conditions for which thermal mass can produce comfort indoors. To achieve these objectives, the work has been divided into three parts.

- Part A: First part describes the methods and procedures used for carrying out a field study of thermal comfort and then elaborate the methods used for defining the boundaries of thermal comfort zones for naturally ventilated buildings.
- Part B: Second part elaborates the methods and procedures used for carrying out the experimental study for evaluation of thermal performance of high mass in naturally ventilated buildings.
- Part C: Using the results of Part A and Part B to develop a bio-climatic boundary of ambient conditions using Building Bio-Climatic Design Chart for the use of thermal mass in buildings for composite climate of India.

3.2 Part A: defining thermal comfort zones for naturally ventilated buildings

Internationally accepted standards like ISO 7730 [**5**], ASHRAE Standard 55−2013 [**4**] and EN 15251 [**6**] for defining thermal comfort conditions, are based on Fanger's heat balance model of the human body. However, heat balance approach to determine comfort fails to accommodate the impact of adaptation, i.e. psychological, physiological and socio-cultural aspects of occupant comfort, which are very prominent in naturally ventilated buildings [**35**]. The evidence of the critical role played by adaptation in defining comfort standards in different types of buildings and climates lead researchers criticizing the universal applicability of single comfort model based on heat balance approach [**170**]. An alternative is an adaptive model, primarily based on the results of field studies, also has been researched since the 1960s [**7**] [**8**] [**163**]. According to the adaptive hypothesis, contextual factors and past thermal history modify the occupant's thermal expectations and preferences. Research on adaptive comfort has revealed that occupants in naturally ventilated buildings are more flexible towards variations in outdoor environmental conditions and use a larger variety of adaptive controls to make their indoor environment thermally comfortable.

In the present research, thermal comfort field study was conducted in thirty-two naturally ventilated buildings, collecting a total of 2610 samples spread over a total period of five years, covering all seasons, age groups, clothing types, and building types. The transverse type questionnaire as per the requirement of Class-II protocol of field measurement used in this study was taken from the study conducted by Dhaka et al. [**83**] for the same climatic region. The questionnaires were administered to building occupants through trained surveyors to record sensations and preferences for air temperature, relative humidity and air velocity on ASHRAE Standard 55−2013 seven point and five point scales. The collected data was used to evaluate thermal comfort of occupants and study the methods of thermal adaptation in naturally ventilated buildings. Further, findings of thermal comfort from naturally ventilated buildings were used to define the thermal comfort zones at different airspeed ranges. Different stages and processes employed for carrying out this research are shown in the form of the flow chart as presented in Figure 3-1.

3.2.1 Field study protocol and questionnaires

The questionnaire is designed for conducting field studies as per the field measurement protocols. During field studies of thermal comfort, objective and subjective information from the survey environment is obtained to evaluate the thermal perception of occupants and to find out thermal acceptability in different types of buildings.

There are three protocols available for conducting a field study of thermal comfort, namely, Class-I, Class-II, and Class-III protocol. Class-II protocol as per ASHRAE 55−2013 has been used in the present study, which signifies measurement of indoor thermal environment variables using laboratory grade instruments compatible with ISO 7730 standard during right now questionnaire along with a recording of a subjective variables like clothing ensembles and activity level. Measurements are recorded at the height of 1.1 m simultaneously at the same place where the thermal questionnaire is administered [**4**]. The advantage of Class-II protocol is that it can be used to evaluate individual and combined effects of thermal environment variables on thermal perception.

In the present study, the transverse survey method was used to assess thermal perception in different types of buildings. A questionnaire was developed to collect thermal responses from the occupants whereas survey form was used to record environmental variables and surrounding conditions around the subject. In the present study, questionnaire and survey form appended in **Appendix-1** has been used as employed in a previous study by Dhaka et al. [**83**].

3.2.2 Description of survey form

The sensations and preference votes of the occupants for an indoor variable like temperature, humidity, and air movement were recorded at ASHRAE's seven-point sensation scale and five-point preference scale. Various studies across the world have used these scales for subjective evaluation of thermal environment in different climates and building types.

During the study survey form was filled out by the surveyors/researchers and it was used to note down thermal environment variables and also used to record surrounding conditions of the subject. During the study, questionnaire (Part−A) and survey form (Part−B) were used to collect qualitative and quantitative (subjective and objective) assessments. The survey form also observed the condition of the controls used such as open/close window and door, use of blinds/lovers/curtain, use of the fan and fan speed regulator.

The standard clothing ensembles suggested by ASHRAE Standard 55−2013 and traditional clothing choices were provided in the questionnaire to record clothing ensembles. The clothing insulation (clo) was taken from ASHRAE Handbook for fundamental [**42**] and also from the field study performed by Indraganti [**65**] and Mishra and Ramgopal [**112**] for Indian habitants.

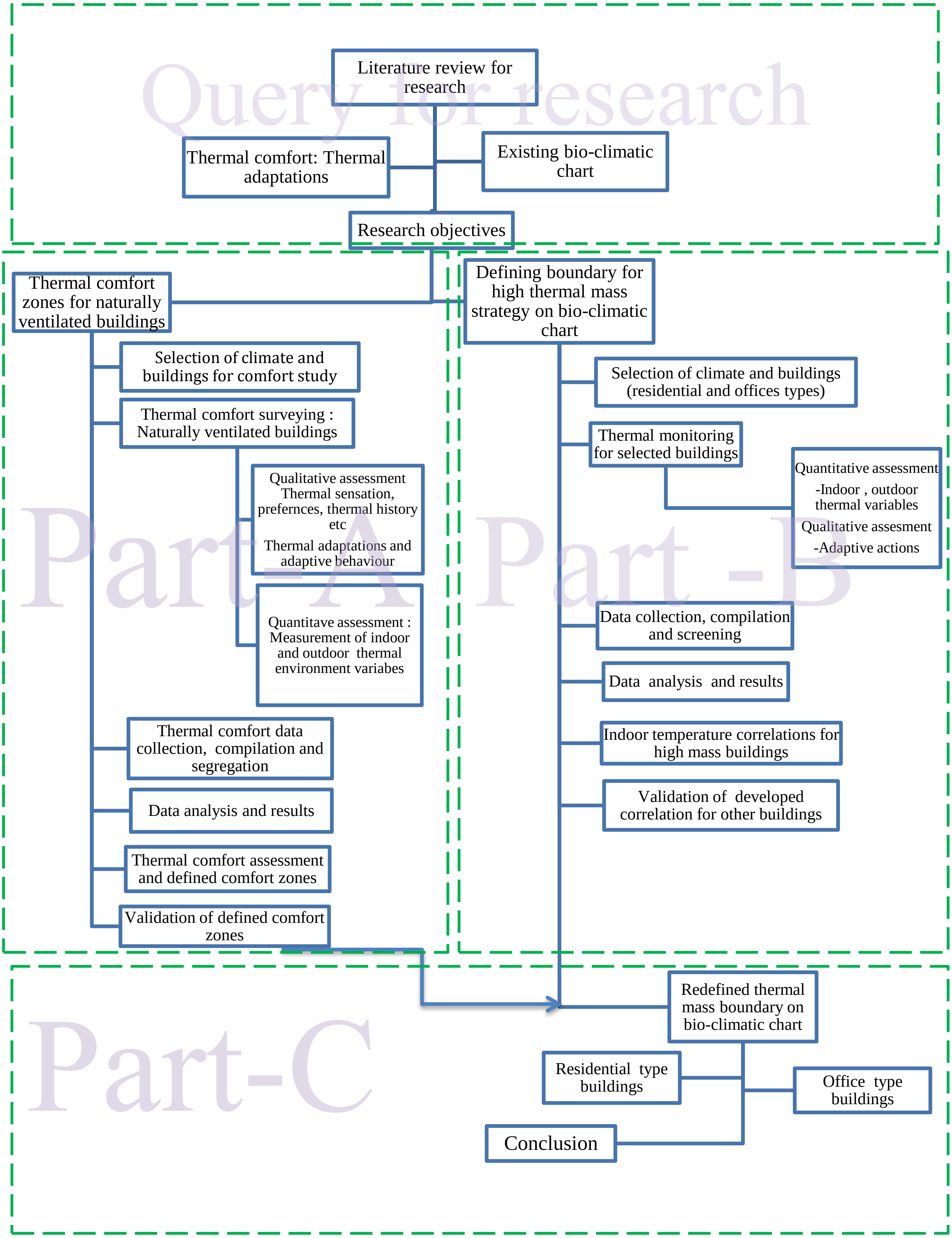


Figure 3-1 Methodology flowchart for the study

The clothing values and activity level checklist used in present study during surveys are appended in **Appendix-2**.

3.2.3 Measuring instruments

Laboratory grade calibrated digital instrument VAC 480 (Make: Testo) was used for the measurement of thermal environment variables as per the Class-II protocol of field study. The outdoor dry bulb temperature was recorded at a weather station (Make: Virtual Instrumentation) installed at institute's office building (CEE Department, MNIT Jaipur) as shown in Figure 3-2. The recorded outdoor temperature at MNIT was assumed to be same for the studied building since the survey buildings are situated in Jaipur and also exist in the similar type of surrounding conditions. Figure 3-3 shows the photographs of VAC 480 instrument with a tripod (A) and different probes used for the study such as globe of 150 mm diameter for measuring globe temperature (B), omnidirectional hot wire anemometer (C), the probe used for air speed measurement (D), data logger (E) and probe employed for temperature and RH measurements (F).

Figure 3-2 Weather station at MNIT, Jaipur

Figure 3-3 VAC 480 instrument for measuring thermal environmental variables

The sensors chosen for the study met the accuracy and response time as per the requirement of ISO 7730 [**5**] and ASHRAE Standard 55−2013 [**4**]. Specifications of the measuring instrument such as measuring variable, instrument name, their make, the range of measuring variable and accuracy of the sensor are shown in Table 3.1.

Table 3.1 Specifications of measuring instruments used

S.No.	Parameter	Make	Instrument	Range	Accuracy	Resolution
1	Outdoor temperature	Virtual instrumentation	Weather station	-40-123.8 ^{o}C	± 0.5 ^{o}C (5-40 ^{o}C)	±0.1 ^{o}C
2	Air temperature	Testo	480 VAC	-20 -70 ^{o}C	± 0.5 ^{o}C	±0.1 ^{o}C
3	Globe temperature	Testo	480 VAC	0-120 ^{o}C	± 0.5 °C	±0.1 ^{o}C
4	Relative humidity	Testo	480 VAC	0-100 % RH	± (1.0 % RH + 0.7 % of reading)	0.1%
6	Air velocity	Testo	480 VAC	0-5 m/s	± (0.03 m/s + 4% of reading)	0.01
7	CO_2	Testo	435-2	0-10,000 ppm	± (50 ppm CO_2 + 2 % of reading)	2%
8	Illumination level	Lutron	LX-101A	0-50,000 lux	± 4 % of 10 digit	

3.2.4 Selection of climate and buildings

India has been divided into five climatic zones, namely hot and dry, warm and humid, temperate, cold and composite climate as shown in Figure 3-4 [**1**] [**45**].

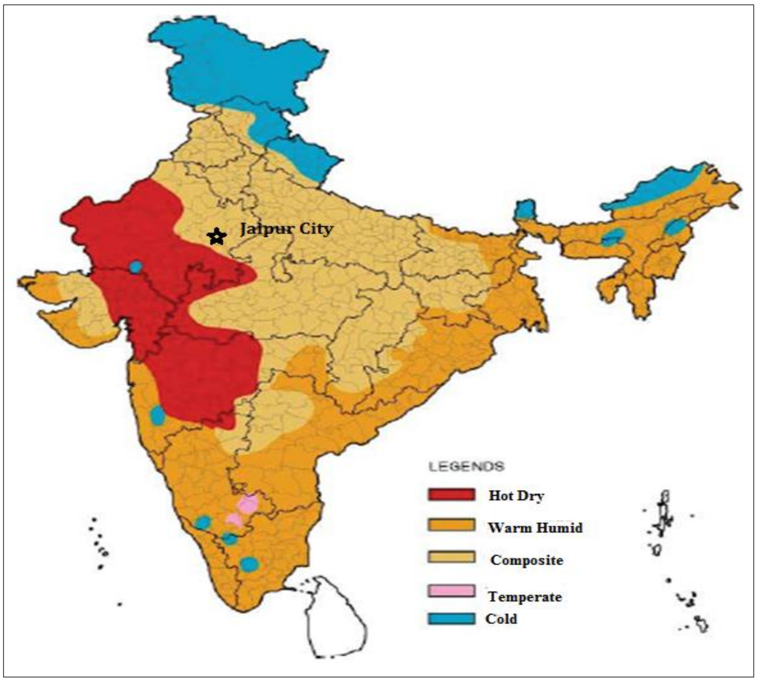
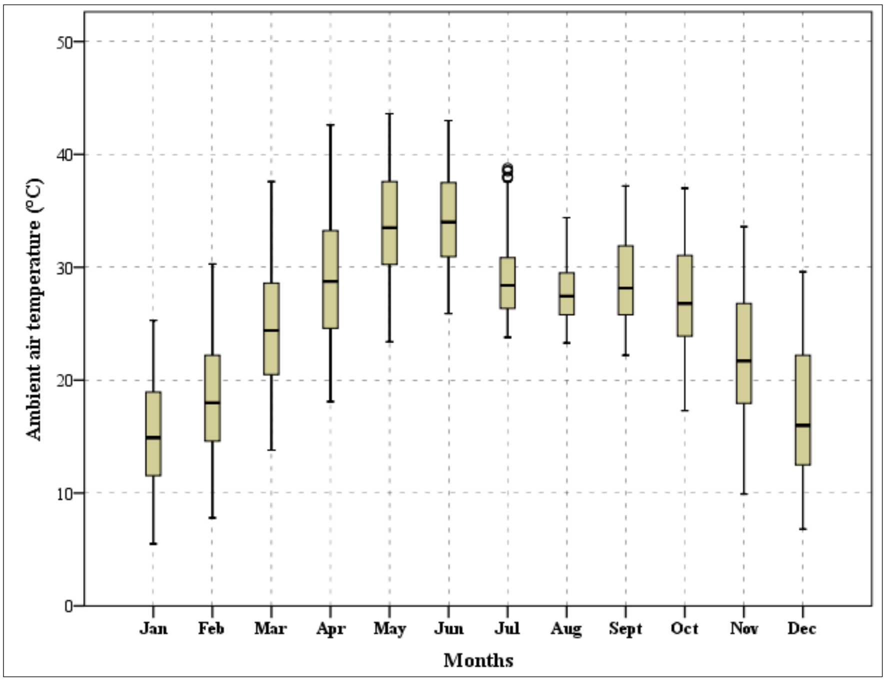


Figure 3-4 Climatic map of India [1**]**

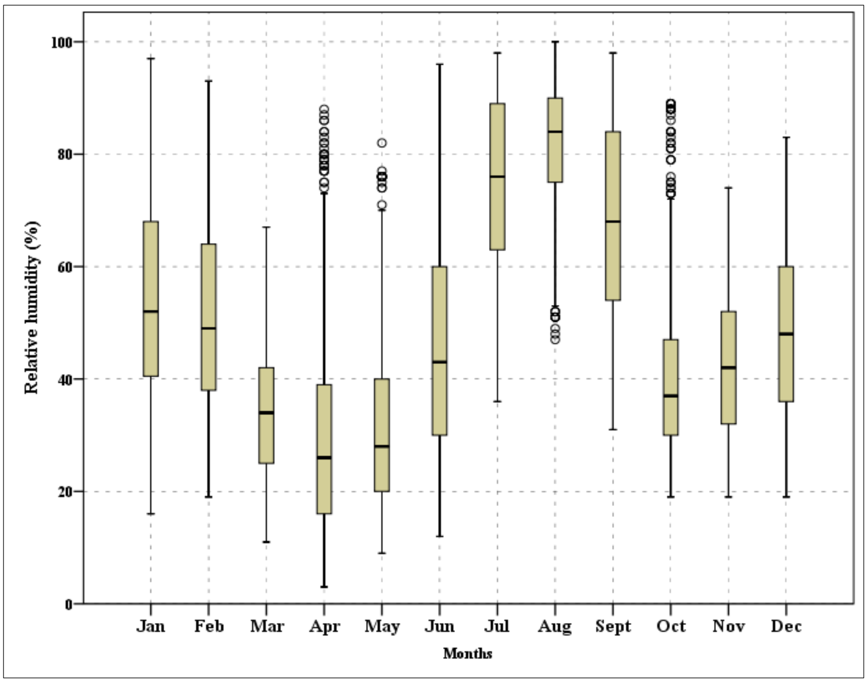
In the present study selected composite climate of Jaipur, due to its diverse climatic conditions. Naturally ventilated buildings of a different type such as office and residential type were selected for performing field studies of thermal comfort to quantify the indoor thermal comfort and prevalent adaptations. Also, the building bio-climatic chart is used as a pre-design tool for evaluation of various passive design strategies to assess the thermal comfort in naturally ventilated buildings. So, this study considered primarily naturally ventilated buildings for the analysis of indoor comfort.

The ambient temperature in a composite climate of Jaipur varies between 4˚C−43˚C, and relative humidity fluctuates between 5%−95%. Figure 3-5 demonstrates variation in DBT and RH in Jaipur from January to December through boxplot, and it was calculated from the outdoor temperatures obtained from the weather file of Jaipur city [**171**]. The monthly mean outdoor temperature was found minimum during winter (15.7˚C) and maximum in summer season (34.6˚C).

Meteorological conditions under this climate vary from scorching hot during summer to chilling cold during winter. Summer peak temperature soars above 45˚C and then falls to about 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 [**172**]. This approach was adopted for categorization of climatic zones of India that are presented in the Energy Conservation Building Code [**1**] and National Building Code of India [**45**]. 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) [**53**].



(a)



(b)

Figure 3-5 Variations in (a) outdoor air temperature and (b) relative humidity, Jaipur

3.2.5 Selection of buildings

Based on the method of controlling indoor environment buildings are usually classified into three categories, namely air-conditioned, naturally ventilated and mixed-mode buildings. Air-conditioned buildings (AC) are those that equipped with Heating, Ventilation, and Air-conditioning (HVAC) system for controlling the indoor conditions throughout the year. Naturally ventilated spaces are those where the thermal conditions of the space are regulated primarily by the occupants through the opening and closing of windows. Low energy fans are also allowed in naturally ventilated buildings. It is expressly noted that in naturally ventilated spaces the windows must be easy to access and operate, and sometimes also called free-running buildings. The buildings which are sometimes operated on air-conditioning mode and remaining time on naturally ventilation mode when conditions are favorable are referred to as mixed-mode buildings. Primarily in the present study, naturally ventilated buildings were selected for performing field study of thermal comfort. Different type of buildings including office buildings and residential buildings in Jaipur were chosen for evaluating indoor conditions through field study. Table 3.2 presents the details of the buildings, mode of operation, ownership, and subjects who participated in the study.

Table 3.2 Buildings and subjects surveyed details

Building details				**Subject's details**		
Building Title	**Type(Office/Residential)**	**Age of buildings (years)**	**Ownership**	**Sample size**	**Male sample**	**Female Samples**
O1	Office	40	Govt.	175	140	35
O2	Office	8	Govt.	95	57	38
O3	Office	25	Govt.	12	7	5
O4	Office	40	Private	25	20	5
O5	Office	10	Govt.	98	85	13
O6	Office	15	Private	5	2	3
O7	Office	15	Private	12	9	3
O8	Office	10	Private	8	7	1
O9	Office	10	Private	12	10	2
O10	Office	40	Govt.	24	24	0
O11	Office	10	Private	7	3	4
O12	Office	30	Govt.	38	33	5
O13	Office	10	Private	36	24	12
O14	Office	30	Govt.	64	54	10
R16	Residential	40	Govt.	248	248	-
R17	Residential	40	Govt.	33	33	-
R18	Residential	40	Govt.	55	-	55
R19	Residential	30	Govt.	5	5	-
R20	Residential	30	Govt.	228	228	-
R21	Residential	40	Govt.	228	228	-
R22	Residential	40	Govt.	108	108	-
R23	Residential	40	Govt.	206	206	-
R24	Residential	25	Govt.	18	12	6
R25	Residential	10	Govt.	335		335
R26	Residential	40	Govt.	38	38	-
R27	Residential	40	Govt.	70	60	-
R28	Residential	30	Govt.	249	240	9
R29	Residential	40	Govt.	32	32	-
R30	Residential	10	Private	38	30	8
R31	Residential	10	Private	73	50	23
R32	Residential	10	Private	35	10	25
All	32			**2610**	**2013**	**597**
R: Residential buildings; O: office buildings						

In this study, the buildings were named as O1−O14 for office stock and R15−R32 for residential stock. These buildings lie within a radius of 10 km in Jaipur city. Buildings selected for the study are both from the government sector and private sector. All the selected buildings are multi-storeyed and wherever possible surveys were conducted on all floors. There was diversity in the nativity, gender difference, clothing variations and activity level among the subjects in each building. The occupational routine of different office buildings (general office, institute, bank, etc.) was similar in activity rate.

3.2.6 Compilation and segregation of data

The present thermal comfort field study is conducted for thirty-two naturally ventilated buildings for more than five consecutive years (April 2011−July 2016). The thermal comfort surveys were conducted covering multiple seasons. The subjects were all Indian nationals, well acclimatized to the composite climate of Jaipur for more than one year. 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 subject responses collected during summer, winter and moderate seasons were 47%, 36%, and 17%, respectively. Figure 3-6 presents the percentage of subject responses for three different seasons and across the months.

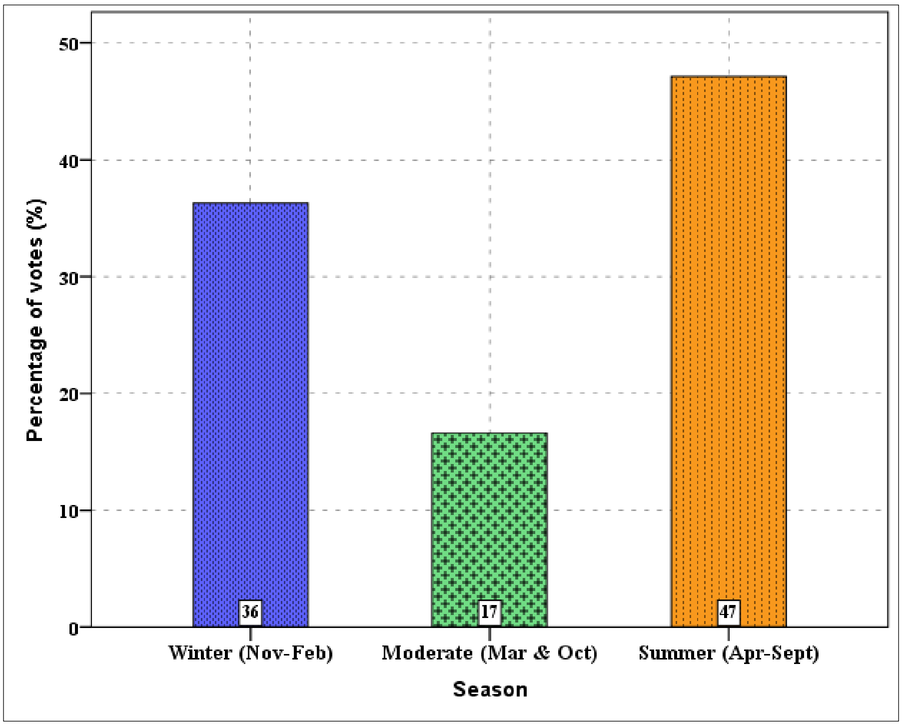


Figure 3-6 Subject responses for three different seasons

Thermal comfort data thus collected from naturally ventilated buildings were used for further analysis. Then data sets were segregated as per the use such as data belonged to different building types, gender i.e. male and female and for various seasons. Broadly, the survey results have not shown a significant difference in responses collected from those categories. Hence, separate detailed analysis for individual groups on building ownership has not been carried out.

3.2.7 Data analysis

The statistical analysis for survey data and the graphical representation are carried out using statistical tool IBM SPSS (Statistical Package for Social Science) software (v21). Microsoft Excel$^{©}$ spreadsheet program has been used to develop a psychrometric chart. A psychrometric chart is plotted as an x-y plot where the x-axis represents the dry-bulb temperature (T), and the y-axis represents the specific humidity ratio (W). The equations used to develop this psychrometric chart have been referred from ASHRAE Handbook of Refrigeration [**42**].

3.2.8 Thermal sensations and preferences

In comfort survey questionnaire, a thermal sensation of the building occupants was accessed using the question “How do you feel the temperature right now?” In response to thermal sensations recorded, the corresponding thermal preferences were captured with the question “How would you prefer to feel?” Thermal comfort conditions in occupied spaces are also affected by the other thermal environment variable such as relative humidity and air movement. ASHRAE Standard 55−2013 seven-point sensation and five point preference scale were used to record sensation and preference votes for temperature, humidity and air velocity as presented in Table 3.3.

Table 3.3 Description of scales used for recording sensation and preferences in survey questionnaire

	Sensation scale used			**Preference scale used**		
Scale	**Temperature**	**Humidity**	**Air velocity**	**Temperature**	**Humidity**	**Air velocity**
+3	Hot	Very humid	Much moving	-	-	-
+2	Warm	Moderately humid	Moderately moving	Much warmer	Moderately humid	Moderately moving
+1	Slightly warm	Slightly humid	Slightly moving	A bit warmer	Slightly humid	Slightly moving
0	Neutral	Acceptable	Acceptable	No change	No change	No Change
-1	Slightly cool	Slightly dry	Slightly still	A bit cooler	Slightly dry	Slightly still
-2	Cool	Moderately dry	Moderately still	Much cooler	Moderately dry	Moderately still
-3	Cold	Very dry	Very still	-	-	-

3.2.9 Thermal neutrality/comfort temperature

Researchers have applied different approaches to find the thermal neutrality for field studies. However, the two methods are mostly used by researchers across the world to find the thermal neutrality for field studies are: linear regression method and Griffiths' method [**90**]. Linear regression analysis between thermal sensation votes and the indoor air temperature was performed to determine neutral/comfort temperature. The study determined the neutral/comfort temperature of the survey group on an annual basis (complete data) and also on a seasonal basis.

Some researchers have pointed out issues with applying the regression method in the presence of adaptive behavior. It has been stated that the presence of behavioral adaptation in the data tends to artificially lower the regression coefficients and therefore the estimates of the comfort temperature [**10**] [**63**] [**51**] [**173**]. Also, the mean comfort vote which is much different from the neutrality, may also adversely affect the predictive power of the resultant regression equation [**174**]. Hence, survey results of this study have again been used to re-estimate the comfort temperature using Griffiths' method [**90**].

3.2.10 Thermal adaptations: occupant's control

Behavioral use of controls is interconnected with the physiology/psychology of the body and physics of the buildings [**62**] [**70**]. Personal and behavioral controls offer a wide range of acceptable indoor temperature conditions in naturally ventilated buildings. In this study, behavioral adaptations at a personal level have been analyzed, viz. changing clothing levels, use of personal environmental controls like the opening of window/door (for the natural flow of air) and use of a fan (for forced airflow); to make the surrounding environment comfortable.

3.2.11 Method of defining thermal comfort zones for naturally ventilated buildings

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. The method of calculation suggested by the ISO 7730 [**5**] and ASHRAE Standard 55–2013 [**4**] are used to determine extended acceptable temperature ranges for comfort at elevated air speed. ASHRAE Standard 55–2013 comfort boundaries are evaluated considering this climate’s specific clothing variability, the role of air speed, regional preferences, and expectations. The applicability of these comfort standards is still questioned in developing countries like India with a tropical climate [**44**] [**81**]. Comfort and discomfort votes were plotted on the traditional ASHRAE Standard 55 psychrometric comfort zone including the effects of clo, activity and air speed. The study reveals that these standards need to be expanded to capture occupant’s region-specific adaptations, comfort expectations, and the role of higher air speeds in naturally ventilated buildings in tropical countries like India [**103**]. Hence, the comfort boundaries have been extended reflecting the results of this study, particularly for naturally ventilated buildings.

ASHRAE Standard 55−2013 recommends 80% acceptability for the thermal environment with the percentage of people dissatisfied (PPD) should be lower than 20%. We are proposing new comfort zones at different air speed, encompassing the comfortable votes (±1 thermal sensation votes) from naturally ventilated buildings ensuring that at least 80% occupants are lain in proposed comfort zones.

3.2.12 Validation of defined thermal comfort zones

To validate these proposed comfort zones at different air speed ranges the comfort surveys from an extended period of July 2015 until June 2016 has been used. A total of 648 subject’s 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.

3.3 Part B: thermal performance analysis for high mass buildings

Experimental investigation of high thermal mass buildings for thermal performance has been carried out for all one year covering full summer and winter season in composite climate of Jaipur. The commonly constructed buildings in composite climate of Jaipur are of high thermal mass in which multiple layers of stone or brick burned are used in external walls. This type of conventional construction is common in almost all region of the composite climate of India [**155**] [**156**]. Two residential and two office high thermal mass buildings of different construction materials were selected for long-term monitoring. Different stages and processes employed for carrying out this part of the present research are shown in Figure 3-1. External walls are constructed of brick/stone of 0.23m−0.30m and gypsum plaster of 0.012m−0.015m thickness on both sides, and roofs are built of 0.15m Reinforced Cement Concrete (RCC) with mortar. The buildings are selected based on similar building plan and functionality which are prevalent in this climatic zone. The buildings considered are naturally ventilated with no mechanical cooling system.

Simultaneously, measurements of thermal environment variables like temperature, humidity, air speed and luminance level were recorded using HOBO U-12 type loggers (Figure 3-7). A detailed specification of the measuring instrument such as measuring variable, instrument name, and their make, range of measuring variable and accuracy of the sensor is shown in Table 3.4. Data loggers were placed on the inter-room partition wall of the buildings at the height of around 1.5m from the floor as found in various studies [**111**] [**175**] [**176**]. It was assumed that temperature recorded at this point would be the average temperature of different points in the residential and office building.

Since the occupants tend to modify the indoor environments by their adaptive actions to restore comfort, details of occupant’s adaptive actions taken are also reported. Data is compiled for different building types and season, and then analysis was carried out for the development of correlations to predict indoor temperatures for thermal performance of these monitored buildings.

Figure 3-7 Hobo U-12 type loggers

Table 3.4 Specifications of measuring instruments used

Measuring variables	**Name of instrument**	**Measurement Range**	**Resolution**	**Accuracy**
Temperature	Hobo U-12	-20° to 70°C	0.03°C at 25°C	± 0.35°C from 0° to 50°C
Relative Humidity	Hobo U-12	5% to 95% RH	0.03% RH	±2.5% from 10% to 90% RH
Light Intensity	Hobo U-12	1 to 3000((lumens/ft2)	N.A.	N.A.
Outdoor temperature	Weather station (MNIT, Jaipur)	-40-123.8 ˚C	± 0.5˚C (5-40 ˚C)	

3.3.1 Thermal performance analysis and correlations development

In the present study, the monitored data are used to evaluate the thermal performances of a high mass buildings in the summer and winter season, separately. Indoor temperature predictions, for a particular building but different climatic conditions, based exclusively on outdoor climatic parameters, were shown to be possible both for non-occupied and occupied unconditioned buildings. The constants in these formulas were specific to a given building, without taking into account the thermo-physical characteristics of the envelope [**118**]. Since the functionality of thermal mass buildings is different in summer (for the cooling purpose) and winter season (for the heating purpose). So, in present study mathematical correlations are developed for the monitored high mass buildings during summer and winter season, separately, according to a procedure described in Givoni and Kruger [**121**].

The daily outdoor minimum, maximum, and average temperatures, as a set, and the indoor temperature parameter of interest were analysed through the patterns of relationship. Based on these indoor and outdoor temperature relationships, outdoor ambient parameters have been observed that were useful for development of mathematical correlations.

The measured data of each season then divided into parts; the first part was used to generate correlations based on the measured data (generation) and the second part was used for validation of the corelations by independently measured data. In the summer season the ‘‘generation" period was based on measured data of June and August and validation period was based on independently measured data of July and September. While for winter season ‘‘generation" period was based on measured data of November and January and validation period was based on independently measured data of December and February. Independent measured indoor data of at least 28 days in each month has been used for development of correlations and validation.

3.3.2 Statistical analysis for developed correlations

The ‘Linest function’ in Microsoft excel© data analysis tool has been used to develop multiple regression relations for prediction of indoor temperatures for the different season. The linear estimation function uses the ‘least squares’ method to determine the straight line that best fits the data, and then returns an array that describes the line. The statistical analysis has been carried out based on R^2 value, ‘F–statistic’ analysis and ‘t–statistic’ analysis to determine the accuracy of the obtained correlations and parameters of concerns. Here, the assessment has done by finding the critical level of F in the F table, taking the level of significance value=0.01. The hypothesis test determines whether each slope coefficient is useful in estimating the dependent variable. The t−value is obtained by

$$\mathbf{t = m_n \div se_n} \qquad (\mathbf{3.1})$$

where, ‘m_n’ is the nth slope coefficient and ‘se_n’ is the estimated standard error of the nth coefficient [**177**]. If the absolute t-value is sufficiently high, it can be concluded that the slope coefficient is useful in estimating the dependent value. The critical value of ‘t’ is found by using the TINV function in Excel spread sheet at a defined α value. Each of the independent variables in developed correlations is tested for the statistical significance by using the above relation.

3.3.3 Field validation of developed mathematical correlations

A partial monitoring has been carried out for other high thermal mass building in existing dwellings of this climatic region to check the robustness and validation of developed correlations. The partial monitoring was conducted for two residential and two office buildings different from monitored buildings. Monitored buildings were having similar thermal mass, construction material, and management of building as used for long-term monitoring buildings. The monitoring has been carried out for 30 days during peak summer and winter season viz. in June 2015 and December 2015 months, using Hobo U-12 loggers.

3.4 Part C: defining high thermal mass boundary on BBCC

3.4.1 Existing building bio-climatic design chart (BBCC)

Givoni [**14**] [**25**] proposed his BBCCs which were devoted to predicting the indoor conditions of the building according to the outdoor prevailing climatic conditions as shown in Figure 1-2. His charts are readily understandable as they were laid out on the standard psychometric chart, which is familiar to building professionals throughout the world. Also, Givoni’s BBCCs incorporate thermal comfort envelopes as suggested by ASHRAE Standard 55 and climatic boundaries or envelopes for which indoor comfort can be achieved.

3.4.2 Method for defining thermal mass boundary on BBCC

The boundary line, which represents the climatic conditions below which high thermal mass buildings with adequate night ventilation cooling can provide internal thermal comfort conditions, was developed by Givoni [**124**]. Givoni [**14**] proposed a boundary defining “the outdoor maximum temperature below which indoor comfort can be maintained in a well-designed building as a function of vapor pressure.” The limit is based on the relationship between indoor maximum temperature and average vapour pressure. Further, He proposed two limits/boundaries for the use of high thermal mass in buildings for developed and developing countries, up to a maximum ambient dry bulb temperature of 36˚C and 38˚C, respectively. He suggested that developing countries inhabitants can be comfortable at higher temperature limits due to acclimatization of their hot environmental conditions.

The main issue behind the construction of bio-climatic design charts for the building is to determine the comfort zone for a particular climate and specific adaptations [**178**] [**179**]. Thus, in previous sections, a study of thermal comfort based on adaptive approach, comfort boundaries on the psychrometric chart are defined for this climatic region at different airspeed ranges.

Adopting the methodology suggested by Givoni [**14**] following steps have been taken to define the climatic boundary of ambient conditions for the use of thermal mass in building through building bio-climatic design chart approach.

- Based on measured outdoor conditions during thermal monitoring of thermal mass buildings, the relationships between the average ambient vapor pressure (mm of Hg) and the average outdoor temperature range during peak summer months was obtained.
- The relation between the maximum indoor temperature of thermal mass buildings and the outdoor temperature range during peak summer period has been investigated experimentally.
- The boundary of ambient conditions for thermal mass is based on the relationships between the maximum indoor temperature and the outdoor temperature range during peak summer days.
- The developed boundary followed a tilted line based on the relation between average outdoor diurnal swing and average vapor pressure. The dependence on vapour pressure (moisture content of the air) recognizes that the diurnal temperature swing decreases as humidity ratio rise.

3.4.3 Simulation study: sensitivity analysis for developed boundary of high thermal mass

The climatic boundaries for the use of high thermal mass in naturally ventilated residential and office buildings through building bio-climatic design approach have been developed for this region. However, these boundaries are ambiguous and depend upon building construction type (thermal mass in building envelope), internal gains, and management of buildings (schedules) as found in previous studies [**20**] [**160**]. So, the developed boundaries are further investigated using simulation techniques for different construction type and at various internal gains for naturally ventilated residential and office buildings.

3.5 Chapter summary

This chapter summarizes the methodology of the present study, divided into three parts. The first part (Part A) of the present study details the methods used for assessment of thermal comfort and adaptations of studied subjects in naturally ventilated buildings. Furthermore, it illustrates the application of results used to define the thermal comfort zones on the standard psychrometric chart for naturally ventilated buildings in composite climate of Jaipur. In the second part (Part B), the methods adopted for thermal monitoring and the prediction of indoor temperature for evaluation of thermal performance of high thermal mass buildings has been described. In Part C, the methodology for the defining climatic applicability of high thermal mass in naturally ventilated buildings using extended comfort boundaries for indoor comfort is discussed.

CHAPTER 4

THERMAL PREFERENCES AND OCCUPANT BEHAVIOR IN NATURALLY VENTILATED BUILDINGS

4.1 Preamble

This chapter presents the assessment of the indoor thermal environmental conditions, thermal comfort, and adaptations in naturally ventilated buildings of Jaipur city defined under composite climatic zones of India. In the present chapter, the results from this adaptive comfort study i.e. comfort expectations, seasonal clothing adaptations and use of various controls; subjects undertook to make their surrounding thermally comfortable are analyzed using the filled survey data collected as per the methodology explained in **Chapter 3**.

4.2 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 thirty-two naturally ventilated buildings. The present thermal comfort study was conducted for five years from April 2011 to July 2016. Occupants completed a total of 2610 questionnaire based comfort surveys in naturally ventilated buildings. The transverse type questionnaire was used as per the study conducted by Dhaka et al. (2013), at the height of 1.1 m from the floor level as per Class-II protocol [**4**] [**5**] of field study. Section-A of the questionnaire (**Appendix 1**) consists of thermal sensation and preference votes for environment conditions such as air temperature, relative humidity, and air velocity on ASHRAE 55−2013 seven-point sensation scale and five-point preference scale, respectively. Section–B of the survey form is used to measure the environmental parameters and the environmental conditions surrounding the study subjects (Figure 4-1).

Figure 4-1 Survey environments during field study

4.2.1 Sample size calculation

The selection of subjects and the quantifiable sample size is important in the field study of thermal comfort. The proportional stratified random sampling method was used for estimation of sufficient samples for thermal comfort study. For the purpose of sample size calculation, the confidence interval is assumed to be 95% (z value=1.9) and margin of error ‘e’ to be 10%. The sample size is calculated using equation (4.1) [**180**]:

$$\boldsymbol{n} = \frac{\boldsymbol{z^2 \times N \times \sigma^2}}{(\boldsymbol{N-1})\boldsymbol{e^2 \times z^2 \times \sigma^2}} \qquad (\mathbf{4.1})$$

Where,

n = required sample

z = value of confidence level C.I. (for 95% it is 1.9)

N = is the total population

e = Standard error of mean (assumed to be 10%)

σ = Population variance

The selection of the sample was based on occupancy of different building types. N is a constant with the value 30,00000 is assumed (total finite population) for Jaipur city as per Indian Census of 2011. Also based on a pilot survey study of 200 occupants in different building types the population variance has been observed is 0.90. The total 347 sample size calculated using equation (4.1). In the present study, a total of 2610 thermal comfort surveys has been obtained in different types of buildings which are sufficient for thermal comfort assessment of different building occupants. Details of these samples are presented in following sections.

4.2.2 Sample size and description

- 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 female samples are less compared to male samples. This is due to the typical workforce of women occupants found in Indian offices and institutional buildings [**174**].
- The subjective thermal responses summarized for one month were not taken on the same day. It is done to assess different climatic conditions prevailing in a particular month.
- 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 study conducted between 9:00 a.m. and 6:00 p.m. local time (IST).
- The subject responses of 19.1% (N=438) collected during the moderate season (March and October), 33.7% (N=952) during the winter season (November to February) and 47.2% (N=1220) samples collected during summer season (April to September).
- Out of the total samples, 77.12% (N=2013) belonged to male respondents and remaining 32.88% (N=597) were collected from female respondents. Figure 4-2 depicts subject's responses for different seasons and months during the field study.

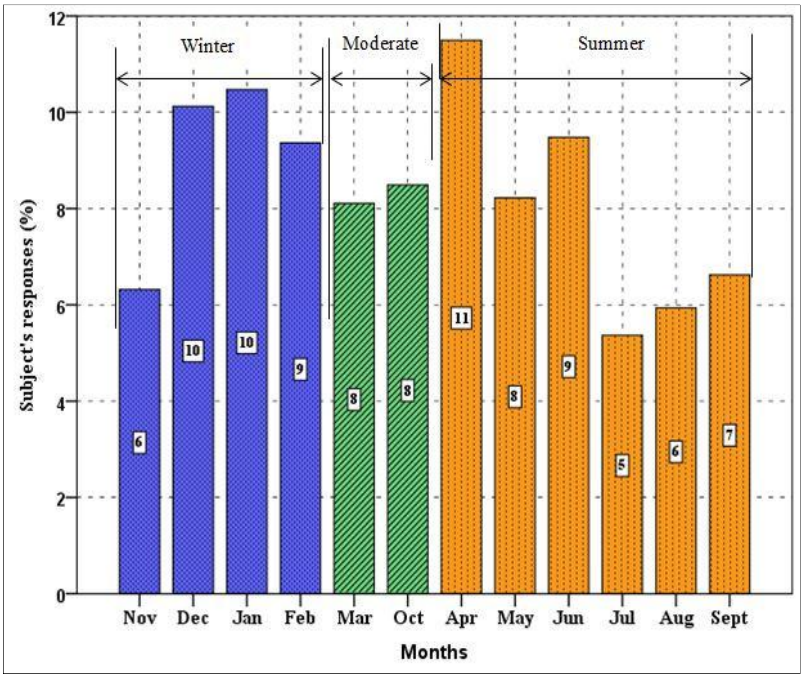


Figure 4-2 Seasonal and monthly variations of subject responses for naturally ventilated buildings

4.2.3 Physical characteristics of subjects

A detailed description of sample size; each subject's physical characteristics such as age, weight, body surface area, clothing insulation, and activity level has been recorded for all seasons, a summary of the same is presented in Table 4.1.

- The average age of male samples is 24 years (N=2013, SD=7.78) while that of female samples is fund to be 21 years (N=597, SD=4.8). Standard Deviation (SD) states the shape of the distribution. Lesser the Standard Deviation (SD) signifies that value of the particular parameter is very close to mean of that parameter.
- The average age, body surface area and weight of female samples were found lower in comparison to male samples. Body surface area was calculated using equation as given by DuBois Body Surface Area [**181**] and mentioned in the ASHRAE Handbook of Fundamental [**42**].
- For clothing insulation and metabolic rates, we used the standard checklists provided in ASHRAE Standard 55-2013. Clo-values for Indian women clothing including the cotton salwar–kameez, sari etc. that are not available in ASHRAE Standard 55- 2013 and ISO 7730 were taken from other India specific studies [**70**] [**112**]. Personal environment variables such as activity level (metabolic rate, 1 met = 58.2 W/m^2) and

clothing insulation (1 clo=0.155 m^2K/W) were recorded during the interaction with the subjects.

- Clothing insulation for female samples was found a bit higher and varied slightly more than male samples. Maximum clothing insulation was found 1.22 clo during winter season while minimum clothing insulation about 0.15 clo was found during peak summer months (April, May, June). The clothing assembles considered in the present study was excluding the insulation effect of the chair.
- The mean activity of the subjects was observed to be nearly sedentary activity, i.e. 1.06 met, and it shows that the subjects were mostly seated or doing light office work.

Table 4.1 Summary of subject's details

Variable	**Seasons**															
	Summer				**Moderate**				**Winter**				**All seasons**			
	Male		**Female**		**Male**		**Female**		**Male**		**Female**		**Male**		**Female**	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Sample size	**882**		**312**		**270**		**119**		**861**		**166**		**2013**		**597**	
Age	27	10.4	22	6.8	22	6.2	21	3.6	24	5.1	20	2.1	25	7.8	21	4.8
Weight (kg)	65.9	11.30	52.1	7.16	64.4	10.02	51.9	7.09	64.0	11.63	50.7	7.18	63.8	9.83	51.4	7.12
BSA	1.75	0.16	1.53	0.13	1.73	0.18	1.51	0.11	1.76	0.18	1.49	0.14	1.75	0.17	1.50	0.13
$I_{cl,tot}$(clo)	0.31	0.08	0.42	0.09	0.34	0.07	0.43	0.08	0.67	0.22	0.65	0.20	0.41	0.19	0.46	0.19
Activity (Met)	1.08	0.15	1.1	0.11	1.07	0.17	1.03	0.11	1.04	0.10	1.01	0.07	1.06	0.14	1.06	0.11

M: Mean of sample; SD: standard deviation of sample size; $I_{cl,tot}$: Total clothing insulation; BSA: Body surface area.

4.2.4 Surveyed building characteristics and envelope specifications

A present field study of thermal comfort is carried out in naturally ventilated buildings of different usages, such as hotels, office and institutional buildings in Jaipur city. Operation and maintenance cost of naturally ventilated buildings are lower as compared to the air-conditioned buildings. Occupant encounters variable environmental conditions in naturally ventilated buildings throughout the day and different seasons. In a naturally ventilated building, during discomfort, inhabitants use all sorts of adaptive opportunities and controls such as operable windows, doors, blinds, curtains, fans and fan regulator for adjustment of air velocity, and so on to make themselves comfortable to the changing thermal environmental conditions [**97**]. Buildings selected for the study are both from the government sector and private sector as described in Table 3.2.

Photographs of different buildings surveyed during the survey are appended in **Appendix 3** along with the conventional material used in buildings for composite climate of India. The studied buildings are 5−40 years old and constructed of conventional construction materials. The conventional wall is built using brick/stone of 0.23m−0.30m and gypsum plaster of 0.012m−0.015m thickness on both sides. This type of conventional construction is common in almost all government buildings which are more than 20 years old. The ones built in last five years have large glazing area and some insulation in walls to compensate for conventional material budget and provide more comfort inside the buildings. Window assemblies had a single clear glass of 3mm thickness, and very few are doubled glazed windows.

4.2.5 Environmental controls in surveyed buildings

Adaptive thermal comfort approach is based on the fundamental assumption that "if a change produces discomfort; people react in ways which tend to restore their comfort" [**10**]. Rijal et al. [**64**] [**182**] explained that availability and appropriate use of adaptive controls are the key to the better performance of the building and improve the state of thermal comfort. Uses of these adaptive controls are also affected by seasonal and climatic variation in indoor conditions. So people, especially in naturally ventilated buildings, uses all sorts of adaptive opportunities, i.e. changing clothing, opening windows, use of ceiling fan, etc. to feel comfortable with the change of thermal environment surrounding them. It was observed during the study that most of the survey spaces were provided operable windows and fans to overcome the discomfort. Some of the buildings also offered controls like blinds/louvers, adjustment of ventilators and use of evaporative coolers during harsh summer conditions. Few buildings used steel screen over windows to prevent entry of insects/mosquitos from outside, especially during rainy season. Figure 4-3 shows the adaptive controls and survey environment from the study buildings.

Figure 4-3 Available occupant's environmental controls

4.3 Assessment of indoor and outdoor thermal parameters

4.3.1 Outdoor environment conditions

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. Monthly variations of outdoor dry bulb temperature (15.4˚C–34˚C) and relative humidity (18%–78%) in composite climate of Jaipur are illustrated in Figure 4-4. This, significant variation in outdoor dry bulb temperature affected indoor temperature and thereby occupant comfort temperatures.

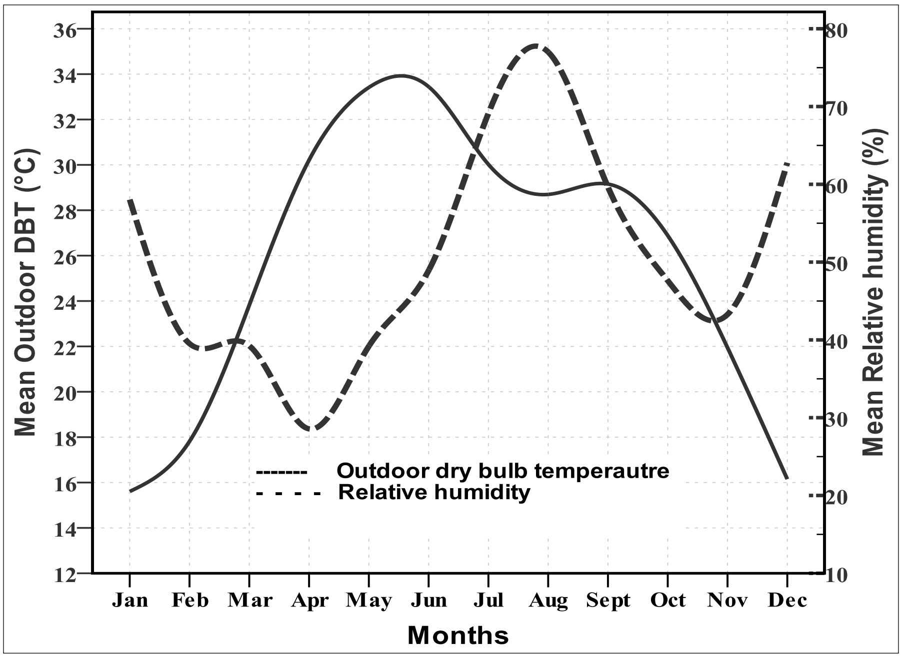


Figure 4-4 Monthly variations in outdoor temperature and humidity of Jaipur city

4.3.2 Indoor environment conditions

Room air temperature was found varied between 14.4˚C−39.1˚C, and relative humidity was recorded from 8%−96%. Figure 4-5 depicts the variation in indoor and outdoor environmental parameters observed during the field study for all seasons. The naturally ventilated buildings experienced a significant variation 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. Table 4.2 demonstrates summary of measured indoor and outdoor thermal environment variables on a seasonal basis.

Subjects in naturally ventilated buildings for this climatic region are found responsive to various adaptive actions, viz. opening of window and doors, using fans to maintain comfort, and this phenomenon is quite pronounced at the elevated temperatures and relative humidity in the summer season. It was observed that mean room air velocity increased with the increase in mean room air temperature from winter season to summer season of the study. Correspondingly, the mean air velocity was observed to be higher during the summer (Mean V_i=0.62 m/s, SD=0.39) than during the moderate season (Mean V_i=0.57 m/s, SD=0.37) and winter season (Mean V_i=0.27 m/s, SD=0.19), respectively. The higher indoor velocity in naturally ventilated buildings especially in summer and the moderate season was found due to the use of ceiling fan.

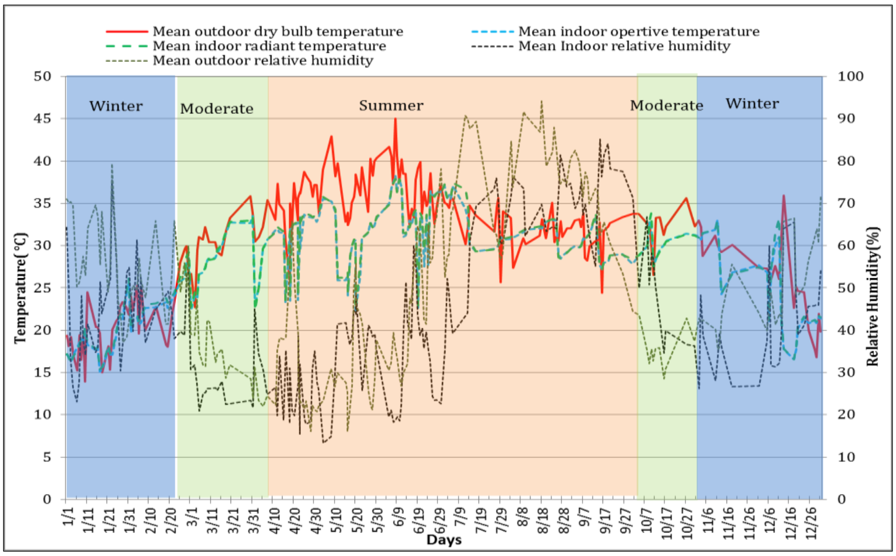


Figure 4-5 Details of daily mean outdoor and indoor environmental parameters observed during the field study for all seasons

Table 4.2 Descriptive data of indoor and outdoor environmental parameters observed during study

Parameters	**Seasons**							
	Summer		**Moderate**		**Winter**		**All seasons**	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Sample size	1220		438		952		2610	
T_{mm}	30.2	3.44	25.6	3.02	17.5	2.87	25.0	6.66
T_o	34.0	3.39	31.3	2.77	22.8	4.38	29.4	6.56
T_{max}	44.2	3.92	37.6	2.86	33.6	2.25	44.2	3.20
T_{min}	19.3	2.96	13.8	2.15	5.5	2.55	5.5	2.62
T_a	31.7	2.87	29.1	2.97	21.9	3.62	27.7	5.49
T_{op}	31.8	2.86	29.2	2.89	22.1	3.60	27.8	5.42
T_g	31.9	2.87	29.3	2.84	22.4	3.60	28.0	5.37
RH	46	20.1	32	12.2	43	13.8	43	17.8
Va	0.62	0.39	0.57	0.37	0.27	0.19	0.60	0.43
$I_{cl,tot}$	0.34	0.15	0.34	0.06	0.67	0.14	0.42	0.15
Met	1.08	0.13	1.06	0.14	1.04	0.10	1.06	0.12

T_{mm}: Outdoor monthly mean temperature (˚C); T_o: Outdoor air temperature (˚C); T_a: Indoor air temperature (˚C); T_{op}: Indoor operative temperature; T_g: Indoor globe temperature (˚C); RH: Indoor relative humidity; V_i: Indoor air velocity (m/s); $I_{cl,tot}$:Total clothing insulation(clo); Met: Metabolic activities.

4.4 Subjective thermal variables: evaluation of sensation and preference

During the field study of thermal comfort, a questionnaire was administered to building occupants to record sensations and preferences for thermal environment variables and simultaneously, physical measurements of indoor environment variables were recorded considering Class-II protocol of field measurement [**4**]. In this section, a detailed analysis has been carried out for sensation and preferences for environmental variables i.e. room air temperature, relative humidity and air velocity.

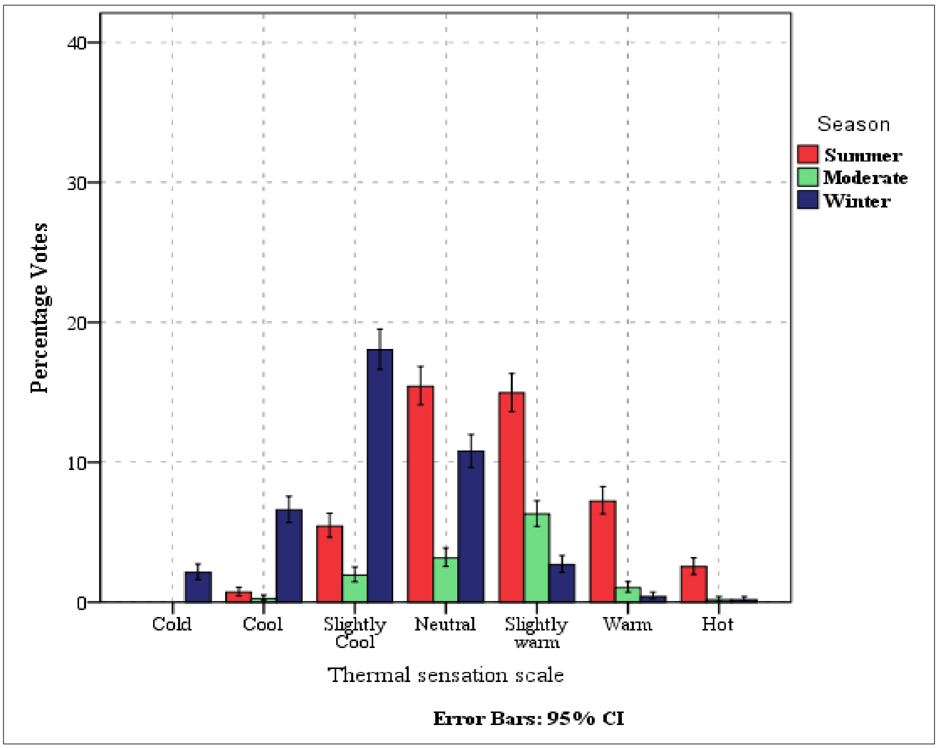
4.4.1 Thermal sensation (TS) and preference (TP) for temperature

In the survey questionnaire, a thermal sensation of subjects was accessed using the question "How do you feel the temperature right now?" The subject voted on ASHRAE seven-point thermal sensation scale which has the range from hot (+3) to cold (−3). Figure 4-6 (a) and (b) shows the distribution of subject responses collected for thermal sensation and preferences during summer, moderate and winter season, respectively at 95% confidence interval. Following observations were made.

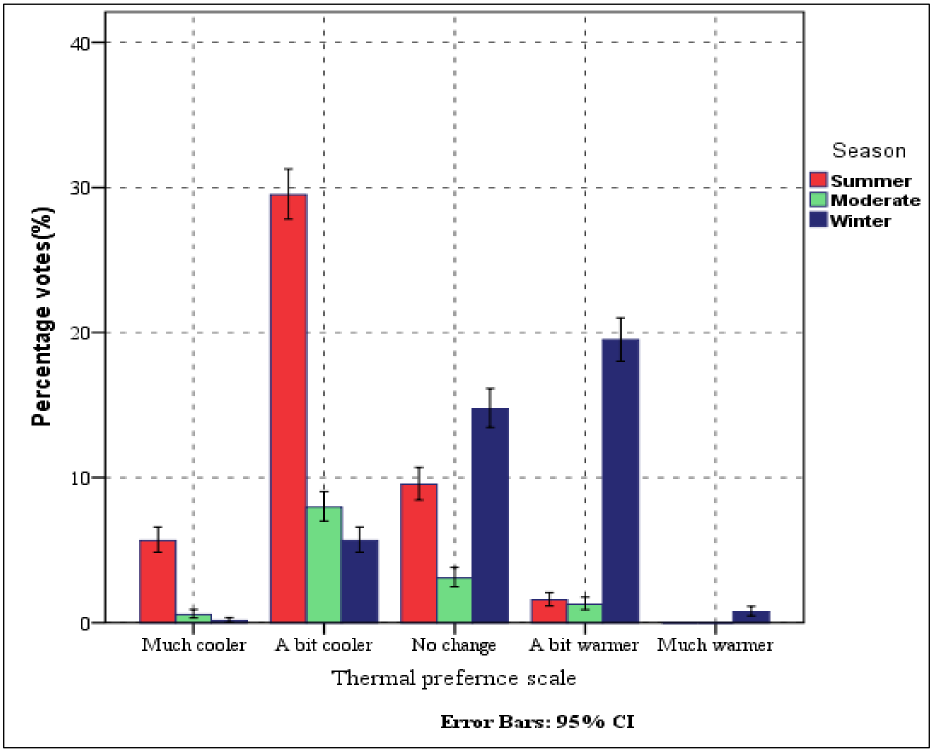
- About 79%, 92%, and 70% of the subject's responses were found in comfort band (±1 sensations) in summer, moderate and winter season, respectively. Occupants feel hot and cold discomfort during peak summer and winter months due to an unfavourable indoor condition in naturally ventilated buildings.

- A total of 82% of the subjects felt thermally comfortable (including ±1 sensations) at prevailing indoor conditions, and 18% subjects voted outside these comfort conditions on an annual basis. Also, the results of the present study corroborate to the findings of other adaptive comfort studies conducted in naturally ventilated spaces for similar climatic conditions and cultural backgrounds.
- The mean value of sensation votes for all seasons was found to vary slightly higher than neutral in naturally ventilated buildings (Mean Thermal Sensation Vote, TSV= +0.16, SD=1.24). These results show that subjects are more tolerant and adaptive towards higher temperature fluctuations encountered inside naturally ventilated buildings.
- During the summer season, the subject's mean thermal sensation was greater 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).
- Figure 4-7 shows the distribution of thermal sensation votes across different indoor temperature conditions inside the surveyed buildings through boxplot. It can be seen that the occupants voted 'neutral' for varied indoor temperature conditions and voted under 'cold' and 'hot' sensations scale at very low and very high indoor temperature conditions.

Table 4.3 depicts the statistical analysis of sensation and preference votes of building occupants for indoor variables i.e. temperature, relative humidity and air velocity on the seasonal basis for naturally ventilated buildings. From the Table 4.3 it can be seen that over an annual cycle, average thermal sensations varied between slightly warm to slightly cool. These results show that occupants are satisfied with their thermal environment and feel comfortable under varied fluctuations of indoor conditions for different seasons in this region.



(a)



(b)

Figure 4-6 Distribution of subject responses collected for (a) thermal sensation (TSV) and (b) thermal preference (TP) of temperature at 95% confidence interval

Table 4.3 Descriptive data of subjective thermal sensation and preference variable

Variables	Seasons							
	Summer		Moderate		Winter		All seasons	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Sample size	**1220**		**438**		**952**		**2610**	
TSV	0.67	0.92	0.56	0.92	-0.75	0.76	0.16	1.24
TP	-0.84	0.66	-0.51	0.78	0.37	0.80	-0.22	0.92
HSV	+0.21	1.26	-0.23	0.87	-0.35	0.82	0.13	1.09
HP	-0.17	1.01	0.00	0.68	+0.10	0.66	0.00	0.85
AVS	-0.35	1.09	-0.25	1.01	-0.10	0.62	-0.10	0.97
AVP	0.67	0.72	0.61	0.71	0.20	0.65	0.49	0.72
PMV	1.73	1.48	0.22	1.40	-1.90	1.18	0.14	2.15
PPD (%)	56.03	35.48	35.65	30.40	66.48	33.98	56.07	35.59

TS: Thermal sensation votes; TP: Thermal preferences; HSV: Humidity sensation vote; HP: Humidity preference; AVS: Air velocity sensation vote; AVP: Air velocity preference; PMV: Predicated mean vote; PPD: Predicted percentage dissatisfied

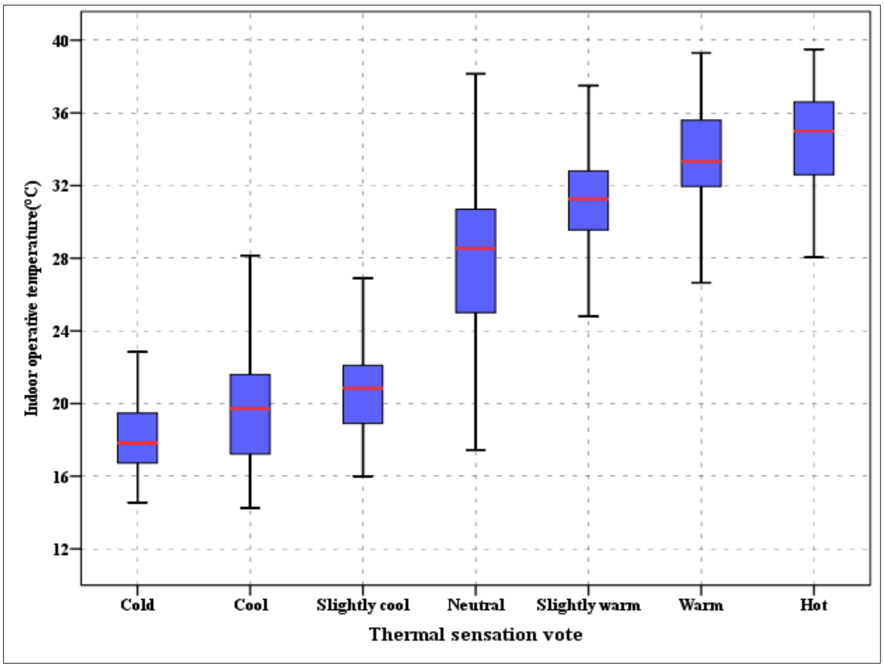


Figure 4-7 Distribution of thermal sensation votes for indoor operative temperature through boxplots

In response to thermal sensations recorded, the corresponding thermal preferences were captured with the question “How would you prefer to feel?” It can be observed from the Table 4.3 that the preference for a cooler environment dominates across the seasons, with a mean value of −0.22 (SD= 0.92). Using the scale described above, the mean preference for temperature change was −0.84 (SD=0.66) in summer, −0.51 (SD=0.78) in moderate seasons and

+0.37(SD=0.80) in winter. This pattern is found to be matching with the results reported by Fountain et al. [**183**] for hot climates. Figure 4-8 shows a cross-tabulated summary of thermal preference votes and thermal sensation votes. It can be seen from the figure that 51% subjects found the temperature neutral at the time of voting and want no change in temperature.

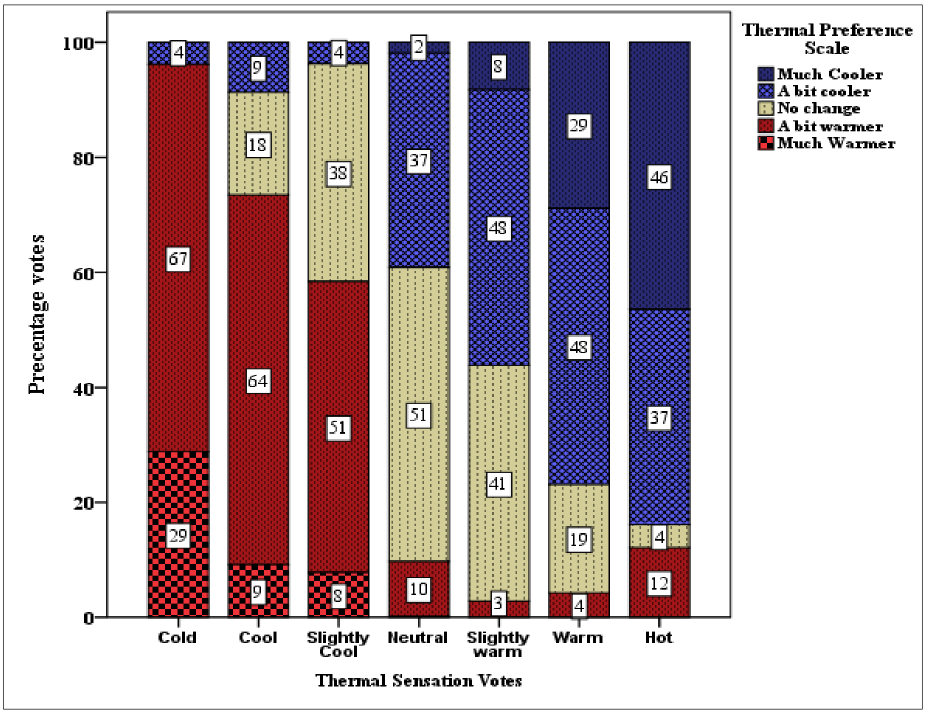


Figure 4-8 Cross-tabulated summary of thermal preference and thermal sensation votes

4.4.2 Humidity sensation (HSV) and preference (HP)

Humidity sensation scale in ASHRAE seven-point scale varies as very dry ‘−3’, moderately dry ‘−2’, slightly dry ‘−1’, acceptable ‘0’, slightly humid ‘1’, moderately humid ‘2’ and very humid ‘3’. Indoor relative humidity during the study was found varying between 8%−96%. The sensation for humidity and preferences were asked on ASHRAE seven point and five point scale, respectively. Following observation were made based on data analysis.

- Mean humidity sensation (HSV) for all data sets in all naturally ventilated buildings was +0.13 at a mean 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 as shown in Table 4.3. Subsequently mean humidity of 46.9%, 32.5%, and 43.2% were observed for summer, moderate, and winter season, respectively.

- Further analysis shows that more than 52% of subjects found humidity between 32%-38% acceptable at prevailing indoor humidity conditions.
- Figure 4-9 demonstrates the distribution of humidity sensation votes across different indoor humidity conditions inside the surveyed buildings through boxplot. In the present study, the occupants accepted the prevailing humidity conditions ranging from 10%−75%. At lower or higher indoor humidity conditions, residents voted towards dry or humid sensation scale and found uncomfortable.

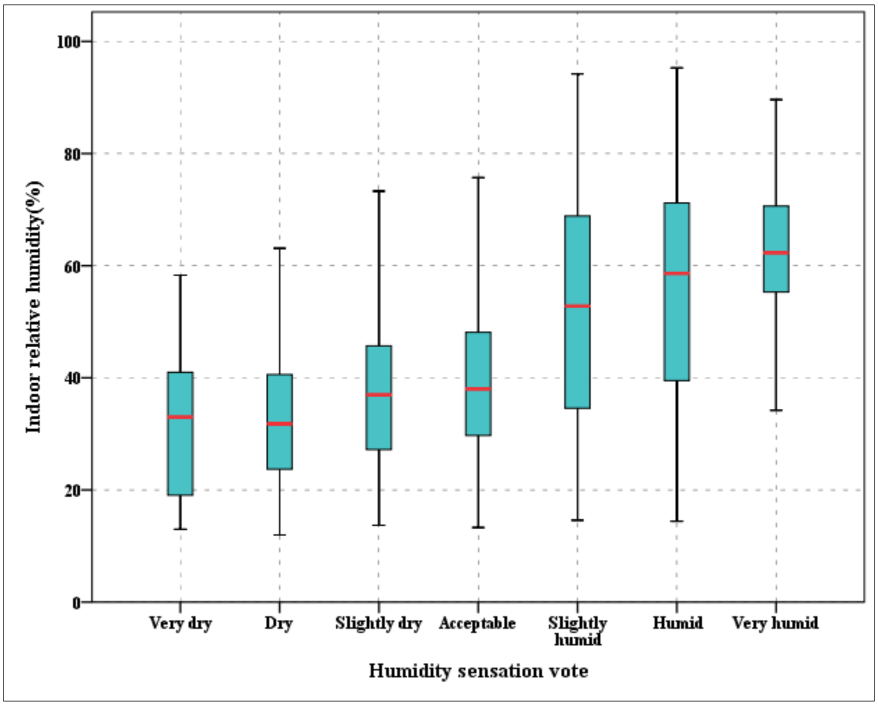


Figure 4-9 Distribution of humidity sensation votes for indoor operative temperature through boxplots

Figure 4-10 show the cross-tabulated summary for humidity sensation votes and humidity preferences votes. A maximum of 73% subjects accept the prevailing humidity conditions during the study and still want no change in humidity. Very few subjects accept and prefer to stay in slightly dry humidity conditions (25%) and slightly humid conditions (37%). The reason is acclimatization of subjects for such a wide variation in humidity conditions, prevailing for this region.

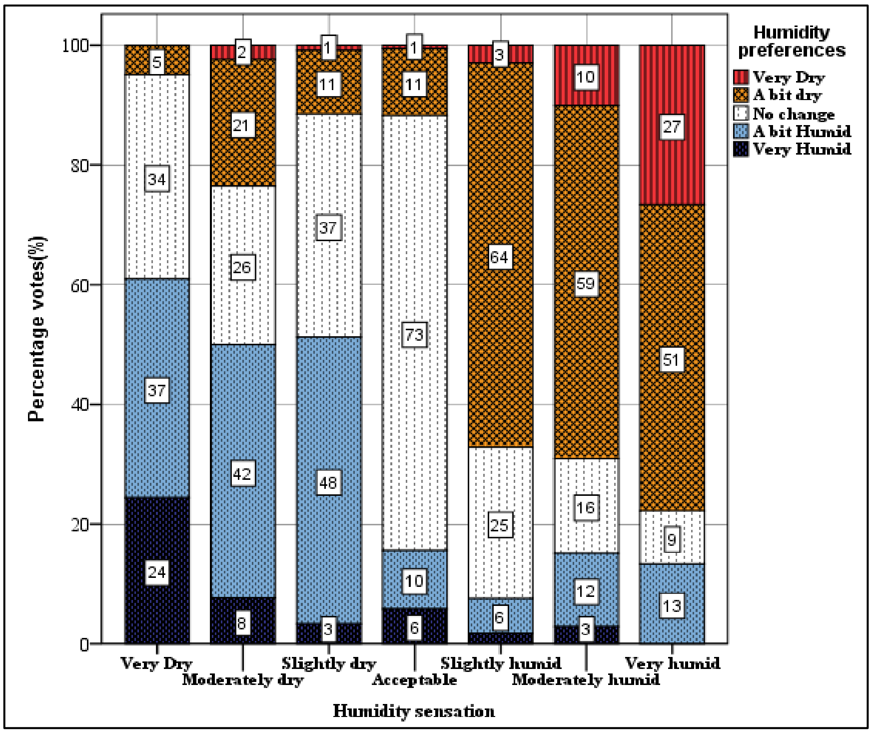


Figure 4-10 Cross-tabulated overview of humidity preference (HP) and humidity sensation (HSV) votes

4.4.3 Air velocity sensation (AVS) and preference (AVP)

During the study, subjects were asked to rate the sensation and preferences for prevailing air velocity around them on ASHRAE's seven-point and five-point scale, respectively as shown in Table 4.3. In the surveys, mean air velocity was found higher as the season got warmer from winter to summer. It was observed as 0.27 m/s during winter, 0.57 m/s during moderate and 0.62 m/s during the summer season. The indoor air velocity was found highest during summer and moderate season due to use of ceiling fan in almost all naturally ventilated buildings. Figure 4-11 represents the distribution of air velocity sensation votes compared to measured air velocities prevailing inside the surveyed buildings through boxplot. The study shows a significant variation in air velocity measurements across the sensation votes. The corresponding occupant mean sensation of air velocity 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. In addition, as temperatures rise from winter to summer, the preference for more air velocity increases. This reflects typical high air velocity preference of Indian subjects living in composite climatic conditions. Figure 4-12 that most of the subjects preferred to have higher air velocity than prevailing indoor air velocity at elevated temperatures. This trend can also be visualized in a mean air velocity preference vote shown in Table 4.3. The average air velocity preference votes were 0.67 in summer, 0.61 in moderate seasons and 0.20 in winter, respectively. This corroborates with other studies conducted in hot and warm countries, reporting that inhabitants in such countries prefer higher air velocity to make themselves comfortable at higher temperatures [**65**] [**44**] [**53**] [**81**] [**174**] [**184**]. A total of 64% subjects preferred to stay at the prevailing air velocity conditions.

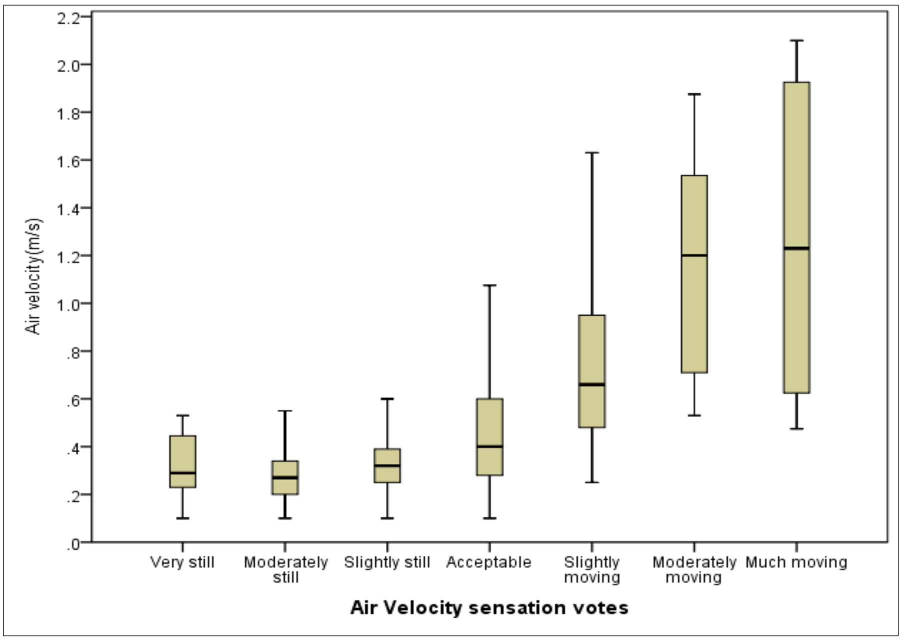


Figure 4-11 Distribution of air velocity sensation votes over indoor air velocity through boxplots

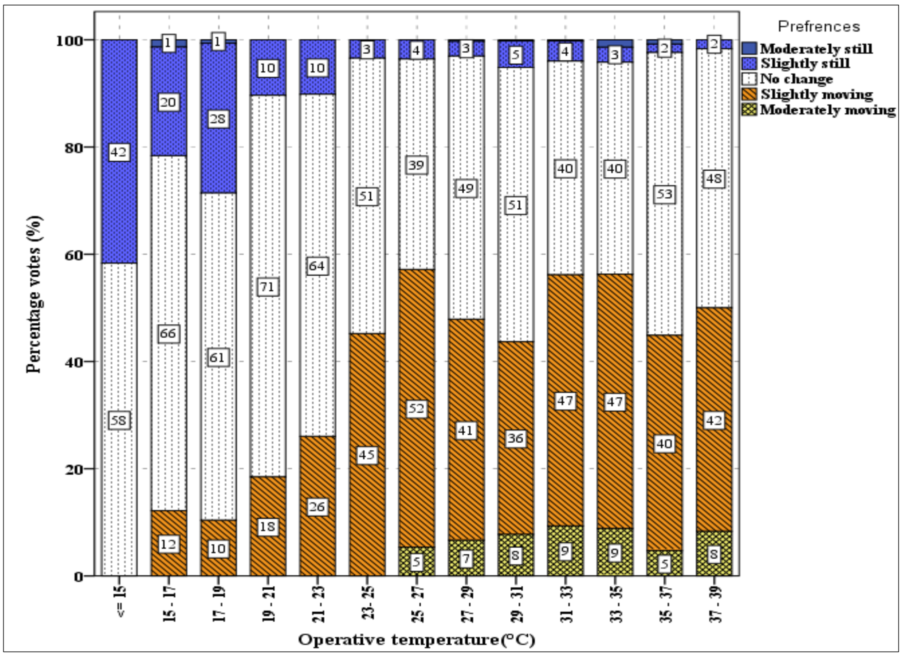
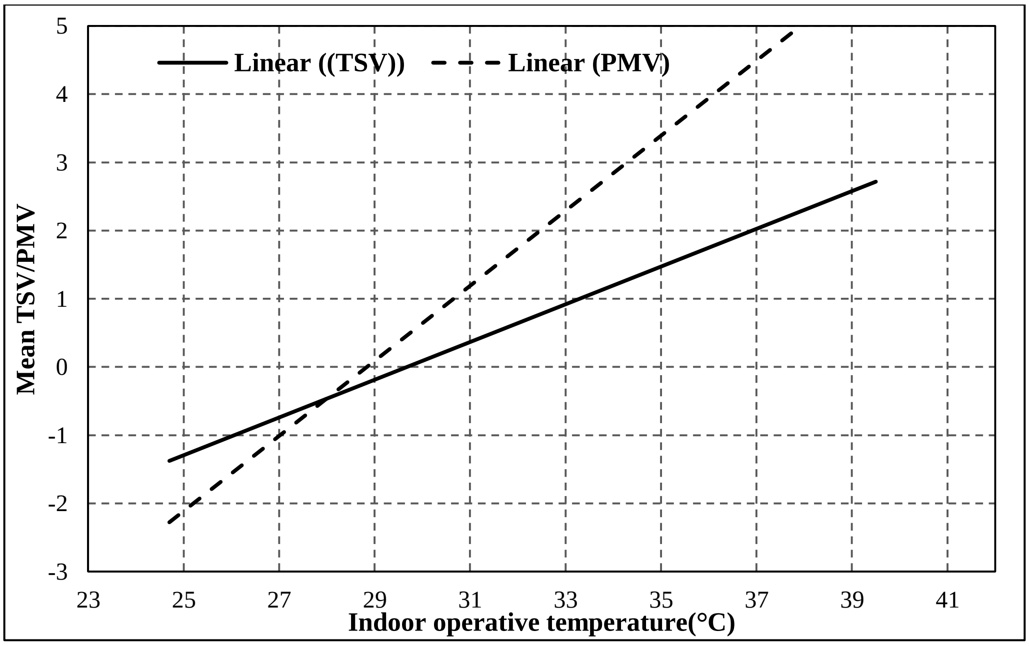


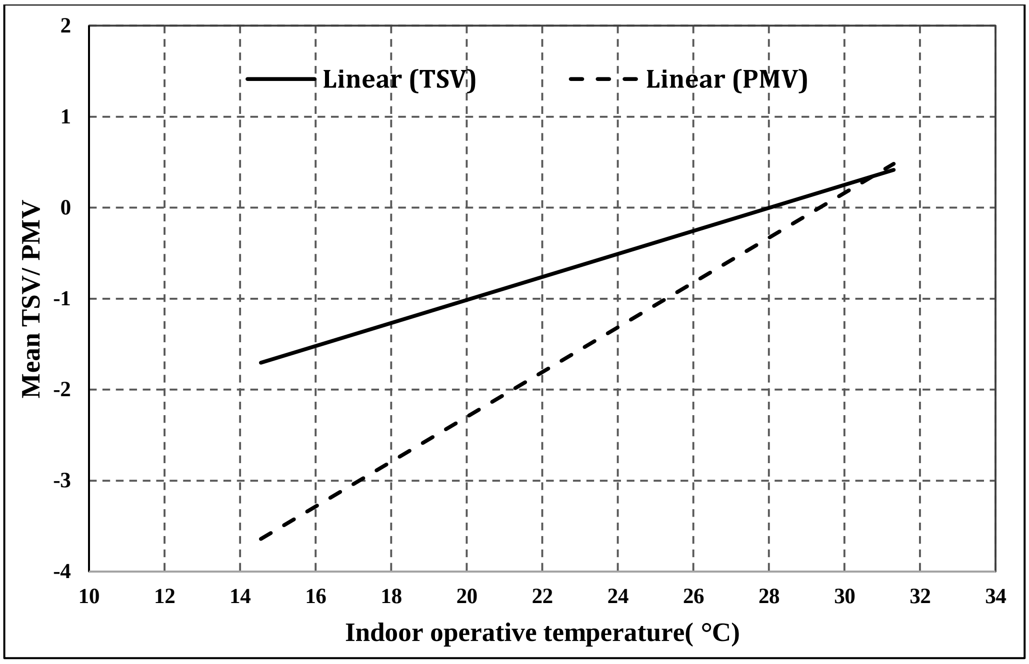
Figure 4-12 Distribution of the preference votes across air velocity over operative temperature (binned to 2 ˚C)

4.4.4 Evaluated and actual thermal sensation response: PMV and TSV

The study calculated the thermal comfort indices such as PMV and PPD using the procedure defined in standards ISO 7730 and ASHRAE 55-2013 and then compared the PMV index with the thermal sensation votes. PMV values at +3 and -3 represents 100% thermal dissatisfaction. Fanger's heat balance model of thermal comfort prescribed the comfort limit within PMV bandwidth of ±0.5. Figure 4-13 shows us that there is a discrepancy between PMV with TSV across different seasons. Mean PMV was found to be 0.14 and the corresponding PPD was 56.17%. In summer season, PMV was found to be overestimating the actual thermal sensation votes (TSV) while in winter season, it was found underestimating the actual mean votes. The answer to deviation of PMV from AMV is documented in various literature studies for thermal comfort [**11**] [**37**]. The main reasons are estimation techniques of metabolic rate (ISO 8996), clothing insulation (ISO 9920) and environmental parameters used in its empirical relations.



(a)



(b)

Figure 4-13 Comparison between thermal sensation and PMV index for different seasons: (a) summer, and (b) winter

4.5 Calculation of comfort temperature

Comfort temperature is defined as the temperature at which a person feels thermally comfortable at fixed variables like environmental parameters, clothing and activity level [**4**] [**80**]. The comfort temperature can be defined as 'the indoor air temperature' at which, a normal subject will vote 'neutral' on the thermal sensation scale (TSV). However, in the case of naturally ventilated buildings, it is always advisable to apply the concept of range of comfort temperatures. Here the term range of comfort temperature is used because it involves the physiological, psychological and behavioral adaptations of the occupants. Two methods are commonly used in thermal comfort field study to determine the comfort temperature.

1. Linear regression method
2. Griffiths' method

Further sections examine the thermal neutrality using linear regression technique and using Griffiths' method.

4.5.1 Linear regression method

Linear regression of thermal sensation and indoor air temperature is one of the methods for evaluating the neutral temperature in field studies. Using the regression method, the neutral temperature is determined by setting the thermal sensation to neutral (zero). The thermal responses of subjects in the form of an acceptable comfort temperature range, comfort temperature, and thermal sensitivity can be deduced from a linear regression model of thermal sensation votes against indoor air temperature. Linear regression analysis was performed between subject’s thermal sensation votes and corresponding room operative temperature as depicted in Figure 4-14. Linear regression analysis was also performed between thermal sensation and globe and air temperature to determine the neutral temperature as described in Table 4.4.

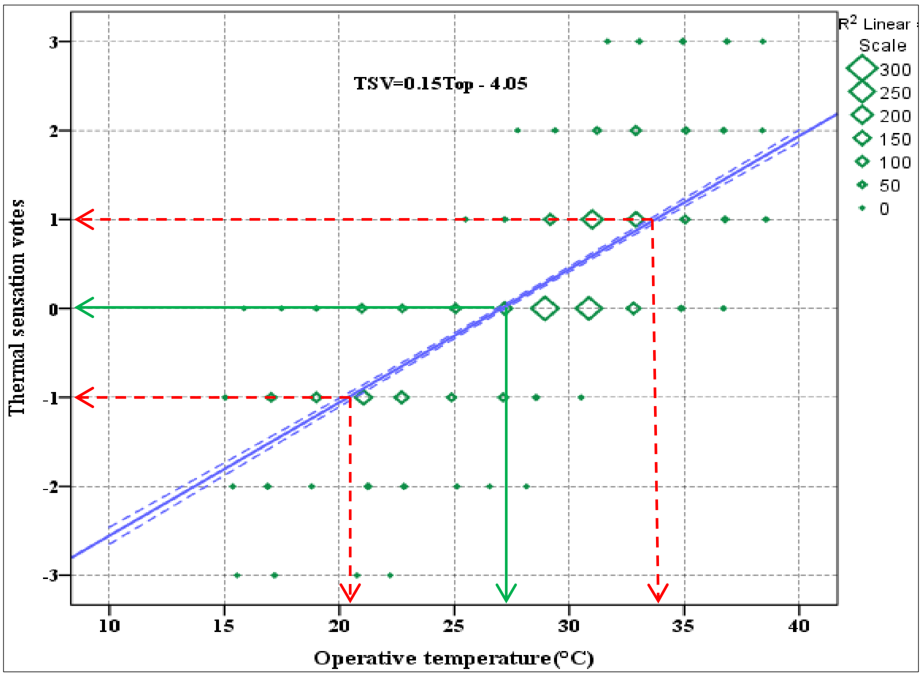


Figure 4-14 Linear regression of thermal sensation with indoor operative temperature (lines with 95 % CI are also shown)

Linear regression between subject's thermal sensation votes and corresponding room operative temperatures was performed in two ways. First, collectively for all the data sets over the year, and then separately for each of the three seasons, as shown in Table 4.4. The relationship between thermal sensation and room operative temperature is shown by regression equation (4.2).

- For combined year round analysis, a neutral temperature of 27.2˚C has been found for all data set combined. A comfort band of 21.0˚C–33.1˚C (i.e. corresponding to the TSV of –1 to +1) is obtained through the results of regression analysis.

- The slope of the equation (4.2) is $0.15^{\circ}C^{-1}$ indicating that for every 6.7˚C change in indoor temperature, thermal sensation vote would have a unit change. Lower slope is also indicative of higher adaptation of the subjects to the indoor conditions encountered.
- A similar slope of $0.19^{\circ}C^{-1}$ and a comfort band of 13˚C was obtained by Nicol and Roaf [**71**] for a study conducted in Pakistan, which has quite similar climatic and cultural background. Indraganti [**51**] [**174**] recorded $0.31^{\circ}C^{-1}$ in the residential environments in Hyderabad for their comfort studies.
- Interestingly, recent study under IMAC (India Model for Adaptive Comfort) project has also revealed a regression slope of $0.13^{\circ}C^{-1}$ for naturally ventilated office buildings in India and found much closer to the regression coefficient of the present study [**81**].

$$\mathbf{TSV = 0.15 \times T_{op} - 4.05} \qquad (\mathbf{R^2 = 0.56, S.E. = 0.001, p < 0.001}) \qquad (\mathbf{4.2})$$

where TSV is Thermal Sensation Vote, T_{op} is indoor operative temperature (˚C), S.E.is standard error, and p is significance level for linear regression method.

Table 4.4 Linear regression models, Griffiths' comfort temperature (GC=$0.5^{\circ}C^{-1}$), temperature when voting neutral (T_n)

Case	**N**	**Regression Models**	**R^2**	**T_n (˚C)**	**Mean T_n**	**N_n**	**Mean T_c (˚C) (GC=0.5 $^{\circ}C^{1}$)**
All Season data	**2610**	TSV=0.149 T_g-4.06	0.55	**27.2**	**28.1**	**1040**	**27.9**
		TSV=0.148T_a-3.98	0.56	26.9	28.1		
		TSV=0.149T_{op}-4.05	0.56	27.2	28.4		
Summer season	**1220**	TSV=0.182T_g-4.99	0.31	**27.4**	**30.5**	**504**	**30.6**
		TSV=0.181T_a-4.98	0.31	27.5	30.4		
		TSV=0.180T_{op}-5.04	0.31	28.0	30.5		
Moderate season	**438**	TSV=0.177T_g - 5.04	0.42	**28.5**	**29.5**	**202**	**29.5**
		TSV=0.184T_a-5.19	0.43	28.2	29.1		
		TSV=0.186T_{op}-5.28	0.44	28.4	29.3		
Winter season	**952**	TSV=0.101T_g-2.99	0.28	**29.6**	**24.6**	**334**	**24.0**
		TSV=0.113T_a-3.18	0.29	28.1	24.2		
		TSV=0.109T_{op}-3.14	0.29	28.8	24.9		

N=Sample size; TSV= Thermal sensation vote; T_g= Indoor globe temperature (˚C); T_a=Indoor air temperature (˚C); T_{op}=Indoor operative temperature (˚C); T_n=Regression neutral temperature; T_n= Indoor temperature when voting neutral (˚C); N_n= Sample size (voting 'neutral' on the sensation scale); T_c= Griffiths' comfort temperature (˚C) with 0.50 as coefficient.

[a] The regression models are all significant at ($p<0.001$).

4.5.2 Griffiths' method

Some researchers have pointed out issues with applying the regression method in the presence of adaptive behavior. It has been stated that the presence of behavioral adaptation in the data tends to artificially lower the regression coefficients and therefore the estimates of the comfort temperature [**13**] [**63**] [**88**] [**87**] [**37**]. Also, the mean comfort vote which is much different from the neutrality (Table 4.4), may also adversely affect the predictive power of the resultant regression equation. Hence, survey results of this study have again been used to re-estimate the comfort temperature using Griffiths' method as given below through equation (4.3).

$$\mathbf{T_C = T_g + \frac{0 - TSV}{G}} \tag{4.3}$$

Where T_c is the comfort temperature (˚C), T_g is the indoor globe temperature (˚C), TSV is the thermal sensation vote, and G is the Griffith constant (0.50˚C^{-1})

In applying the Griffiths' method, Nicol and Humphreys et al. [**13**] [**173**] used the constants 0.25, 0.33 and 0.50 for a seven-point thermal sensation scale. Upon applying each of the three coefficients, it has been observed that there is hardly any change in the mean comfort temperature with each coefficient (Table 4.5). Analysis of mean indoor globe temperature for neutral votes on the sensation scale has shown close agreement with comfort temperature while using the Griffiths' method with 0.50˚C^{-1} as Griffith's coefficient. Therefore, Griffiths' comfort temperature, T_c, obtained using 0.50˚C^{-1} (with least standard deviation) is used in the subsequent analysis. The comfort temperature calculated using a coefficient of 0.50 is indicative of a 2˚C rise for unit perturbation in sensation vote, which is smaller as compared to linear regression approach applied in this study as well as other similar studies. The mean indoor comfort temperature by Griffiths' method is 27.9˚C in naturally ventilated buildings. The finding is in close agreement with the neutral operative temperature observed in Singapore: 28.5˚C [**78**], and Hyderabad: 28.0˚C [**80**] [**174**] in natural ventilated buildings.

Table 4.5 Comfort temperature predicted by Griffiths' method

Mode	GC (°C^{-1})	T_C (°C) (Indoor air temperature)			T_C (°C) (Globe temperature)		
		N	Mean	S.D.	N	Mean	S.D.
Naturally ventilated	0.25	2610	27.2	3.8	2610	27.6	3.6
	0.33	2610	27.3	3.5	2610	27.7	3.4
	0.50	2610	27.4	3.2	2610	27.9	3.1
	Voting Neutral	1040	28.1	1.6	1040	28.1	1.5

N= Sample size; GC= Griffiths' constant (°C^{-1}); T_c= Griffith comfort temperature (°C); S.D. =Standard deviation

Figure 4-15 shows the frequency distribution of Griffiths' comfort temperature with 0.50 as the coefficient for the naturally ventilated buildings in composite climate of Jaipur. It shows a majority of people voting around the mean Griffiths' temperature.

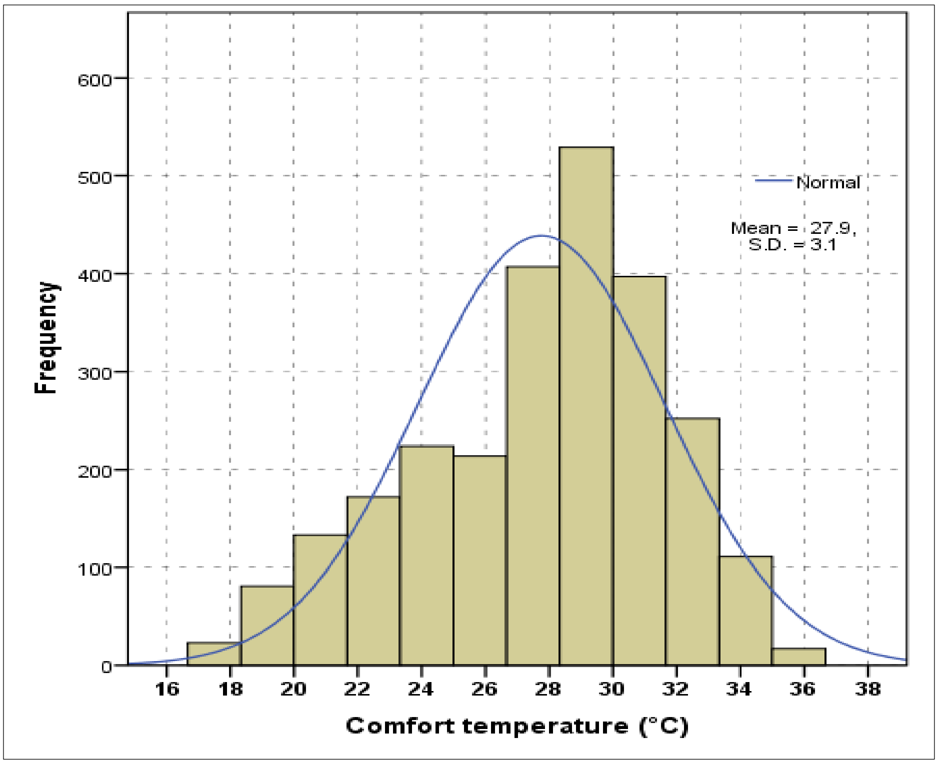


Figure 4-15 Frequency distribution of comfort temperature obtained using the Griffiths' coefficient of 0.50(GC=0.5˚C^{-1})

4.5.3 Comfort temperature: seasonal variation

The comfort temperature is known to be varying across the seasons [**11**]. The comfort temperature variations were observed across the season as well as within one season as shown in Figure 4-16. The mean comfort temperature calculated using Griffiths' method is 30.6˚C in summer, 29.5˚C in moderate and

24˚C in winter, respectively in naturally ventilated buildings. Thus, the seasonal variation of mean comfort temperature is about 6.6˚C. The results show that comfort temperature is related to the change in outdoor air temperature, which in composite climate of Jaipur is very high (~45˚C) during summer to appreciably low in winter (~4˚C).

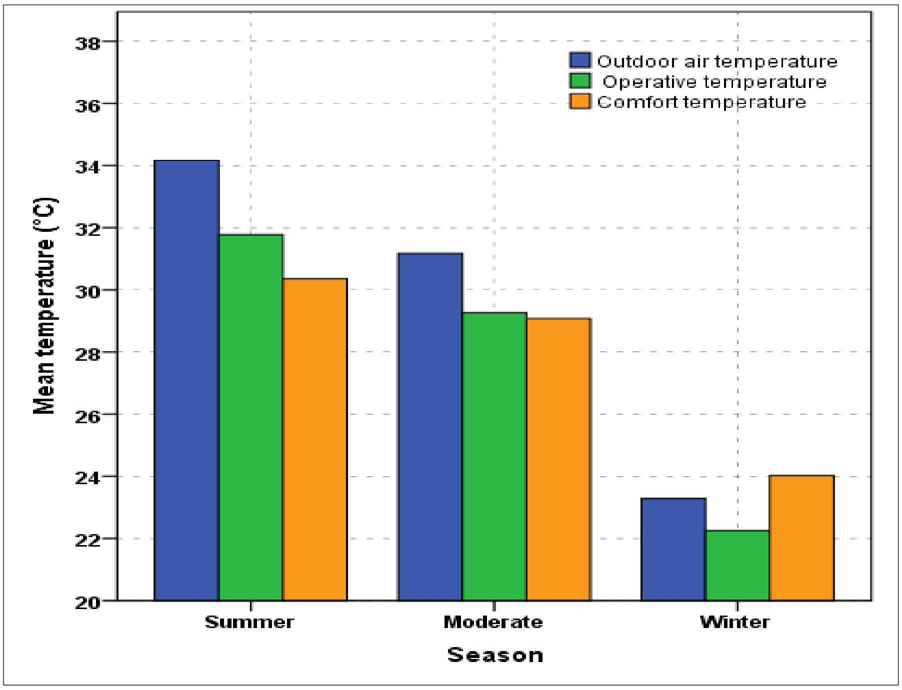


Figure 4-16 Seasonal variations of comfort temperature (Griffith constant 0.5 ˚C^{-1}) for naturally ventilated buildings

4.6 Analysis of occupant's behavioral adaptation and controls

Human beings show an amazing ability to adapt to the dynamics of nature. Adaptive actions can be broadly classified into three categories, viz. (i) Behavioural adaptation (personal level, environmental level, socio-cultural level) (ii) Physiological adaptation (acclimatization) and (iii) Psychological adaptation (expectation and preferences) [**11**]. Behavioral use of controls is interconnected with the physiology/psychology of the body and physics of the buildings [**62**] [**66**] [**182**]. In the succeeding sections, behavioral adaptations at a personal level have been analyzed, viz. changing clothing levels, use of personal environmental controls like the opening of window/door (for the natural flow of air) and use of a fan(for forced airflow); to make the surrounding environment comfortable.

4.6.1 Adaptation through clothing insulation

The mean values of clothing were found a bit higher for female occupants than male occupants across all seasons. Clothing values continuously increased from the summer (Mean clo=0.34, SD=0.15) to winter season (Mean clo=0.67, SD=0.14), revealing continuous adaptation by occupants through adjusting clothing patterns. Clothing level variations were recorded for each season across the multiple years of study. Clothing levels have been plotted against instantaneous outdoor temperature for winter, moderate and summer seasons in Figure 4-17 (a, b, and c), respectively. This data presents an important characterization of continuous adaptation by building occupants that are taking place season by season. The temperature corresponding to inflexion points (maximum and minimum temperatures) have been noticed as being common between two adjoining seasons, i.e. summer to moderate and moderate to winter. This shows that clothing is the important adaptive opportunity available to occupants to overcome seasonal discomfort. The most preferred clothing level for summer was found to be 0.30 clo, for moderate 0.40 clo and 0.80 clo for winter season of composite climate in India.

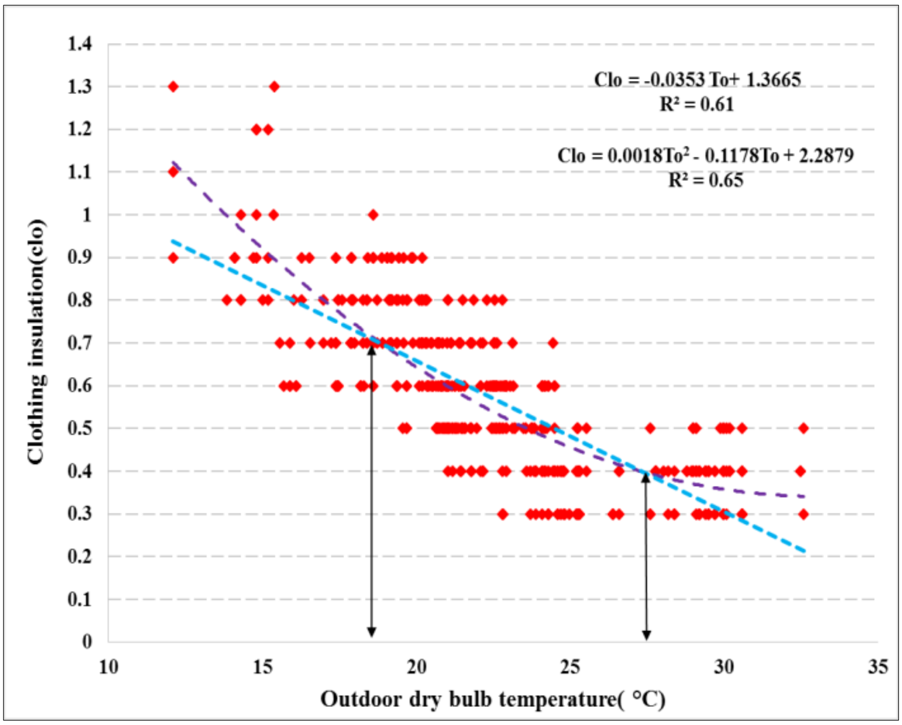
To study the dependence of clothing level on outdoor temperature, linear and polynomial regression analysis was carried out for different seasons. Equations (4.4) to (4.6) represent the polynomial regression for summer, moderate and winter season, respectively.

$$\mathbf{Clo = 0.0005 \times T_o^{2} - 0.049 \times T_o + 1.35 \quad (R^2 = 0.35)} \tag{4.4}$$

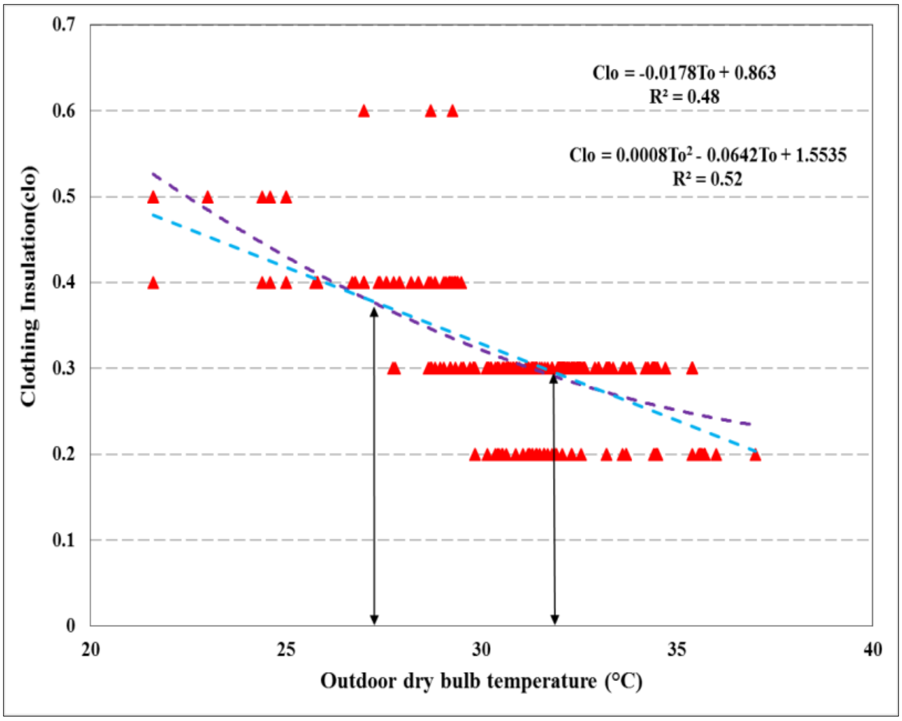
$$\mathbf{Clo = 0.0008 \times T_o^{2} - 0.064 \times T_o + 1.55 \quad (R^2 = 0.50)} \tag{4.5}$$

$$\mathbf{Clo = 0.0018 \times T_o^{2} - 0.118 \times T_o + 2.28 \quad (R^2 = 0.65)} \tag{4.6}$$

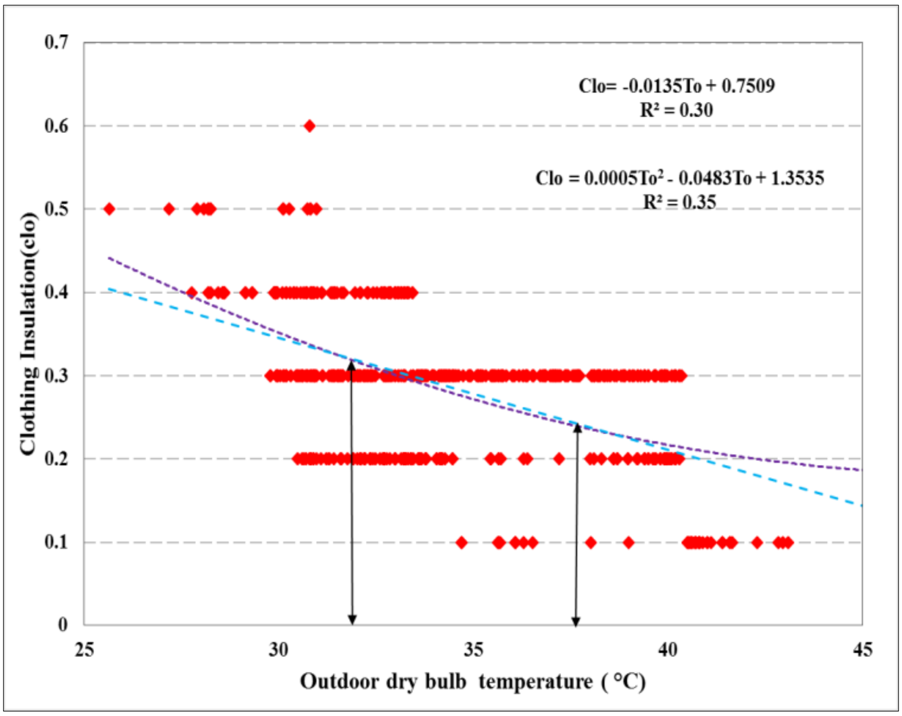
A similar analysis for correlation of clothing insulation and outdoor temperature was carried out by de Dear and Leow [**78**], Mui and Chan [**76**] and Singh et al. [**36**]. This study revealed higher coefficient of correlation for clothing insulation with outdoor temperature than what Mui and de Dear had observed in their field study. As evident from Figure 4-17 (a, b, c), the polynomial regression was found to be more appropriate as compared to the linear regression for capturing variation in region specific clothing.


Clo = -0.0353 To+ 1.3665
R² = 0.61
Clo = 0.0018To² - 0.1178To + 2.2879
R² = 0.65
Clothing insulation(clo)
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10
15
20
25
30
35
Outdoor dry bulb temperature(°C)

(a)


Clo = -0.0178To + 0.863
R² = 0.48
Clo = 0.0008To² - 0.0642To + 1.5535
R² = 0.52
Clothing Insulation(clo)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
20
25
30
35
40
Outdoor dry bulb temperature (°C)

(b)



(c)

Figure 4-17 Variation of clothing with instantaneous outdoor temperature for (a) winter season, (b) moderate season, and (c) summer season

4.6.2 Use of environmental controls for comfort

In Section–B of the questionnaire, adaptive behaviour for controls like use of doors, balcony doors, windows, curtains and other electrical controls like fans, air coolers, and A/Cs was noted down as binary data (0: not in use/closed; 1: in use/open) for analysis. The subjects have adaptively operated the windows, doors, and fans to maintain comfortable conditions indoors. Rijal et al. [**64**] [**72**] [**92**] have used indoor globe temperature as comfort indices for predicting the window or fan opening behavior as temperature increases in naturally ventilated office buildings. However, it has been observed that indoor globe temperature considers the effect of air speed up to 0.2 m/s [**96**]. The mean air speed during the survey period was 0.27 m/s in winter, 0.57 m/s in moderate seasons and 0.62 m/s in summer, respectively. Also, mean air speed observed was up to 0.5 m/s in working 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 2.5 m/s. Since indoor globe does not consider the effect of elevated air speed; we have used operative temperature to analyze the occupant's control behavior for the present study. The operative temperature has been calculated using equations (4.7) and (4.8) as suggested in ASHRAE Standard 55–2013 [**4**] and ISO: 7726 [**185**]. Equation (4.7) is acceptable for occupants engaged in near sedentary physical activity (with metabolic rates between 1–1.3 met), not in direct sunlight, and not exposed to air velocities greater than 0.20 m/s. Equation (4.8) is applicable for occupants engaged in near sedentary physical activity (with metabolic rates between 1–1.3 met), not in direct sunlight, but air velocities greater than 0.20 m/s.

$$\mathbf{t_{op}} = \frac{(\mathbf{t_{mrt}} + \mathbf{t_a})}{\mathbf{2}} \qquad (\mathbf{4.7})$$

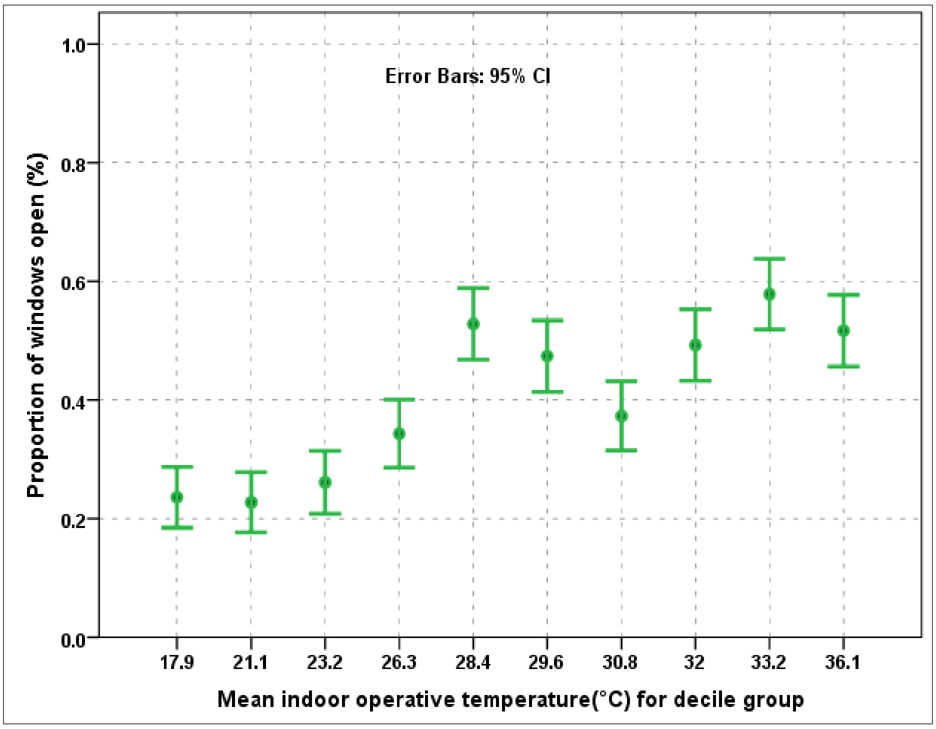
$$\mathbf{t_{op}} = \frac{\left(\mathbf{t_{mrt}} + (\mathbf{t_a} \times \sqrt{\mathbf{10v}})\right)}{\mathbf{1} + \sqrt{\mathbf{10v}}} \qquad (\mathbf{4.8})$$

4.6.3 Window opening behavior

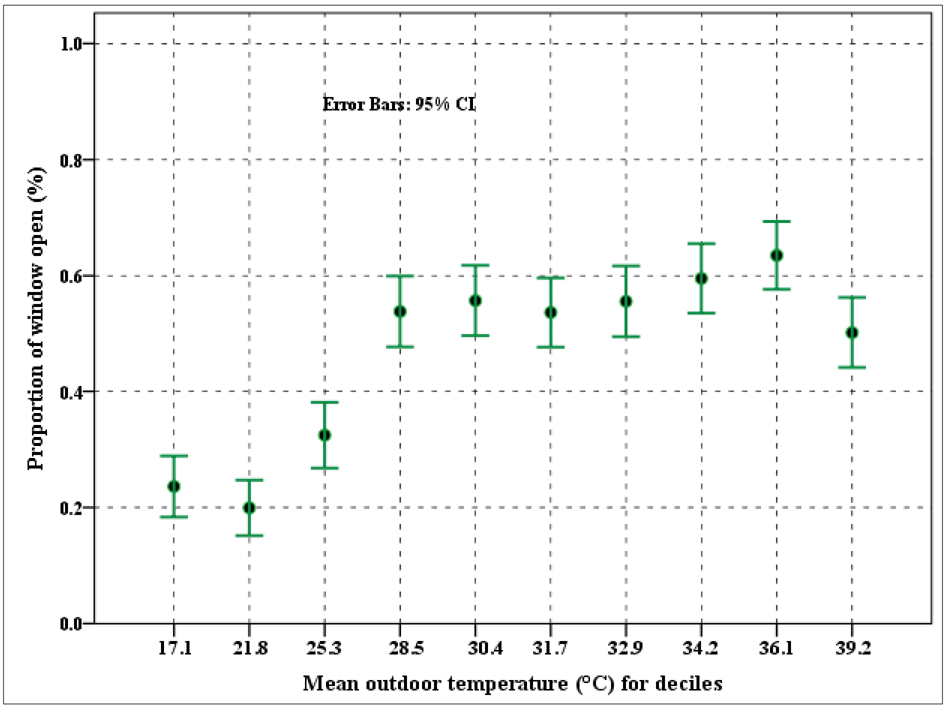
To analyze the window opening behavior in built environment; the methods adopted by Rijal and Nicol [**64**] [**72**] for comfort studies in Pakistan and European buildings has been adopted in this study. To analyze the window opening behavior in built environment; the data were divided into ten groups called deciles (ranked and aggregated group of data), in an ascending order of temperature as shown in Table 4.6. In the present study 40% of total observation, windows were found open (Mean P_w=0.4, N=2610). The proportion of the window opening rises as the indoor operative or outdoor air temperature rises as shown in Figure 4-18 (a) and (b). When mean indoor operative temperature and the outdoor air temperature was about 28.5˚C, the mean proportions of open windows were found to be more than 0.5. The findings for window openings are similar to Nicol and Rijal [**64**] in their Pakistan study, but lower than that of European subjects in office buildings [**72**]. Also, a study for residential buildings in summer and monsoon season of Hyderabad, about 40% of windows were found open at same prevailing conditions [**70**]. People opened the windows in response to the increase in the indoor and outdoor temperatures and reached to a maximum of 60% when mean indoor operative temperature peaks at 33.2˚C. Rijal et al. [**63**] and Indraganti et al. [**75**] observed that the indoor climate, the outdoor climate and a mixture of both might drive the use of controls. Results also reveal that proportion of window open (P_w%) correlate significantly

($p<0.01$) with both indoor operative and outdoor air temperature as depicted in Table 4.7.

Least open windows and doors were found during peak summer months (April–June) as outdoor conditions are very harsh, and entry of outdoor air adds to occupant discomfort. Also, during the rainy season (July and August), despite relatively low air temperature, to prevent entry of mosquitoes and insects breeding, only a limited use of windows is observed. A significant fraction of windows closed during summer season suggests that there might be other more influencing reasons for opening/closing of windows such as noise, pollution, safety. Window opening behavior also found to be varied during the day (aggregated and ranked data of time) as shown in Figure 4-19. Window opening peaked at morning hours, decreased as the day progressed, and gradually increased in the evening. It was noted that windows being closed during mid-day, particularly in summers, to avoid hot breezes coming in.



(a)



(b)

Figure 4-18 Deciles of mean operative temperature (a) and mean outdoor temperature (b) with the proportion of 'windows open' in naturally ventilated buildings

Table 4.6 Deciles of mean indoor operative temperature, outdoor air temperature and the proportion of windows open in naturally ventilated buildings

Deciles	T_{op} (˚C)							T_{out} (˚C)						
	N	Max.	Min.	Mean	SD	Mean*	SD*	N	Max.	Min.	Mean	SD	Mean*	SD*
1	**266**	20.2	14.5	17.9	1.5	**0.24**	0.44	**255**	19.9	11.0	17.1	2.1	**0.24**	0.43
2	**271**	22.0	20.2	21.1	0.5	**0.23**	0.42	**270**	24.0	20.0	21.8	1.3	**0.20**	0.40
3	**255**	24.8	22.0	23.2	0.9	**0.26**	0.43	**260**	26.8	24.0	25.2	0.8	**0.32**	0.47
4	**261**	27.7	24.8	26.3	0.9	**0.35**	0.49	**260**	29.9	26.8	28.5	0.9	**0.54**	0.50
5	**265**	29.0	27.7	28.4	0.4	**0.53**	0.50	**260**	31.0	29.9	30.4	0.4	**0.56**	0.50
6	**250**	30.3	29.0	29.6	0.4	**0.47**	0.50	**265**	32.3	31.0	31.8	0.4	**0.54**	0.50
7	**260**	31.4	30.3	30.8	0.3	**0.38**	0.48	**255**	33.5	32.3	32.9	0.3	**0.56**	0.50
8	**260**	32.5	31.4	32	0.4	**0.49**	0.46	**260**	35.1	33.5	34.2	0.5	**0.60**	0.49
9	**260**	34.3	32.5	33.2	0.5	**0.60**	0.43	**262**	37.2	35.1	36.1	0.6	**0.63**	0.48
10	**260**	39.5	34.3	36.1	1.3	**0.52**	0.50	**262**	45.1	37.2	39.2	1.3	**0.50**	0.50

N : Sample size; T_{op}: Indoor operative temperature; T_{out}: Outdoor air temperature; SD: Standard deviation
***Proportion of windows open**

Table 4.7 Correlation matrix for proportion of window open with outdoor & indoor environmental parameters

	Pearson Correlation Sig. (2-tailed)	P_w (%)	TSV	T_o	T_{op}	T_i	T_g	V_a
P_w (%)	r =	1.00	0.16**	0.24**	0.29**	0.30**	0.29**	0.08**
TSV	r =	0.16**	1.00	0.56**	0.60**	0.60**	0.60**	0.10**
T_o	r =	0.24**	0.56**	1.00	0.87**	0.88**	0.87**	0.12**
T_{op}	r =	0.29**	0.60**	0.87**	1.00	0.96**	0.97**	0.15**
T_i	r =	0.30**	0.60**	0.88**	0.96**	1.00	0.98**	0.15**
T_g	r =	0.29**	0.60**	0.87**	0.97**	0.98**	1.00	0.16**
V_a	r =	0.08**	0.10**	0.12**	0.15**	0.15**	0.16**	1.00

P_w : Proportion of windows open; TSV: Thermal sensation vote ;T_o: Outdoor air temperature (˚C) ; T_{op} : Indoor operative temperature(˚C); T_i : Indoor air temperature(˚C); T_g : Indoor globe temperature(˚C); V_a: Indoor air speed (m/s)

****. Correlation is significant at the 0.01 level (2-tailed)**

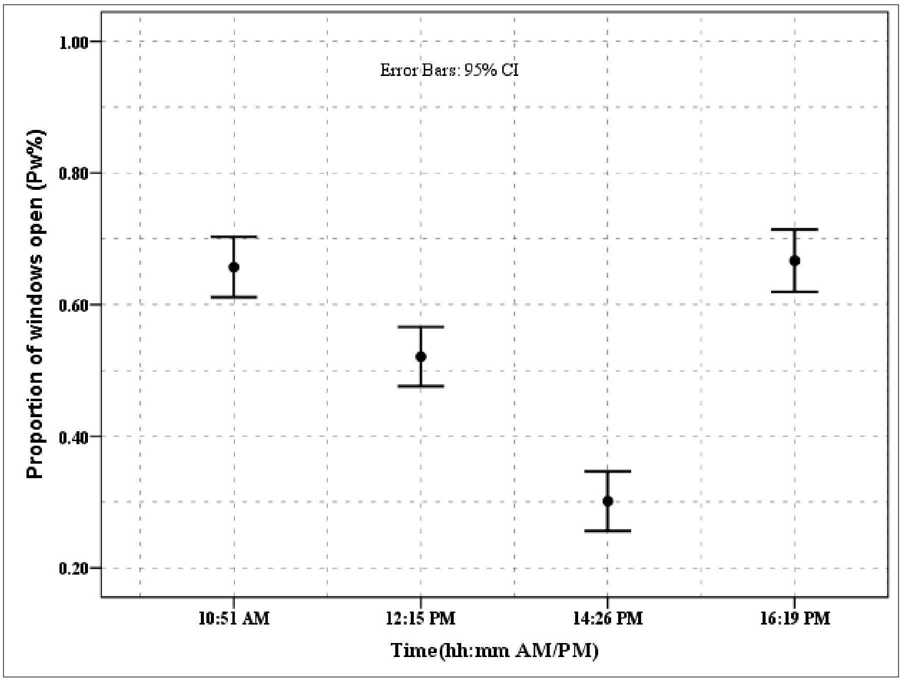


Figure 4-19 Proportion of windows open at various time of the day

4.6.4 Use of ceiling fans

A study conducted for buildings of Roorkee (India) and Bagdad (Iraq), found that air velocities up to 1.5 m/s were acceptable for subjects in hot and warm countries [**184**]. The use of fans significantly increased with the rise in indoor temperature (Pearson’s correlation r=0.76, N=2608, p<0.01). Also, Pearson correlation (r) for the fan use is higher than the window, indicating fan come into use over a narrow range of indoor air temperature. This means controlling air velocity found to be preferred method of thermal adaptation over adjusting clothing and window opening in composite climate of Jaipur. Almost 100% of fan came into use during summer and moderate season. During the pre-winter month of November and pre-moderate month of February, conditions indoor were found slightly warmer with mean temperatures soaring above 26˚C. So, during this period occupants adaptively used windows and fan at low speed to make their environment comfortable.

Figure 4-20 shows the use of the fan with decile of indoor operative temperature for naturally ventilated buildings of the composite climate of Jaipur. The proportion of fans in use (P_f%) reached a maximum of 81% when the mean indoor temperatures peaked at 28.5 ˚C. Similarly, Rijal et al. [**64**] noted around 81%'fans on' at an indoor temperature of 30˚C, in Pakistan. Subjects in the present study are found to have 3˚C higher comfort temperature under 'fan on' use than when 'fan was off' (29.6˚C as against 26.6˚C).

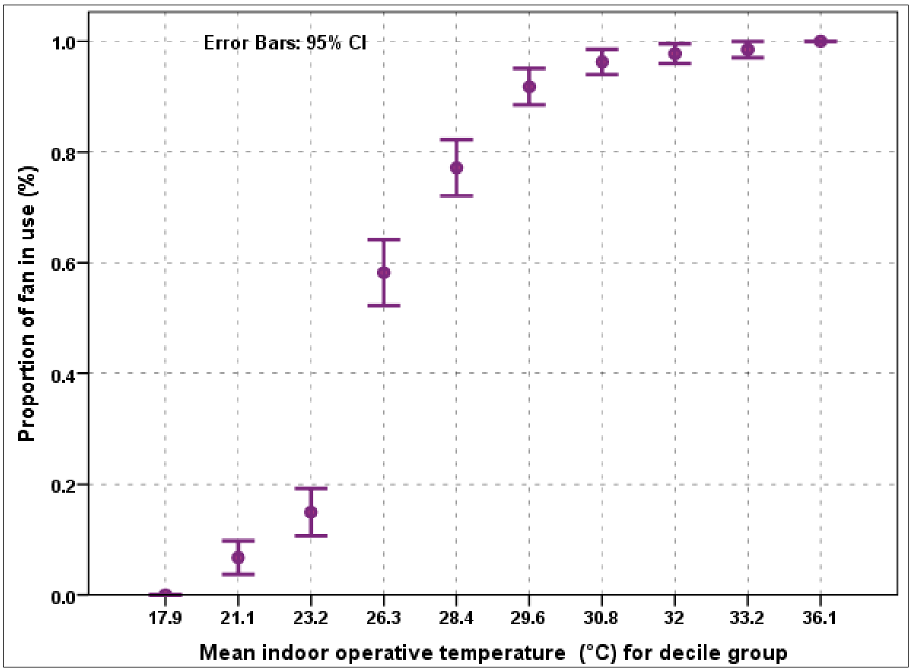


Figure 4-20 Deciles of mean operative temperature with the proportion of 'Fan in use' in naturally ventilated buildings

4.6.5 Use of controls across the seasons

The window opening trend, use of a fan, use of external door and mean air velocity (at 95% confidence interval) observed in naturally ventilated spaces across all season and months is shown in Figure 4-21. The mean proportion of windows and doors open to the external environment were found to be 0.56 and 0.64 during the summer season and relatively low in winter season 0.27 and 0.40, respectively. The low proportion of external door and windows were found due entry of outdoor air adds the extra heat into indoor air temperature which increases the discomfort conditions. Similarly, during peak winter months of January and February, occupants closed the external door to restrict the cold draft from outside air at very low temperature. Also, in this field study, we also recorded other controls like use of blinds, curtains and balcony door which occupant’s uses as other possible controls to make themselves comfortable at excursion of indoor temperature. Occupants effectively used blinds and curtains to reduce internal gain and glare inside the buildings during peak summer and months viz. May and June. Similarly, the use of blinds and curtains further decreases during peak winter months of January and February to restrict the cold draft during this period.

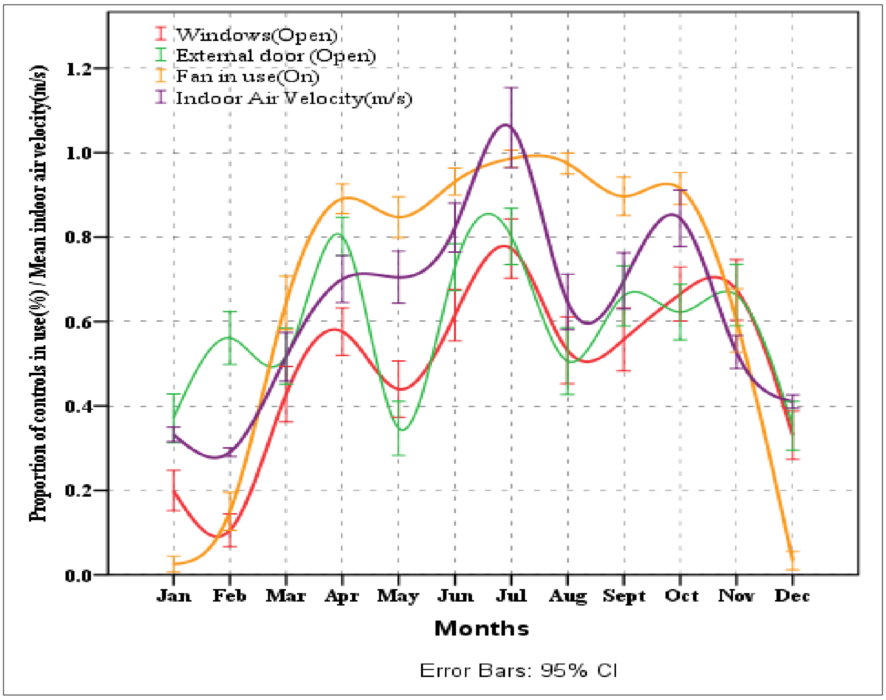


Figure 4-21 Proportion of controls in use and prevailing indoor mean air velocity for all seasons in naturally ventilated buildings

4.7 Logistic regression analysis to predict the use of windows and fans

Rijal et al., [**63**] [**64**] [**72**] Haldi and Robinson [**69**] made use of logistic regression analysis to predict occupant’s control behavior in naturally ventilated buildings for binary data recorded during field study (fan on: 1, fan off: 0). In the present study, we have also adopted the same logistic regression method to predict the window opening and fan use behavior. The relationship between the probability of windows being open or a fan in use (p) and the indoor or outdoor temperature (T) can be predicted using equations (4.9) and (4.10).

$$\mathbf{Logit\ (p) = log\left[\frac{p}{1-p}\right] = bT + c} \qquad (4.9)$$

$$\mathbf{p = \frac{e^{(bT+c)}}{[1 + e^{(bT+c)}]}} \qquad (4.10)$$

p is the probability that the fan is in use, T is the temperature, b is the regression coefficient for T and c is constant in the regression equation. The logistic regression equations from (4.11) to (4.14) were obtained in between the window opening and fan use and temperatures for naturally ventilated buildings.

- **Window opening:**

$$\mathrm{Logit(p)} = 0.109\ T_{op} - 3.24(\ n = 2610, r^2 = 0.11, p < 0.001) \qquad (4.11)$$

$$\mathrm{Logit(p)} = 0.081\ T_o - 2.54(\ n = 2604,, r^2 = 0.11, p < 0.001) \qquad (4.12)$$

- **Fan use:**

$$\mathrm{Logit(p)} = 0.54\ T_{op} - 15.13(\ n = 2608, r^2 = 0.70, p < 0.001) \qquad (4.13)$$

$$\mathrm{Logit(p)} = 0.37\ T_o - 10.30(\ n = 2628, r^2 = 0.59, p < 0.001) \qquad (4.14)$$

T_{op} is indoor operative temperature (˚C), T_o is outdoor air temperature (˚C) and r-square is Cox and Snell R. Even though the coefficient of determination is low, the equations are statistically significant ($p<0.001$). The logistic regression coefficient for the fan use is higher than the window, indicating fan come into use over a narrow range of indoor air temperature. The regression coefficient of the window or fan use shows a higher correlation with indoor operative temperature than the outdoor temperature. This indicates that the subjects are more driven to use building controls as a response to change in indoor temperature rather than outdoor temperature. Using these equations, we estimated about 80% fans were switched on, and 50% windows were open at 29˚C of indoor operative temperature, respectively. Figure 4-22 shows the logistic regression lines for window open and fan on with indoor operative temperature, thus plotted using the above equations (4.11) and (4.13).

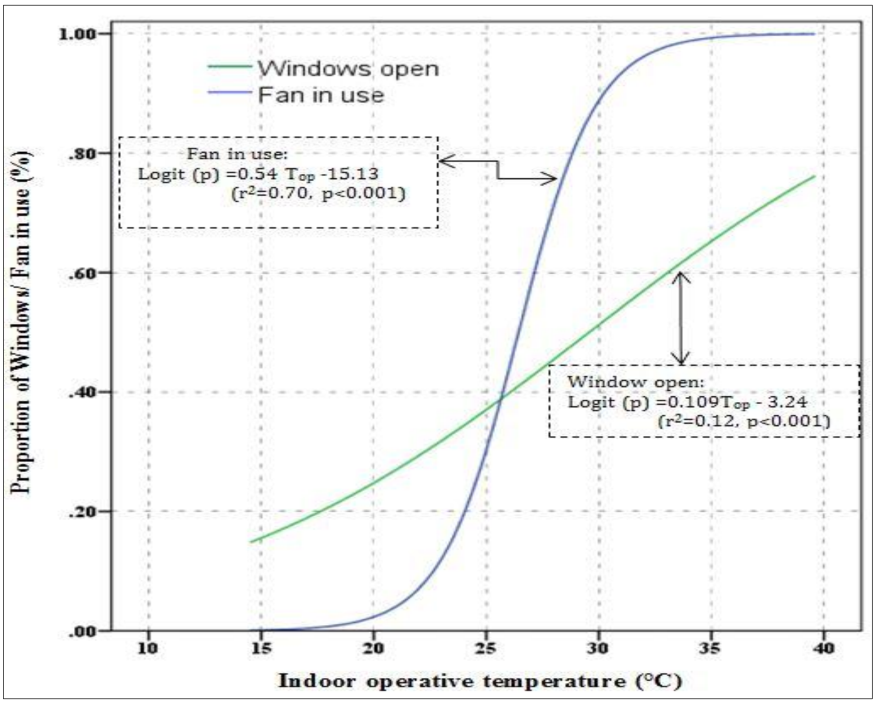


Figure 4-22 Logistic regressions for window and fan open with indoor operative temperature

Figure 4-23 (a), and (b) shows the prediction of windows open and fan in use using the regression equations (4.11) and (4.13) with measured data during the field study. As can be noticed there is a good agreement between predicted fan and window operation with measured data. Thus, it can be concluded that using these equations, schedule of windows opening and fan usage at various indoor temperatures can be reasonably predicted. This predicted value can further be utilized by simulation based studies such as predicting indoor conditions, heat transfer studies.

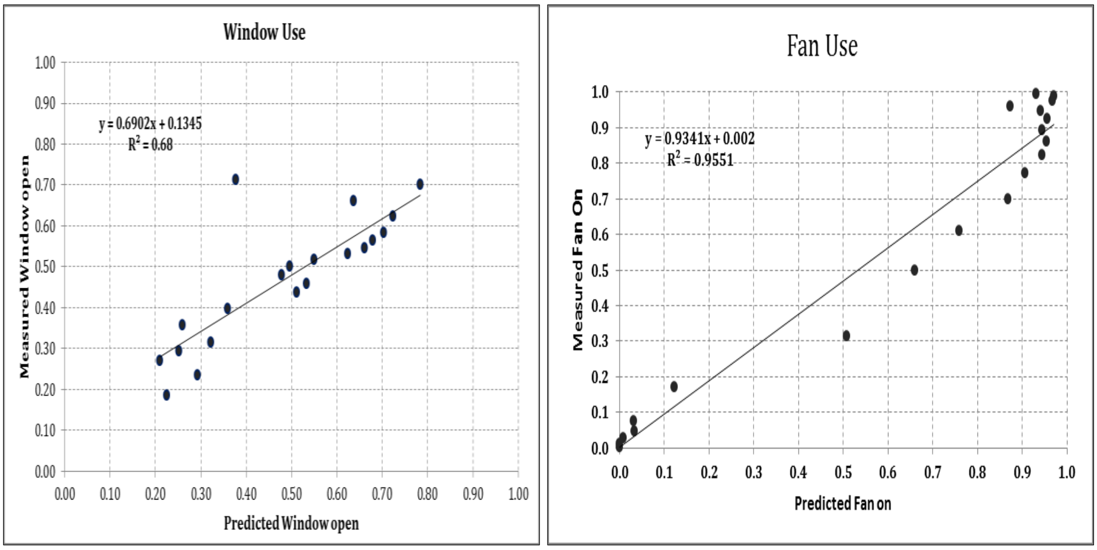


Figure 4-23 Linear relations between measured and predicted values for (a) windows open and (b) fan in use

4.8 Chapter summary

This present chapter summarized the findings of a thermal comfort field study conducted in thirty-two naturally ventilated buildings in the composite climate of Jaipur. The present study revealed that a total of 82% of the votes(±1 sensations) indicated thermal comfort at prevailing indoor conditions. On an annual basis, the mean comfort temperature, as predicted by Griffiths' method, was found to be 27.9˚C. The seasonal analysis reveals the mean comfort temperature is 30.6˚C in summer and 24˚C in winter, respectively. Thus, the seasonal variation of mean comfort temperature is about 6.6˚C as obtained through Griffiths' method. The mean value of sensation votes for all seasons was found slightly higher than neutral. Mean air velocity increases as the season get warmer. It has been observed as 0.27 m/s in winter, and 0.62 m/s in summer. The corresponding occupant mean sensation of air velocity for the different seasons was -0.35 in summer and -0.10 in winter. This reflects typical high air velocity preference of Indian subjects living in composite climatic conditions. In naturally ventilated buildings of this climate, there is a continuous adaptation in clothing pattern throughout the year, affecting occupant sensations and preferences. The most preferred clothing level for summer is 0.30 clo and 0.80 clo for winter. This study also analyzed the occupant's adaptive behavior for controls like the use of doors, windows, curtains and other electrical controls like fans and speed regulators. In the present study 40% of total observation, windows were found open (Mean P_w=0.40, N=2610). The proportion of window opening reaches to a maximum of 60% when mean indoor operative temperature peaks at 33.5˚C. The percentage of fans in use (P_f%) increased as the temperature increased, and it reached a maximum of 81% when the mean indoor operative temperatures peaked at 28.5˚C. Use of fans elevated the comfort temperature by about 3˚C in naturally ventilated buildings. Finally, equations for predicting fan use and window opening have been developed using the logistic regression method. The predicted data of fan and window usage obtained through the equations matched fairly with measured data. The results from this study indicate that subjects in naturally ventilated buildings are more comfortable at temperature higher than recommended in Indian codes or International standards for buildings.

CHAPTER 5

DEFINING THERMAL COMFORT ZONES FOR NATURALLY VENTILATED BUILDINGS

5.1 Preamble

The ASHRAE Standard 55–2013 comfort zone is defined as the range of climatic conditions within which a majority of persons would feel thermally comfortable. It has been investigated through literature study that some problems exist; when these comfort standards are used to evaluate the indoor conditions in naturally ventilated buildings especially in tropical countries [**14**] [**12**] [**44**] [**101**]. People particularly in hot and warm climates; feel comfortable under naturally ventilation conditions while indoor environmental parameters were found far away from traditional comfort zones [**186**].

The comfort zone defined in ASHRAE 55–2013 partially account for the acclimatization, comfort expectations and behavioral adaptation of the inhabitants in tropical countries like India [**14**] [**75**]. 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 [**12**] [**174**] [**187**].

This generates the need for an alternative standard that would have more relevance to the variable indoor environments in naturally ventilated buildings, including climatic variations and other contextual adaptations in which occupants have a higher degree of control over their indoor environment.

5.2 Comfort zone of ASHRAE Standard 55-2013

ASHRAE Standard 55–2013 defines an acceptable comfort zone on a psychrometric chart, specifying boundaries of operative temperature and humidity for sedentary activity (1–1.3 met) and defined clothing (0.5–1 clo) as shown in Figure 2-4 (e). The comfort zone on the psychrometric chart is mainly used for tightly setting temperature and airflow conditions delivered by the Heating, Ventilation and Air Conditioning systems (HVAC), typically eliminating thermal and air speed variability or occupant control in buildings. This standard is not limited to any particular building type. However, various field studies throughout the world have questioned the uniform comfort conditions suggested by these standards.

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 [**10**] [**34**]. Owing to individual preferences, it is impossible to specify a thermal environment that will satisfy everybody [**11**] [**37**]. As a result, ASHRAE Standard 55–2013 [**4**] and ISO standard 7730 [**5**], 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. The same assumption has been taken for the analysis presented in this study.

5.3 Segregation of thermal comfort data and analysis

In the thermal comfort surveys for the present study, mean air speed was found to be 0.27 m/s in winter, 0.57 m/s in moderate seasons and 0.62 m/s in summer, respectively. Following observations have been made based on thermal comfort study.

- 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.

- Mean air speed observed was below 0.5 m/s in working 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 found up to 1.5 m/s.

Therefore, the indoor air speed data was regrouped into three groups: up to 0.2 m/s, 0.2–0.5 m/s, and 0.5–1.5 m/s for further analysis. The air velocities up to 0.2 m/s are assumed to still air as suggested in ASHRAE Standard 55–2013, for 0.2–0.5 m/s are with natural air flow through the opening of windows or doors, and more than 0.5 m/s is fan assisted, or fan forced air flow.

As defined in ASHRAE Standard 55 thermal comfort zone extends from 20˚C in winter to 27˚C in summer given a relative humidity range of 20%–80% for still air conditions up to 0.20m/s, with some high-temperature limitations on humidity [**4**]. However, at higher relative humidity, the sensation of thermally comfortable exists at lower operative temperature, which is shown along a tilted line on the psychrometric chart. These tilted lines are functions of operative temperature, relative humidity, and air speed under standard clothing (0.5–1.0 clo) and activity level (1–1.3 met), so different comfort zones have been estimated on psychrometric chart for the different combination of clothing, air speed, and relative humidity effects. In the present study, we have considered comfort zones at different air speed with extended acceptable temperature range as obtained by ISO 7730 [**5**] and ASHRAE Standard 55–2013 [**4**] calculation method as shown in Figure 2-6. Hence, different comfort zones were estimated on the standard psychrometric chart at different clothing, activity, and airspeed combinations i.e. 0.5 m/s, 1 m/s, and 1.5 m/s.

A total of 2610 samples from thirty-two naturally ventilated buildings has been used to evaluate the applicability of existing comfort boundaries/zones namely ASHRAE Standard 55 comfort zones in naturally ventilated buildings for this climatic region. 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) employed in the PMV/PPD model, well accepted in defining acceptable thermal comfort ranges. 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.

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 5.1 represents the distinct conditions or "**cases**" considered for plotting comfortable votes on the ASHRAE Standard 55 comfort zone.

Table 5.1 Cases considered for plotting of comfortable votes (-1, 0, +1) by season on the psychrometric chart

Cases	Clo values	Air speed (m/s)
Summer and Moderate season	Up to 0.3 clo	0 to 0.2 m/s (still air)
		0.21 to 0.5 m/s (natural air flow)
		0.51 to 1 m/s (fan forced air flow)
		1.1 to 1.5 m/s (fan forced air flow)
	0.31 to 0.6 clo	0 to 0.2 m/s (still air)
		0.21 to 0.5 m/s (natural air flow)
		0.51 to 1 m/s (fan forced air flow)
		1.1 to 1.5 m/s (fan forced air flow)
Winter season	0.0 to 0.6 clo	0 to 0.2 m/s (still air)
		0.21 to 0.5 m/s (natural air flow)
	0.61 to 1.2 clo	0 to 0.2 m/s (still air)
		0.21 to 0.5 m/s (natural air flow)

5.3.1 Thermal sensation votes during summer season

Figure 5-1 and Figure 5-2 describes the distribution of subjects' comfortable votes on ASHRAE Standard 55 comfort zones for different air speed and up to maximum clothing insulation level of 0.6 clo found in the summer season. Plotting of comfortable votes (±1 votes) on ASHRAE Standard 55-2013 comfort zones the following observations were made.

- During the summer season, more than 90% comfortable votes were found outside the ASHRAE Standard 55 comfort zone for still air condition for all clothing levels (up to 0.6 clo).
- More than 80% comfort votes were found away from ASHRAE Standard 55 comfort zones for same clothing insulation level upto 0.6 clo and for air velocity ranges of 0.2–0.5m/s (natural air flow) and 0.5–1.5m/s (fan forced air flow) as shown in Figure 5-2. But it can be seen from figure that at higher clothing levels (0.6 clo), comfort votes shifted towards a lower temperature range, almost ignoring the effect of air movement.

- These observations indicate that comfort zone for occupants in naturally ventilated buildings in composite climate of India is larger than one proposed by ASHRAE Standard 55.
- Some votes were found comfortable at higher relative humidity (more than 80%) even at low air speed (~0.2 m/s), this is because of acclimatization of occupants to their environmental conditions as described in **Chapter 4** under **section 4.4.2 and 4.4.3**.

Nicol [**184**] 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. In the present study, the votes were found comfortable up to 35˚C when fan is used in naturally ventilated buildings as shown in Figure 5-2. The results of the present study are consistent with the findings of Nicol [**12**] and Khedari et al. [**187**] 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.

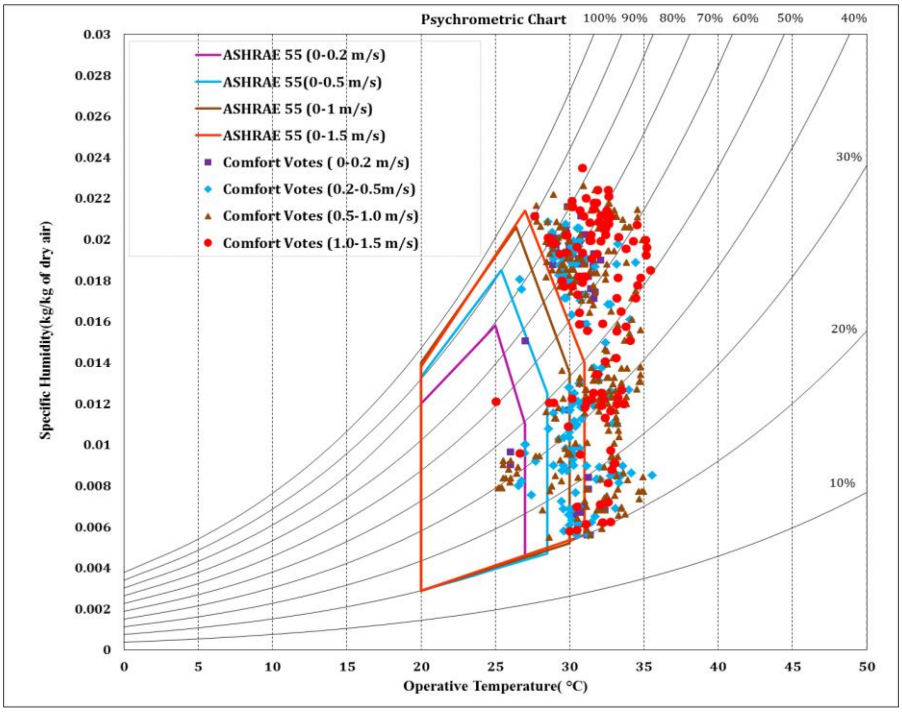


Figure 5-1Plot of ASHRAE 55 comfort zones and summer comfortable votes (±1) for different air speed, activity and clo combinations (clo: upto 0.3 clo, activity: 1met-1.2 met and air flow: 0-1.5m/s)

Also, inhabitants of this region are accustomed to its environmental conditions and can tolerate higher temperature and humidity, feeling comfortable in naturally ventilated buildings [**54**] [**70**]. Numerous field studies have shown that fan use in naturally ventilated buildings shifts the comfort temperature limit up to 4˚C [**12**] [**44**] [**174**]. Chow et al. [**188**] found that more air movement could cause an inherent pleasant sensation of freshness in addition to thermal comfort.

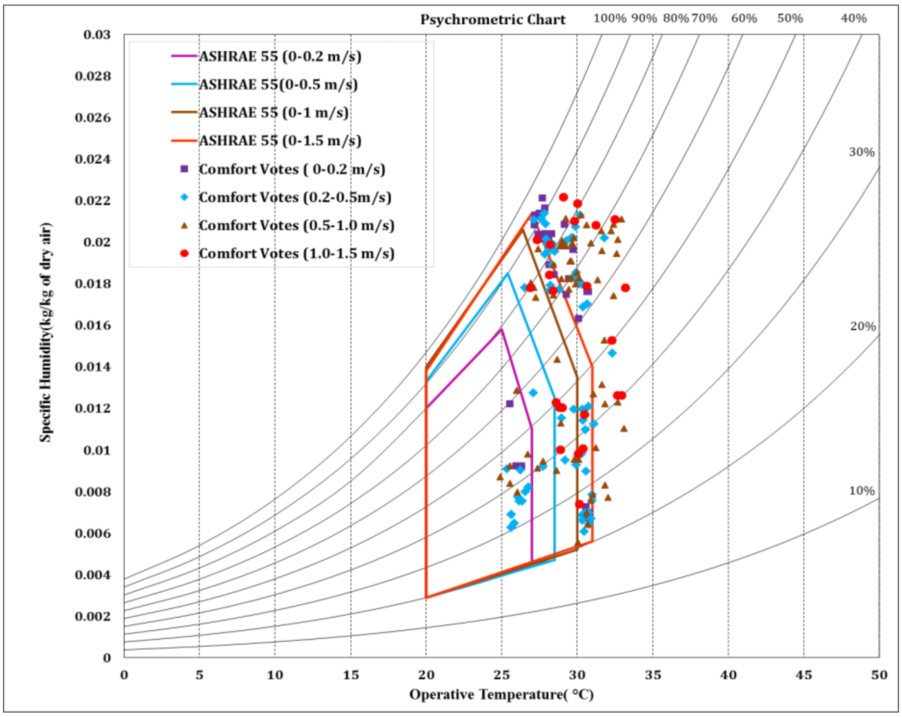


Figure 5-2 Plot of ASHRAE 55 comfort zones and summer comfortable votes (±1) for different air speed, activity and clo combinations (clo: 0.3 clo-0.6 clo, activity: 1met-1.2 met and air flow: 0-1.5m/s)

5.3.2 Thermal sensation votes during moderate season

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. Following observations were made while plotting the comfortable votes for the moderate season on ASHRAE Standard 55 comfort zones:

- 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 0.5–1 m/s, as shown in Figure 5-3 and Figure 5-4.
- A closer look at Figure 5-3 and Figure 5-4 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.

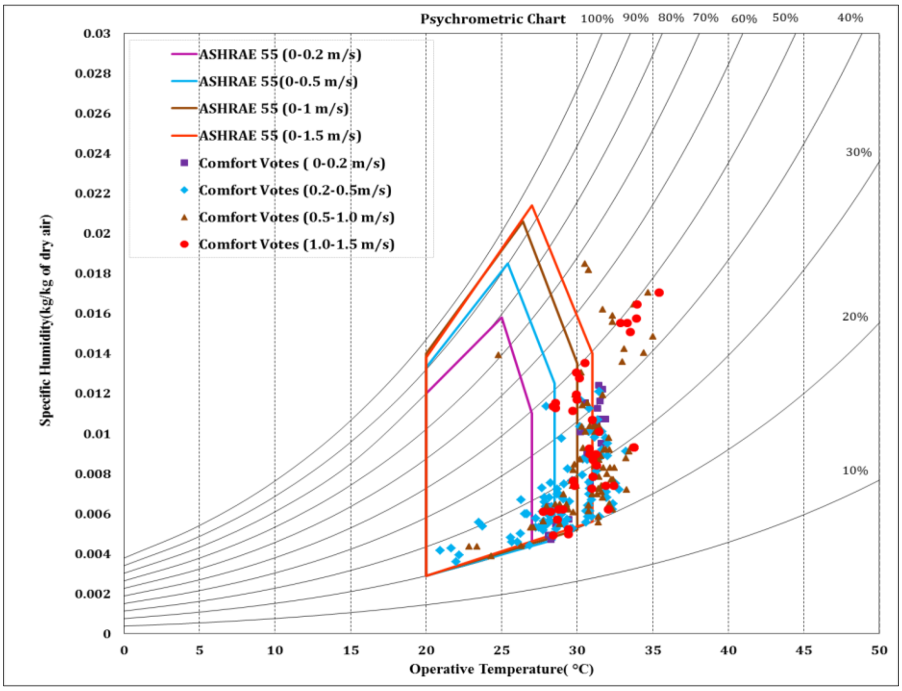


Figure 5-3 Plot of ASHRAE 55 comfort zones and moderate comfortable votes (±1) for different air speed, activity and clo combinations (clo: upto 0.3 clo, activity: 1met-1.2 met and air flow: 0-1.5m/s)

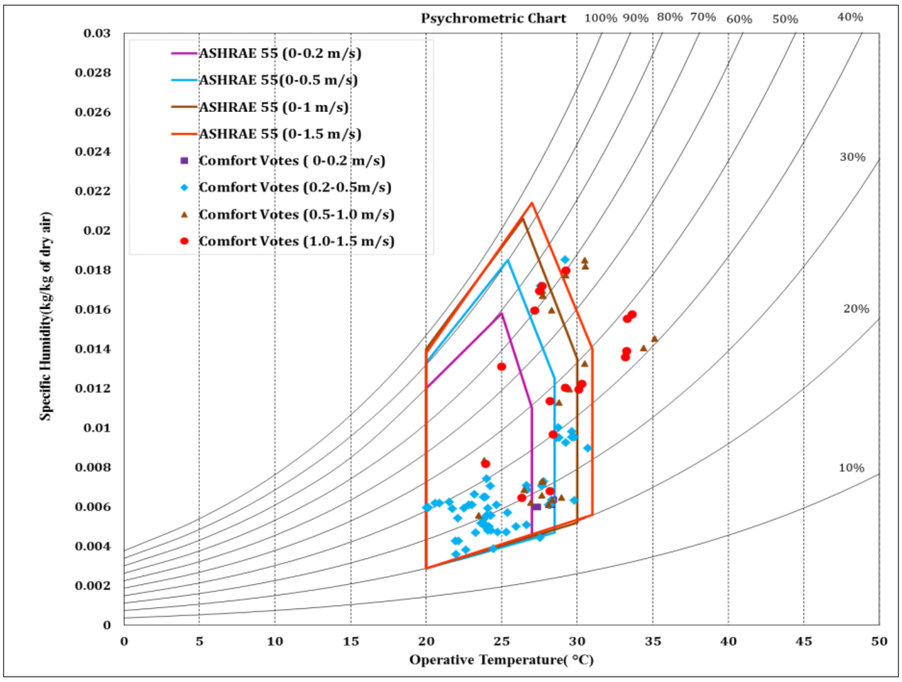


Figure 5-4 Plot of ASHRAE 55 comfort zones and moderate comfortable votes (±1) for different air speed, activity and clo combinations (clo: 0.3 clo-0.6 clo, activity: 1met-1.2 met and air flow: 0-1.5m/s)

5.3.3 Thermal sensation votes during winter season

In the winter months, 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.

Conditions didn’t change drastically but steadily, as the season changed from moderate to winter. During the pre-winter month of November and pre-moderate month of February, conditions indoor were found slightly warmer with mean temperatures soaring above 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. Thus, some votes were found at mean indoor air speed higher than 0.2 m/s but not more than 0.5 m/s.

The clothing level of the subjects also changed from minimum of 0.3 clo (during the pre-winter month of November) to a maximum which is found to be more than 1.22 clo(peak winter month of December and January), providing an insulating effect towards surrounding environmental conditions. Comfortable votes for clothing level range up to 0.6 clo and 0.6–1.2 clo for different indoor air speed are plotted on the psychrometric chart as shown in Figure 5-5 and Figure 5-6. The comfortable votes for clothing level ranges of 0.6–1.2 clo and 0.2–0.5 m/s indoor air speed are plotted on the psychrometric chart as shown in Figure 5-6. At these higher clothing levels, subjects also have no exposed parts of their body, so the effect of higher air velocities from 0.2–0.5 m/s is also negligible. This can be seen from Figure 5-6 that almost all the votes lay in comfort zone even at a higher indoor air speed of 0.5 m/s.

From Figure 5-5 and Figure 5-6 following observations were made:

- 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 0.6–1.2 clo, comfortable votes start deviating from ASHRAE Standard 55–2013 winter boundary and

shift towards lower temperatures. At clothing insulation ranges of 0.6–1.2 clo, subjects feel comfortable at temperatures as low as 16˚C in this region, revealing acclimatization of its inhabitants towards cold outdoor conditions.

Rohles and McCullough [**77**] 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 large fluctuations of temperature they face in naturally ventilated buildings [**11**] [**54**] [**36**] [**79**].

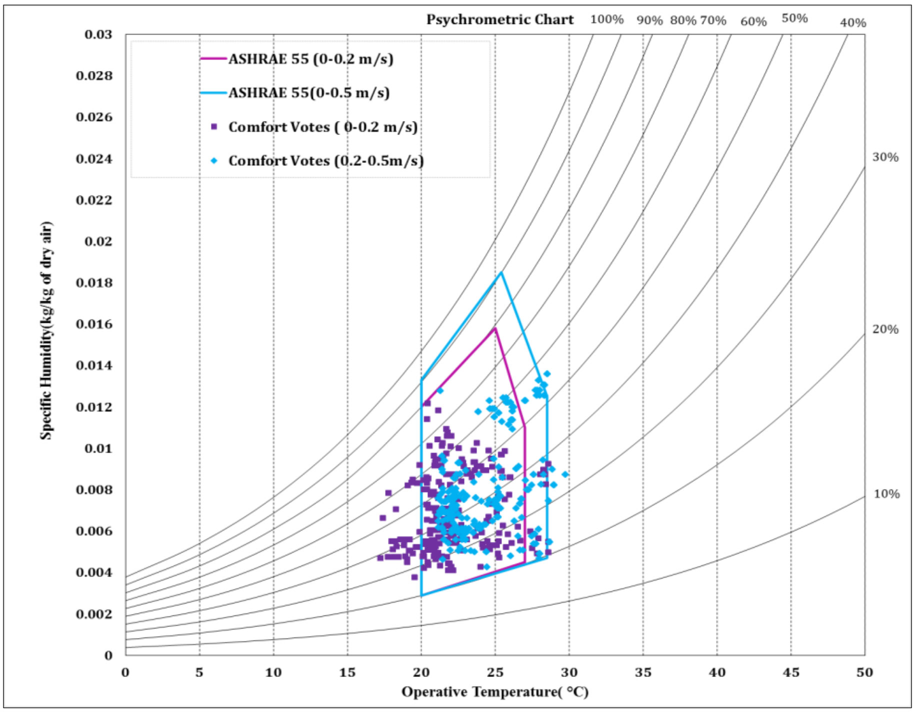


Figure 5-5 Plot of ASHRAE 55 comfort zones and winter comfortable votes (±1) for different air speed, activity and clo combinations (clo: upto 0.6 clo, activity: 1met-1.2 met and air flow: 0-0.5m/s)

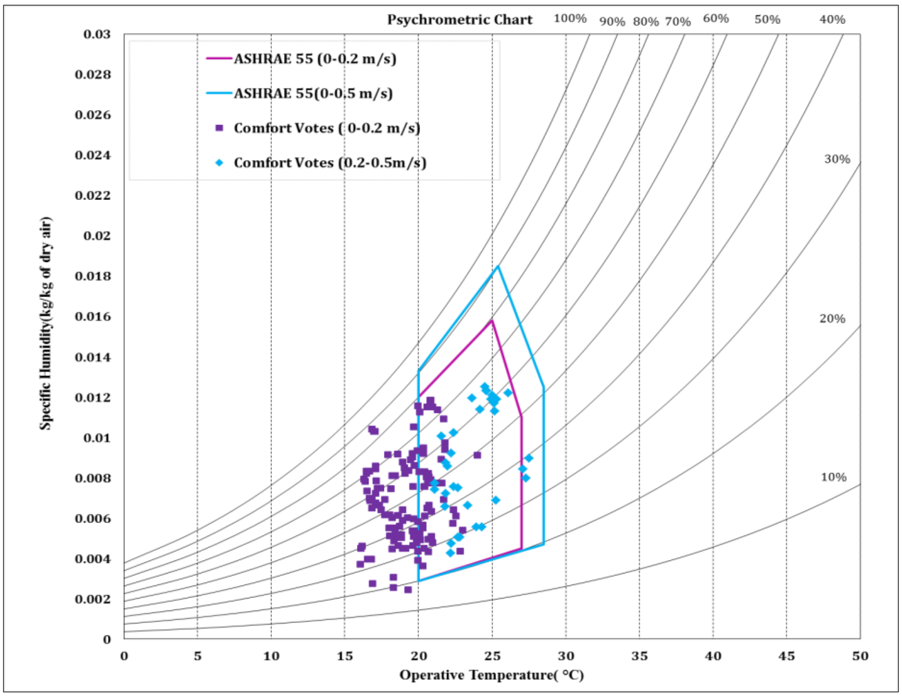


Figure 5-6 Plot of ASHRAE 55 comfort zones and winter comfortable votes (±1) for different air speed, activity and clo combinations (clo: 0.6 clo-1.2 clo, activity: 1met-1.2 met and air flow: 0-0.5m/s)

5.4 Proposed comfort zones: extending thermal comfort zones for naturally ventilated buildings

In the preceding sections, detailed discussions show the fragility of ASHRAE Standard 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 with rare occurrences of naturally ventilated buildings [**12**] [**14**]. Hence, this study focuses on proposing new comfort zones, modified over ASHRAE Standard 55 comfort zone, to suit this region's inhabitants comfort expectation, acclimatization behavior and the role of air speed preferences, especially for naturally ventilated buildings.

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

As per ASHRAE Standard 55–2013, 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% [**11**]. So, ASHRAE Standard 55 recommends 80% acceptability for the thermal environment with the percentage of people dissatisfied (PPD) should be lower than 20 percent as defined in **section 5.3.1.1** of ASHRAE Standard 55–2013.

While proposing extended comfort zone comfortable votes with clothing ranging up to 1.2 clo, activity level between 1–1.2 met and still air conditions up to 0.2 m/s across all seasons i.e. summer, moderate and winter are considered. Figure 5-7 clearly indicates that subjects are comfortable at higher temperatures than the range suggested by ASHRAE Standard 55 comfort zone. A new comfort zone, encompassing the comfortable predominant votes from 18˚C–32˚C between the relative humidity of 20%–80% has been proposed for this climatic zone especially for naturally ventilated buildings. 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. While deciding the comfort boundaries for thi climatic zone on psychrometric chart equal numbers of votes were left out of higher and lower side of temperature limits.

Procedure for defining comfort boundaries consists of following steps:

- Since ASHRAE Standard 55–2013 comfort zone for still air condition (shown with envelop 1-2-3-4-5) extends the temperature range of 20-27˚C and relative humidity varies from 20%–80% as shown in Figure 5-7, most of the votes for this study lie outside the current comfort zone.
- A new comfort zone is developed which fits most of the comfortable votes (at most 80%) for this study. It has been found in this study that subjects feel uncomfortable below 20% relative humidity for air velocity up to 0.2 m/s. So, considering lower limit for relative humidity as 20%, the points of ASHRAE Standard 55 comfort zone, viz. 1 (20 °C) and 5 (27 °C) are shifted to new positions 1’(18˚C) and 5’(32˚C) for winter and summer temperature comfort limit for still air condition, respectively. Point 1’ and 5’ are selected considering an equal number of comfort votes above and below these points.
- In a similar way upper relative humidity for comfort, for still air condition corresponds to 80% relative humidity and also comfortable votes lie below this maximum limit for this study, so point 2 (20˚C)

shifted to 2’ (18˚C) along 80% relative humidity line as shown in Figure 5-7.

- Since ASHRAE Standard 55 suggests same thermal sensation up to relative humidity of 50% for summer envelope but as relative humidity increases (above 50% RH), ASHRAE 55 envelope extends with a tilted line up to 80% relative humidity. So considering the same, proposed comfort zone has a parallel extension for relative humidity range between 50%–80%. Points 3 and 4 on ASHRAE Standard 55 comfort zone are shifted to 3’ and 4’ respectively for proposed comfort zone along the tilted line.

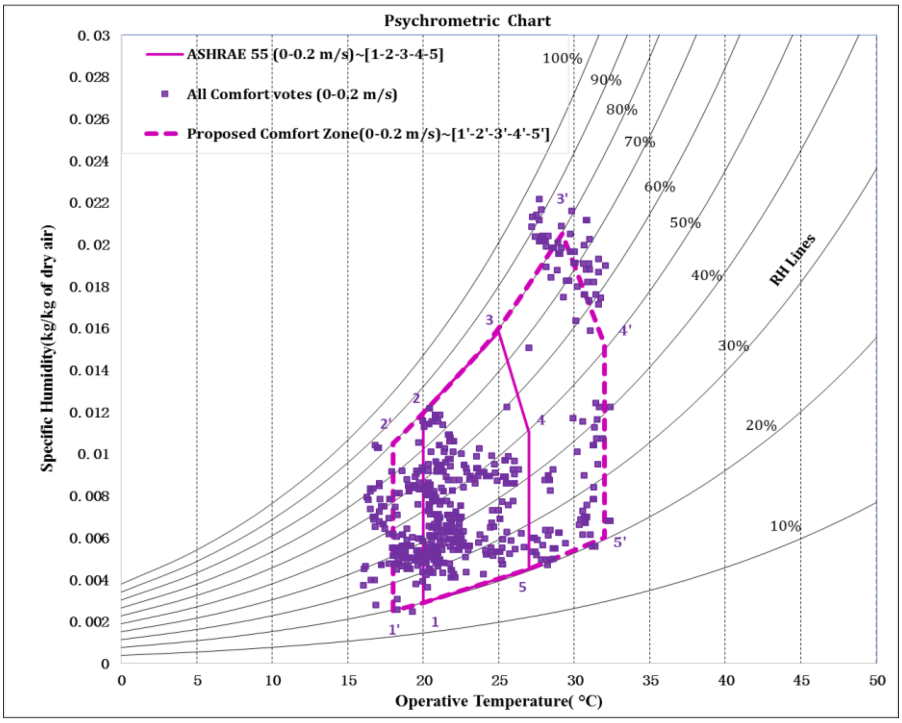


Figure 5-7 Proposed comfort zone for all seasons in composite climate of India (clo: 0-1.2 clo, activity: 1met-1.2 met and still air: up to 0.2 m/s)

5.4.2 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. [**189**] re-evaluated the ASHRAE Standard 55 database and found that temperatures in the range of 25.5˚C –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 Standard 55, towards enhancing the upper comfort limit up to 32˚C [**38**].

- 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 as described in Chapter 4 (**Section 4.6.3 and 4.6.4**).
- This effect was most pronounced on summer days when conditions are mostly uncomfortable due to a temperature excursion.
- Figure 5-8 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%–80% relative humidity.
- However, in the present study, very few votes (less than 20 votes) were found thermally comfortable at relative humidity more than 80% as shown in Figure 5-8. 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 an air speed of 0.5 m/s is drawn considering the upper relative humidity boundary up to 80%.

An extended comfort zone is outlined in Figure 5-8 considering the average air speed effects for all clothing up to 1.2 clo and activity level of 1–1.2 met.

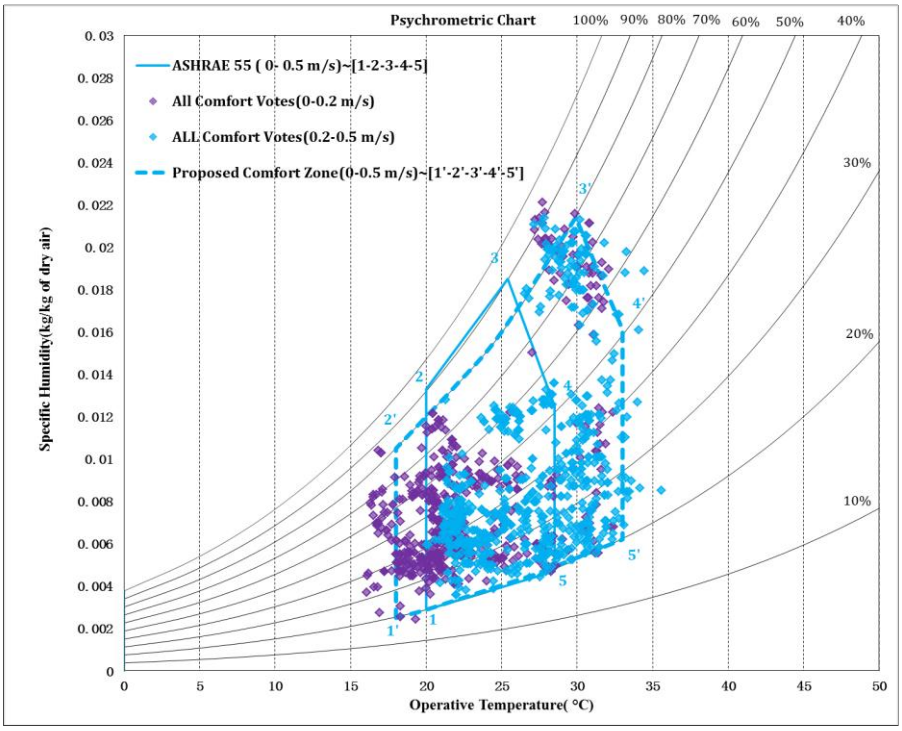


Figure 5-8 Proposed comfort zone for all seasons in composite climate of India (clo: 0-1.2 clo, activity: 1met -1.2 met and air flow: 0-0.5m/s)

5.4.3 Proposed comfort zone: fan forced air flow (0–1 m/s and 0–1.5 m/s)

Figure 5-9 shows the comfort zone, thus developed to reflect thermal comfort votes at air velocities from 0–1 m/s, activity 1–1.2 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 m/s expands the upper comfort boundary up to 34.5˚C. It can be noticed in the comfort zone of ASHRAE Standard 55 at higher airspeed the upper boundary for comfort zone is at 95% relative humidity. However, due to very few votes (<1% of total votes) above 80% relative humidity limits, comfort zone at an air speed of 1 m/s is drawn considering the upper relative humidity boundary up to 80%.

A final comfort zone at air velocities up to 1.5 m/s is shown in Figure 5-10. 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 Standard 55 comfort zone 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 1–1.5 m/s. Since the change in the maximum temperature for acceptability when air speed changes from 1–1.5 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 Standard 55–2013 [**4**] 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 high airspeed limit up to 1.2 m/s defined in ASHRAE Standard 55-2013.

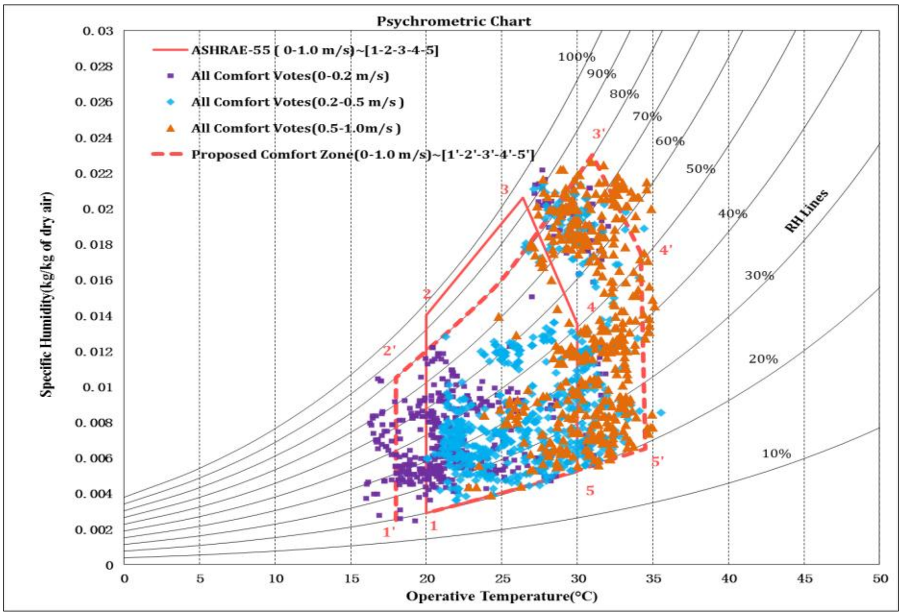


Figure 5-9 Proposed comfort zone for all seasons in composite climate of India (clo: 0-1.2 clo, activity: 1met-1.2 met, and air speed: 0-1.0m/s)

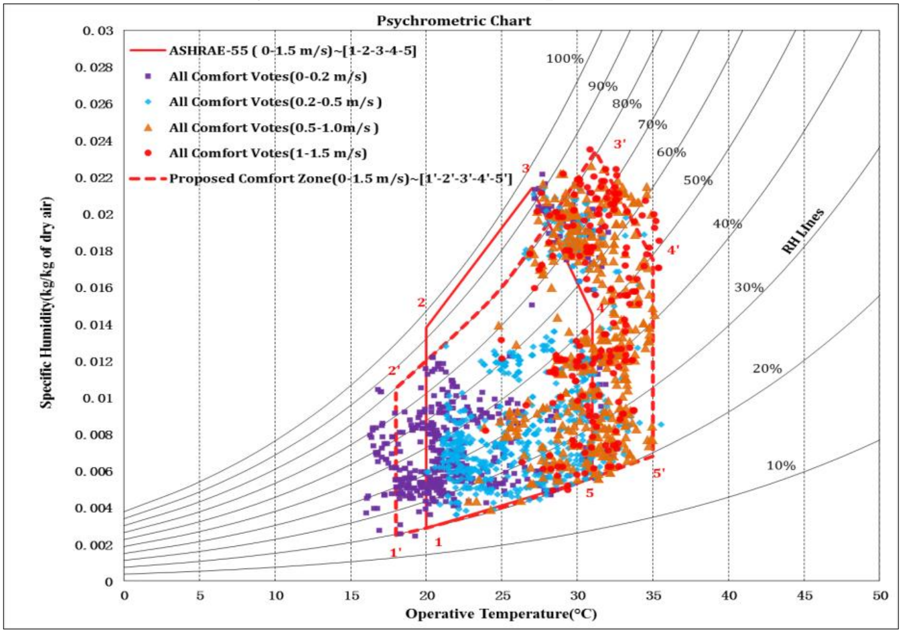


Figure 5-10 Proposed comfort zone for all seasons in composite climate of India (clo: 0-1.2 clo, activity: 1met -1.2 met, and air speed: 0-1.5m/s)

5.5 Validation of proposed comfort zones

The comfort data from the field study is used to define the comfort zones at different airspeed combinations as described in previous sections. However, it can be seen from Figure 5-7 that there were conditions where very few comfort votes lie in proposed zone which may be unreliable for defining comfort limits. Thus, indoor conditions have been continuously monitored, and comfort surveys were collected from different naturally ventilated buildings in composite climate of India. 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 subject's 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.

The validation of proposed comfort zones are based on the following assumptions:

i. Thermal comfort surveys have been collected for conditions where we have limited votes in the proposed comfort zones.
ii. The comfort surveys used in validation are collected for different clothing variations and air speed ranges for the summer, moderate and winter season.
iii. It is assured that comfort votes from this extended database should be at least 10% of what has been used to generate the redefined comfort zones.

Figure 5-11; Figure 5-12 and Figure 5-13 shows the comfortable (±1) votes plotted on the proposed comfort zone for air velocities from 0-0.2 m/s; 0-0.5 m/s; and 0-1m/s respectively. These comfortable votes have been used for each airspeed combinations to validate the proposed comfort zones. It can be seen from Figure 5-11; Figure 5-12 and Figure 5-13 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.

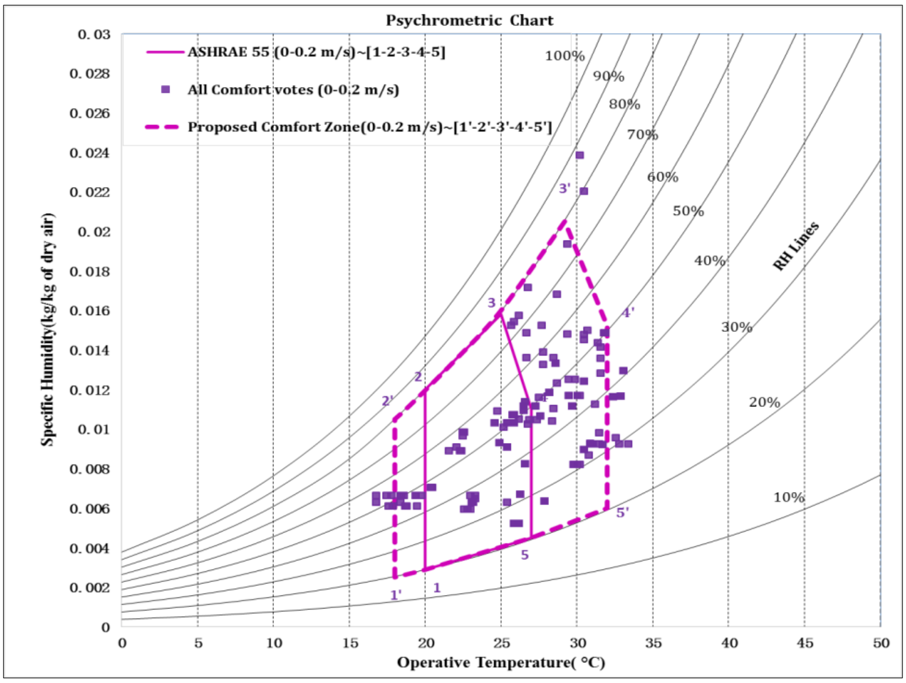


Figure 5-11 Validation of proposed comfort zone for all seasons in composite climate of India (clo: 0-1.2 clo, activity: 1met-1.2 met and air speed: up to 0.2 m/s)

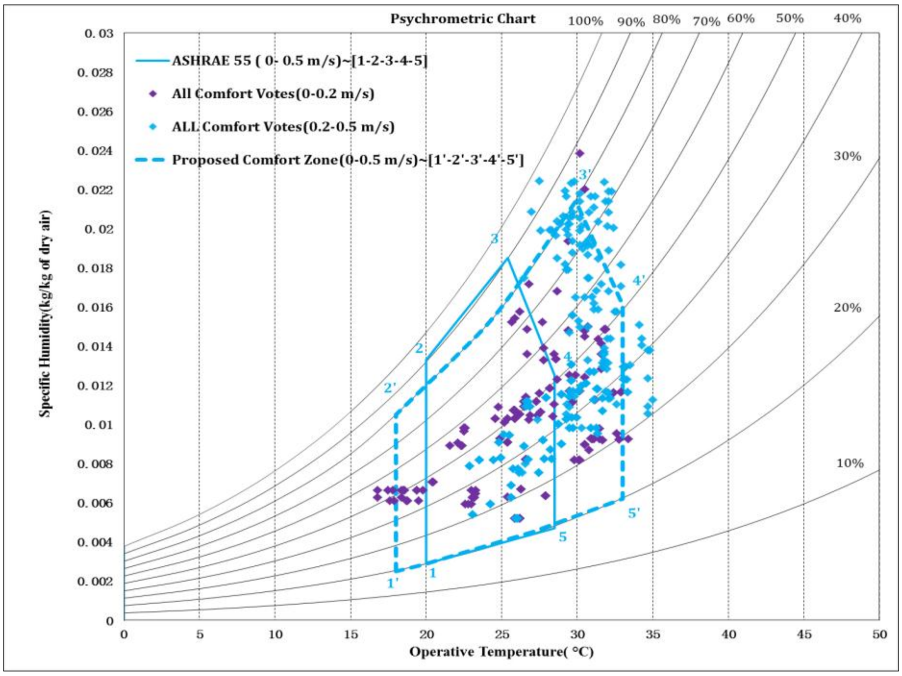


Figure 5-12 Validation of proposed comfort zone for all seasons in composite climate of India (clo: 0-1.2 clo, activity: 1met-1.2 met and air speed: up to 0.5 m/s)

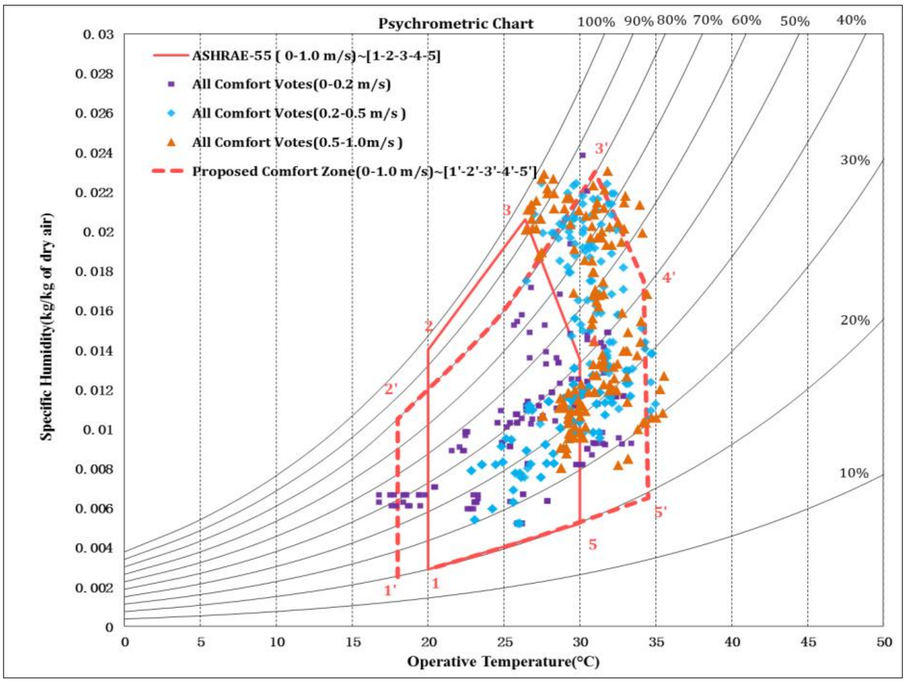


Figure 5-13 Validation of proposed comfort zone for all seasons in composite climate of India (clo: 0-1.2 clo, activity: 1met-1.2 met and air speed: up to 0.5 m/s)

5.5.1 Enhanced comfort zones and percentage peoples dissatisfied (PPD)

The ISO standard 7730 [**5**] and ASHRAE Standard 55–2013 [**4**] recommend that the proportion of people dissatisfied (PPD) should be lower than 20%. 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 5-14; Figure 5-15 and Figure 5-16 shows the uncomfortable votes plotted on the proposed comfort zone for air velocities from 0–0.2 m/s, 0–0.5 m/s and 0–1.5 m/s respectively. It can be seen from Figure 5-14; Figure 5-15 and Figure 5-16 that less than 20% uncomfortable votes lay 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 5.2 also shows the percentage of people dissatisfied in the proposed comfort zones at different airspeed ranges. In all cases, the percentage of people dissatisfied (PPD) are less than 20%, so these comfort zones are suitable for capturing the real dynamic nature of naturally ventilated buildings as well as adaptations of subjects for composite climate of India.

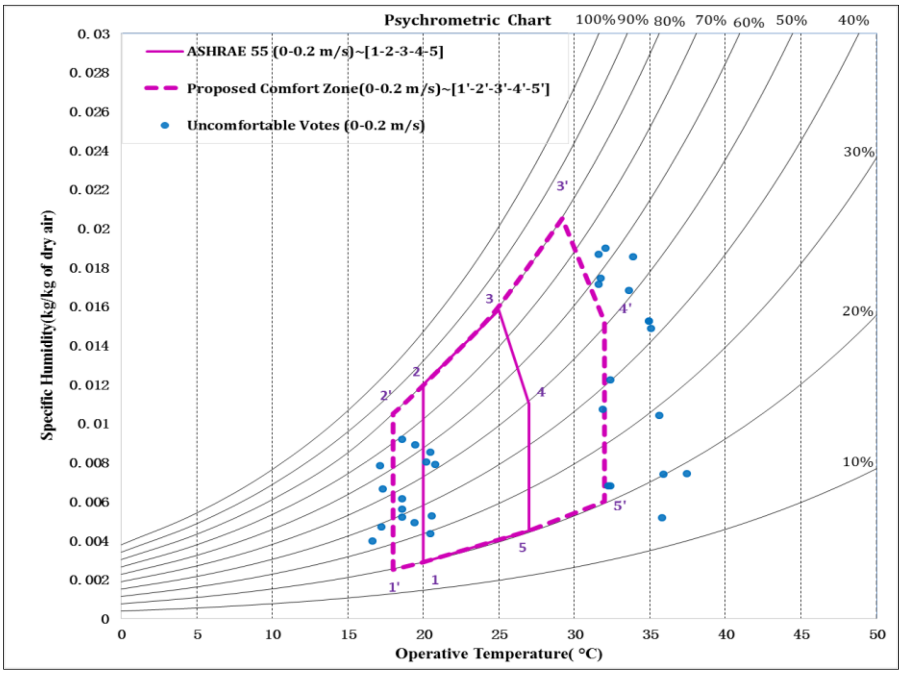


Figure 5-14 Uncomfortable votes in proposed comfort zone for all seasons in composite climate of India (clo: 0-1.2 clo, activity: 1 met -1.2 met and air speed: up to 0.2m/s) less than 20% of all comfort votes (not shown)

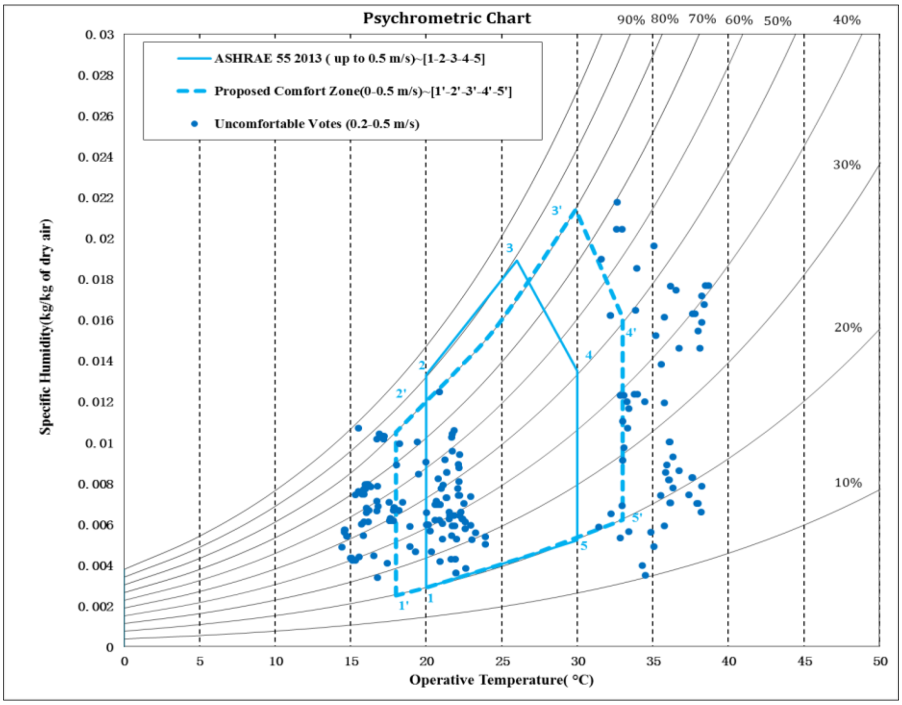


Figure 5-15 Uncomfortable votes in proposed comfort zone for all seasons in composite climate of India (clo: 0-1.2 clo, activity: 1 met -1.2 met and air speed: 0-0.5m/s) less than 20% of all comfort votes (not shown)

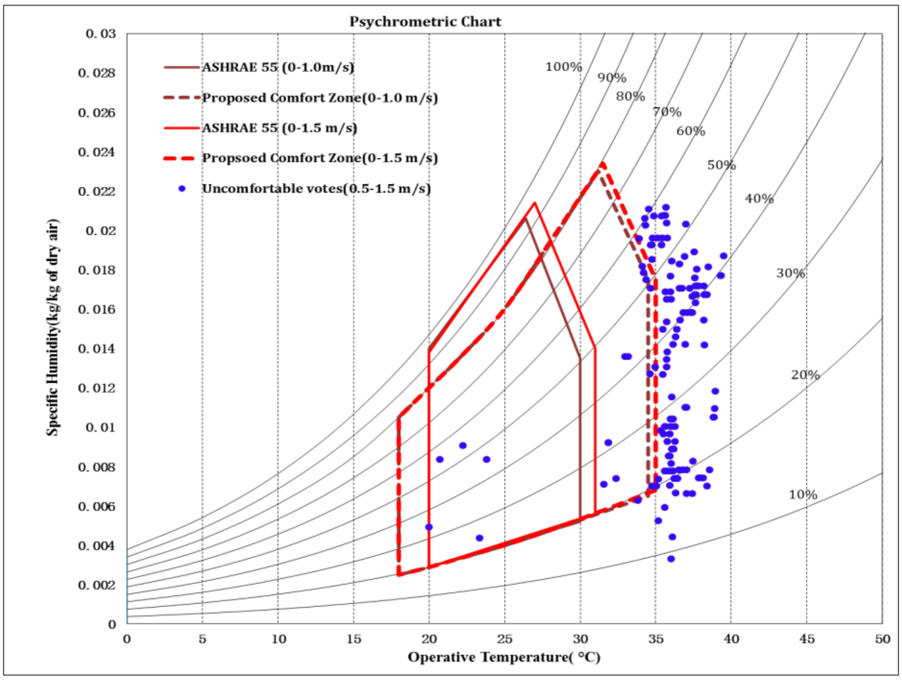


Figure 5-16 Uncomfortable votes in proposed comfort zone for all seasons in composite climate of India (clo: 0-1.2 clo, activity: 1 met -1.2 met and air speed: 0-1.5m/s) less than 20% of all comfort votes (not shown)

Table 5.2 Percentage of people dissatisfied (PPD) in different proposed comfort zones

Season	Clo value range	Air velocity range (m/s)	% Comfortable votes(±1 votes) in Proposed Comfort Zone	% Uncomfortable votes in Proposed Comfort Zone
All seasons	Up to 1.2 clo	0–0.2 m/s	**80 %**	**≤ 20%**
		0–0.5 m/s	**80 %**	**≤ 20%**
		0–1.5 m/s	**80 %**	**≤ 20 %**

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. 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 5-17 indicates that subjects are comfortable at a temperature up to 32˚C (relative humidity~20%–80%) in still air conditions of 0–0.2 m/s and comfortable up to 34.5˚C (relative humidity~20%–80%) at a higher speed up to 1 m/s.

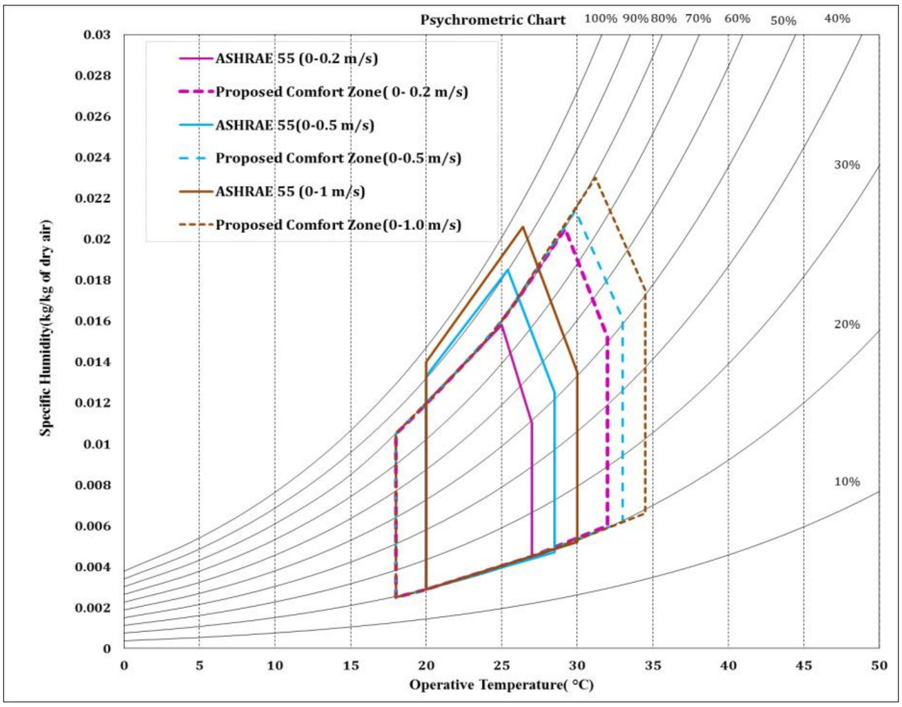


Figure 5-17 Proposed extended comfort zones for thermal comfort for different air velocities in composite climate of India

5.6 Chapter summary

This chapter summarizes the findings of a thermal comfort field study conducted in thirty-two naturally ventilated 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 Standard 55–2013 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 ASHRAE Standard 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 indicates that subjects are comfortable at the temperature up to 32˚C and relative humidity of 20%–80% in still air conditions of 0–0.2 m/s. The comfort zones are further extended up to 35˚C between the relative humidity of 20%–80% at the higher indoor air speed of 1.5 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 1–1.5 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.

CHAPTER 6

DEFINING CLIMATIC BOUNDARY FOR HIGH THERMAL MASS ON BUILDING BIOCLIMATIC DESIGN CHART

6.1 Preamble

About 73% of the energy consumed in Indian residential buildings is used for providing thermal and visual comfort indoors [**1**]. For hot tropical countries like India, where there is a tremendous diversity in climate (hot summers to cold winters), high thermal mass is still considered as the primary construction practice for its residential and commercial buildings [**155**] [**156**]. Traditionally, thermal mass is useful for dampening the wide range fluctuation in the outdoor temperature and maintaining the air temperature within a comfortable range inside the building [**15**] [**131**]. Existing building bio-climatic design chart incorporates climatic envelope/boundary for the use of high thermal mass in buildings, based on experimental field studies conducted by Givoni [**14**] on some thermally heavyweight buildings/chambers in Israel and California.

Researchers [**20**] [**160**] [**190**] have used ASHRAE Standard 55 comfort zone in defining the potential of passive strategies to produce indoor comfort in the buildings through BBCCs approach. The main issue behind the construction of bio-climatic charts for the building is to determine the comfort zone and the boundaries of the different design strategies in the design phase of building [**190**] [**179**]. Thus, in previous chapters comfort boundaries on the psychrometric chart are defined for this climatic zone for different airspeed ranges based on adaptive comfort approach as shown in Figure 5-17. Since this study is motivated towards the development of a building bio-climatic design chart for the use of high mass strategy in buildings through adaptive comfort approach in composite climate of India. Thus work has been extended for the development of polygon using high thermal mass strategy in the composite climate of India through the following tasks:

1. Long-term monitoring of high mass buildings and their thermal performance in different climatic conditions or seasons in the region.

2. Development of correlations between outdoor and indoor temperature to predict the role of high thermal mass in buildings.
3. Finally, defining the climatic boundary of ambient conditions for high thermal mass strategy to develop a customized building bio-climatic design chart for residential and office buildings in composite climate of India.

6.2 Field study description and climatic conditions

Fully functional high mass residential and office buildings in the composite climate of Jaipur were selected for long-term monitoring. The thermal monitoring of buildings with high thermal mass was performed in the composite climate of Jaipur (26.82˚N, 75.80˚E, and 390m mean sea level). Two residential and two office high thermal mass buildings, one with stone construction and other with brick construction were used for this purpose.

Climatic conditions in this region vary from scorching hot during summer to chilling cold during winter seasons. Summer peak temperature soars above 45˚C and 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 [**53**] [**103**]. Since high thermal mass is found to be most effective during peak summer or winter months for the cooling or the heating purposes in late hours [**15**] [**26**]. Therefore, detailed thermal monitoring of selected high mass residential and office buildings were carried out for summer (1 June 2015–30 September 2015) and winter season (1 November 2015–29 February 2016). Climatic data used in the present analysis refers to a local weather station at Malaviya National Institute of Technology (MNIT) campus of Jaipur.

6.3 Selection and description of high mass buildings

The monitored buildings are constructed of conventional construction materials for the region. External walls are built of brick/stone of 0.25m–0.30 m and gypsum plaster of 0.012m–0.015 m thickness on both sides, and roofs are built of Reinforced Cement Concrete (RCC) with an overall thickness of about 0.15m with mortar. Window assemblies are single clear glass panes of 0.003m–0.006m thickness. This type of conventional construction is common in almost all region of the composite climate of India [**156**] [**155**]. The buildings are naturally ventilated and provide adaptive controls such as the use of windows and doors, control of ventilators, the operation of fan and fan speed regulators.

6.3.1 Residential buildings

a) Stone wall construction

The stone wall building used for present study is a double storey building and situated in the residential campus at Malaviya National Institute of Technology, Jaipur. Three family members living in this monitored building are; one male, one female, and one female child. The building built area is 34m^2 and the building is oriented in North–West direction as shown in Figure 6-1 (a). The building has open space in all the four directions, and the external walls are exposed to ambient air. The roof of the building is constructed of Reinforced Concrete with a thickness of about 0.15m with mortar. The building was not equipped with any heating or cooling devices. The construction details and respective thermal properties are presented in Table 6.1.

b) Brick wall construction

The selected building is oriented in the true North direction with total built area of 28m^2. The residential building has two members both male; the age of 30 years. The entire external walls of buildings expose to ambient conditions. External walls are double brick construction with a thickness of 0.23m having plastered, 0.015m–0.020 m, both sides. Building inter-partition walls are made of single brickwork having a thickness of 0.12 m with plaster both side of thickness 0.015m. Construction material used on the roof of the building composes of Reinforced Concrete (RCC) of thickness about 0.15 m. Table 6.2 presents the overall heat transfer and details of construction material used for this building. Window assemblies are single clear glass panes of 3 mm thickness with a window to wall ratio of 30%. Net opening is about 20% of the floor area in the form of doors and windows. The residential building plan is illustrated in Figure 6-1 (b).

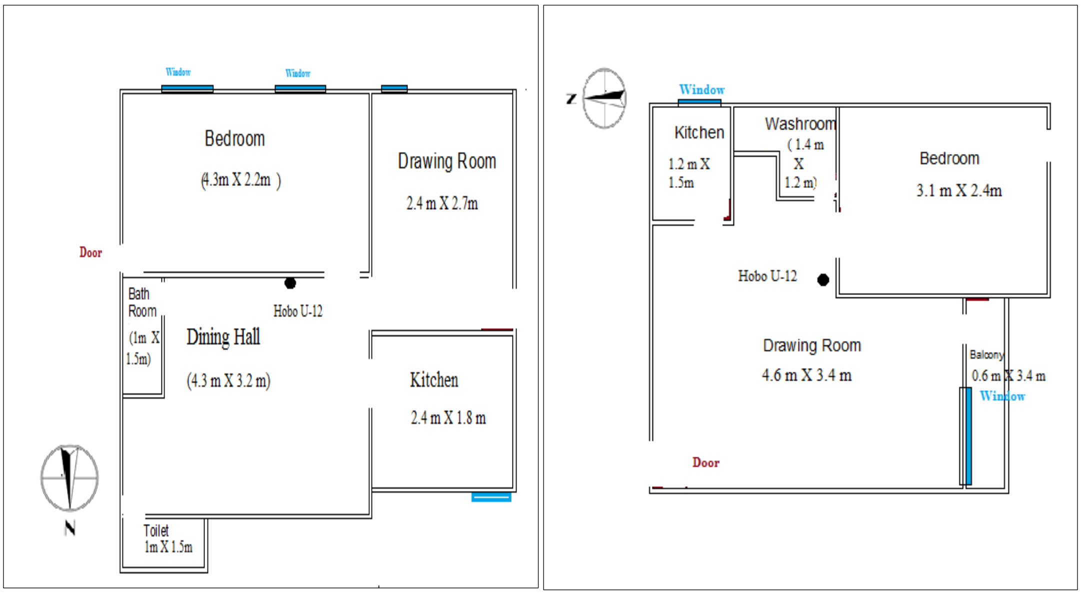


Figure 6-1 Plan layout of monitored high thermal mass residential buildings (a) stone wall construction (b) brick wall construction

Table 6.1 Description and calculated thermophysical properties of monitored stone wall residential building

Layer by Layer construction	**Conductivity (W/m K)**	**Density (kg/m^3)**	**Specific heat (J/kg K)**	**Overall heat transfer coefficient(U-W/m^{2}K)**
External walls				
300 mm Stone	1.83	2515	790	2.761
20 mm Cement/Mortar/Plaster	0.72	1760	840	
Internal walls				
20 mm plaster	0.72	1760	840	2.012
230 mm brick burned	0.85	1500	840	
20 mm plaster	0.72	1760	840	
Floor				
Ceramic tiles	0.8	1700	850	0.647
Poured concrete	1.4	2100	840	
Roof				
20 mm plaster	0.72	1760	840	3.138
150 mm poured concrete	1.4	2100	840	
20 mm plaster	0.72	1760	840	
Openings	**Net area (m^2)**	**U-value (W/m^{2}K)**	**SHGC**	
Single Pane Glass (Generic 3 mm Tinted)	0.30-2.0 m^2	1.96	0.70	
Wooden doors	2.28 m^2	2.02		

Table 6.2 Description and calculated thermophysical properties of monitored brick wall residential building

Layer by layer	**Conductivity (W/m K)**	**Density (kg/m^3)**	**Specific heat (J/kg K)**	**Overall heat transfer coefficient(U-W/m^2K)**
External walls				
20 mm plaster	0.72	1760	840	2.064
230 mm brick burned	0.85	1500	840	
20 mm plaster	0.72	1760	840	
Internal walls				
20 mm plaster	0.72	1760	840	2.914
120 mm brick burned	0.85	1500	840	
20 mm plaster	0.72	1760	840	
Floor				
Ceramic tiles	0.8	1700	850	0.647
Poured concrete	1.4	2100	840	
Roof				
20 mm plaster	0.72	1760	840	3.138
150 mm poured concrete	1.4	2100	840	
20 mm plaster	0.72	1760	840	
Openings	**Net area (m^2)**	**U-value (W/m^2K)**	**SHGC**	
Single Pane Glass (Clear 3 mm glass)	1.0-3.5 m^2	1.96	0.675	
Wooden doors	2.28 m^2	2.02		

6.3.2 Office buildings

a) Stone wall construction

Monitored stone wall office building is a single storey building, in the Mechanical Engineering Department at Malaviya National Institute of Technology, Jaipur. The built up area of monitored office is 14m^2 (Figure 6-2 (a)). The building was mostly unoccupied during the study period, but fan and windows were kept open or closed as per the indoor or outdoor conditions to resemble the experimental conditions more similar to occupied buildings during office hours. The construction details and respective thermal properties are presented in Table 6.3.

a) Brick wall construction

The monitored brick wall office building is a three storey building, in the new Centre for Energy Department at Malaviya National Institute of Technology, Jaipur. Brick wall office building was a three storey building with a built-up area of about 505.6m^2. The experimental room was situated at first floor of the building. The built up area of the experimental room was 18m^2 as shown in Figure 6-2 (b). The room has a door, two windows and glazing with areas 1.7m^2, 3.0m^2, and 1.5m^2 respectively. The window was single pane glass of thickness 3mm with overall WWR of about 20%. The office room was occupied during the study period. The office occupants were free to carry out their normal activities but restricted to use any heating or cooling equipments as per the study requirement. The construction details and thermal properties are presented in Table 6.4.

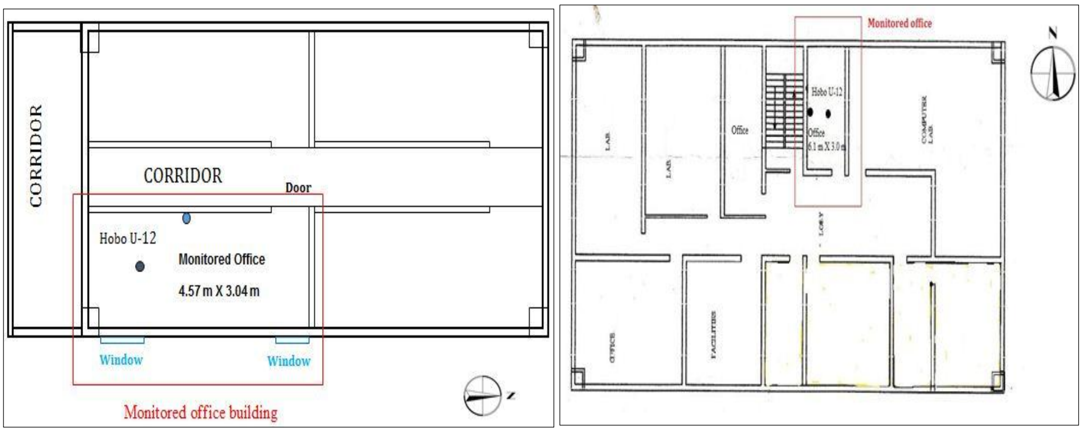


Figure 6-2 Plan layout of monitored high thermal mass office buildings (a) stone wall construction (b) brick wall construction

Table 6.3 Description and calculated thermo physical properties of monitored stone wall office building

Layer by Layer construction	**Conductivity (W/m K)**	**Density (kg/m^3)**	**Specific heat (J/kg K)**	**Overall heat transfer coefficient(U-W/m^{2}K)**
External walls				
300 mm Stone	1.83	2515	790	2.761
20 mm Cement/Mortar/Plaster	0.72	1760	840	
Internal walls				
20 mm plaster	0.72	1760	840	2.012
120 mm brick burned	0.85	1500	840	
20 mm plaster	0.72	1760	840	
Floor				
Ceramic tiles	0.8	1700	850	0.647
Poured concrete	1.4	2100	840	
Roof				
20 mm plaster	0.72	1760	840	3.138
150 mm poured concrete	1.4	2100	840	
20 mm plaster	0.72	1760	840	
Openings	**Net area (m^2)**	**U-value (W/m^{2}K)**	**SHGC**	
Single Pane Glass (Generic 3 mm Tinted)	0.5-2.0 m^2	1.96	0.70	
Wooden doors	2.28 m^2	2.02		

Table 6.4 Description and calculated thermophysical properties of monitored brick wall office building

Layer by layer	Conductivity (W/m K)	Density (kg/m^3)	Specific heat (J/kg K)	Overall heat transfer coefficient(U-W/m^2K)
External walls				
20 mm plaster	0.72	1760	840	2.064
230 mm brick burned	0.85	1500	840	
20 mm plaster	0.72	1760	840	
Internal walls				
20 mm plaster	0.72	1760	840	2.914
120 mm brick burned	0.85	1500	840	
20 mm plaster	0.72	1760	840	
Floor				
Ceramic tiles	0.8	1700	850	0.647
Poured concrete	1.4	2100	840	
Roof				
20 mm plaster	0.72	1760	840	3.138
150 mm poured concrete	1.4	2100	840	
20 mm plaster	0.72	1760	840	
Openings	**Net area (m^2)**	**U-value (W/m^2K)**	**SHGC**	
Single Pane Glass (Clear 3 mm glass)	1.2-3.5 m^2	1.96	0.675	
Wooden doors	2.28 m^2	2.02		

6.4 Instrumentation used for thermal monitoring

Long-term monitoring work includes the measurements of air temperature, relative humidity, and luminance level in the building. Hobo-12 type loggers were utilized for this purpose. Ambient parameters like temperature, relative humidity and average solar radiation (W/m^2) measured by a local weather station present at MNIT campus for all monitoring period were used in this study. A detailed description of instrumentation used and their accuracy is listed in Table 3.4.

6.5 Long term thermal monitoring conditions in high mass buildings

Occupants were advised to carry out their, as usual, living conditions without any restriction during the study period. In the summer season, the role of thermal mass was to reduce the indoor air temperature fluctuations using the high heat storage capacity of building materials like stone and brick in the building structure. So, during the hottest summer period of the year, windows in the buildings were kept closed during the daytime and open during the night to flush out the stored heat in the building envelope. Also, a ceiling fan was commonly used during the day and night, as an adaptive action, to maintain thermal comfort by taking advantage of high air speed. Contrary, during the winter season, high thermal mass in buildings was used to bring up the indoor temperature, by utilizing direct and indirect solar gains during daytime through openings and storing it for later utilization in the evening when it needed most.

Extensive interactions with the occupants of the buildings were carried out to record the adaptive actions practiced by them to make the living condition comfortable. Opening/closing of the window, on/off the ceiling fan and changing clothing levels were the primary adaptation actions. Details of occupant’s probable adaptive actions for some typical days of different seasons have been reported in Table 6.5 and Table 6.6 for residential buildings. Similar adaptive actions were reported from the occupants of office buildings in various periods during the monitoring period. No heating or cooling equipment has been used to modify the indoor temperature except ceiling fan or opening /closing of windows.

Table 6.5 Daily use descriptions of occupant’s behavior in different season in stone wall residential building on typical days

Season	Day/Month	Descriptions
Summer season	Wednesday/3 Jun 2015	The house is occupied mainly by the female member and one child, Free running, Ceiling Fan operating during day and night, Window partially open.
	Tuesday/14 Jul 2015	Normal use, Window open, Ceiling Fan operating, Free running
	Saturday/8 Aug 2015	Raining outside, Windows are open day and night; Ceiling fan was operated.
	Thursday/10 Sept2015	Normal use, Window partially open, Ceiling Fan working, Free running
Winter season	Tuesday/12 Nov 2015	The house is occupied mainly by the female member and one child, Free running, Ceiling Fan working during day and night, Window partially open
	Thursday /17 Dec 2015	Normal use, Window closed, Free running
	Friday/15 Jan 2016	Windows are closed day and night. Normal use.
	Tuesday/9 Feb 2016	Normal use, Window closed, Free running

Table 6.6 Daily use descriptions of occupant's behavior in different season in brick wall residential building on typical days

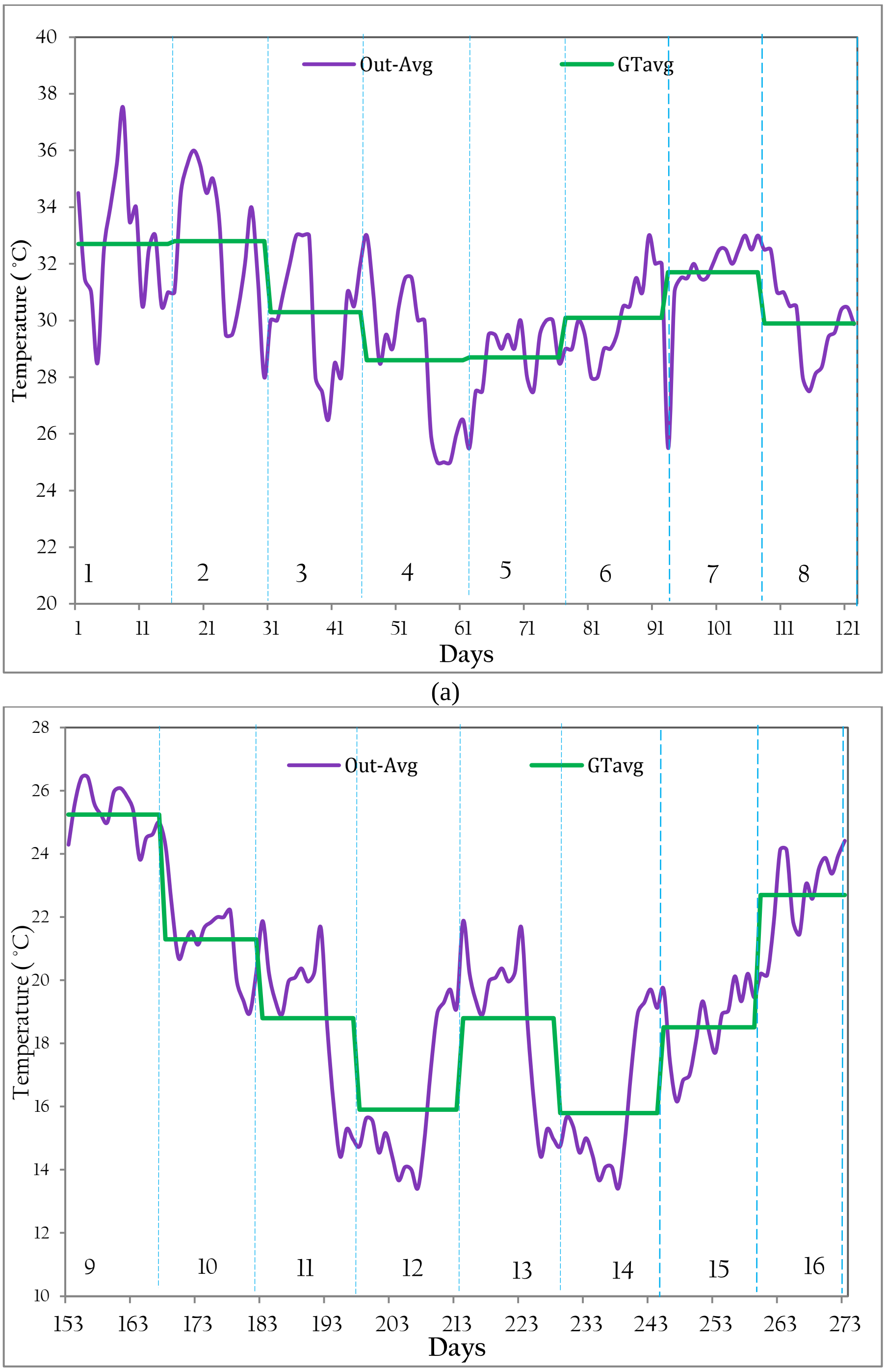
Season	Day/Month	Descriptions
Summer season	Wednesday/3 Jun2015	Free running, Ceiling fan operating during night, Window partially open during the daytime and fully open during the night.
	Tuesday/14 Jul 2015	Normal use, Window partially open, Ceiling Fan operating, Free running
	Saturday/8 Aug 2015	House is closed and empty, raining outside, Windows are open during the day and the night.
	Thursday/10 Sept 2015	Normal use, Window partially open, Ceiling Fan operating, Free running.
Winter season	Thursday/12 Nov 2015	Free running, Ceiling Fan working during night, Window partially open during the daytime but closed during the night.
	Thursday /17 Dec 2015	Normal use, Window closed, Free running
	Monday/25 Jan 2016	House is closed; Windows are closed day and night.
	Tuesday/9 Feb 2016	Normal use, Window is closed during the day and night.

6.6 Seasonal thermal monitoring for residential buildings

In the present study, the monitored data is segregated for evaluating the thermal performances of high mass residential buildings in the summer and winter season, separately. Thermal performance study of selected buildings is based on the indoor and outdoor temperature data.

During the thermal monitoring, it was observed that the outdoor average temperature fluctuates in each month, rising for some days and then drops down in subsequent days. This suggested that the whole monitoring period could be divided roughly into sixteen sub-periods as shown in Figure 6-3. Previous studies show that average of this sub–period has a substantial effect on indoor temperatures [**111**] [**118**] [**175**]. Thus, in the present study, for each sub-period, ''grand'' averages (average temperature for each sub–period, GT_{avg}) were computed for the outdoor temperatures. In the present study, iteration of these different sub–periods, having a duration of 10 days, 15 days and 20 days based on different outdoor average temperatures during correlation development have been carried out to find out the suitable grand average temperature for analysis. From the analysis, it has been observed that a grand average temperature of 15 days produced a substantial effect on indoor temperatures. Thus, each sub–

period has been divided into a span of 15 days in each month during summer and winter season.



(a)

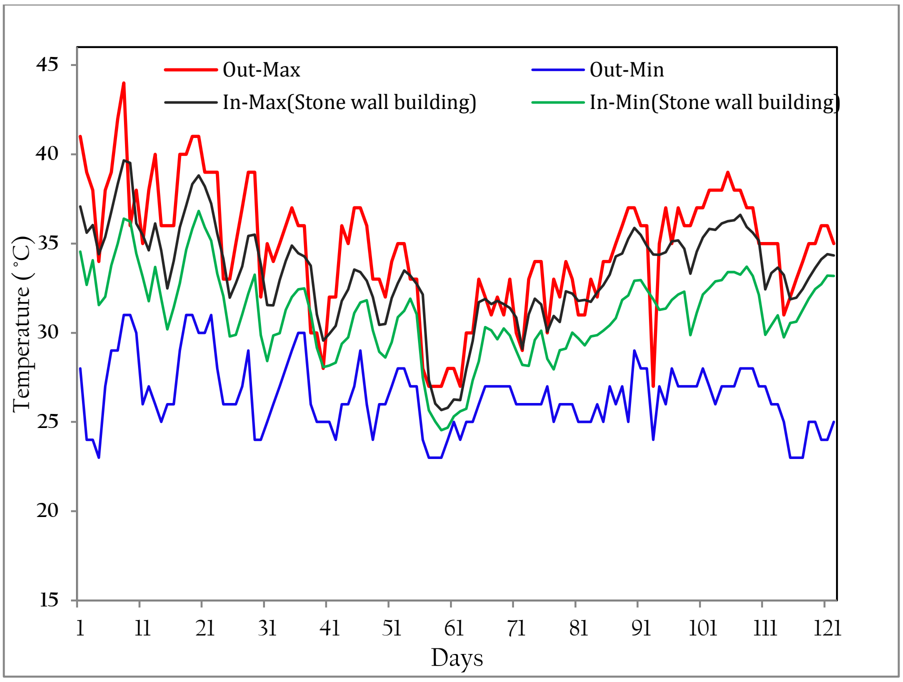
(b)

Figure 6-3 Outdoor average temperatures during the monitoring period with the Grand Average Temperature (GT_{avg}) for (a) summer and (b) winter with different sub-periods

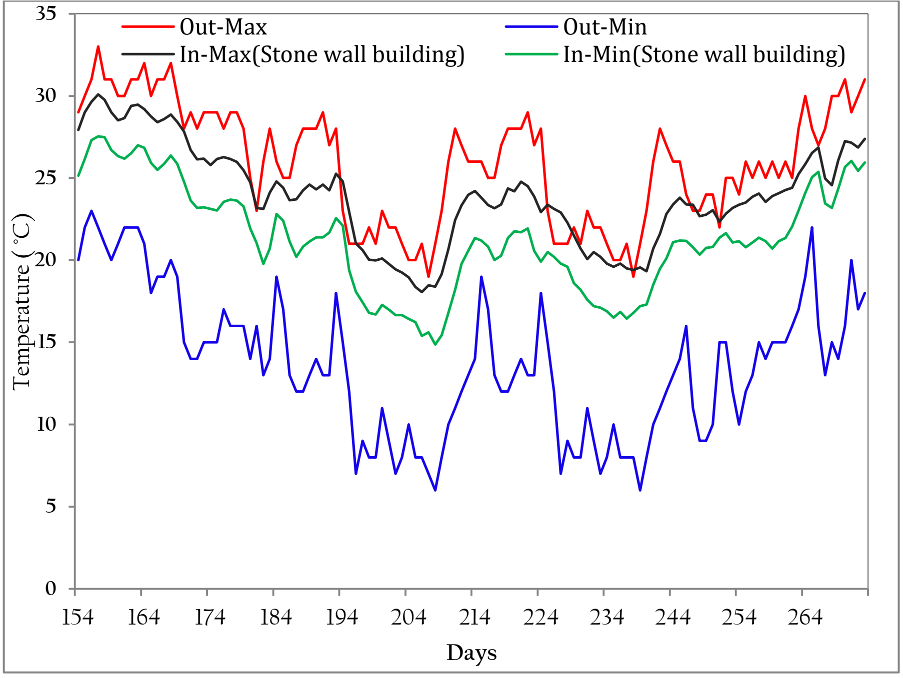
6.6.1 Stonewall residential building

a) Summer performance analysis

During the peak month of the summer, there was a continuous increase in indoor and outdoor temperature due to heat wave conditions prevailing in the summer season of Jaipur climate. The thermal mass of building modulates the indoor temperature very well as lower indoor temperature swing about 2˚C–4˚C and a time lag of 4–5hr has been observed during the summer monitoring period. Figure 6-4(a, b) represents the daily indoor and outdoor temperatures observed for the stone wall building during summer and winter season, respectively. Also, the average indoor temperature during this period was observed 1˚C–2˚C higher than average outdoor temperature as presented in Table 6.7. Higher indoor average temperature above the outdoor temperature is due to the high heat storage capacity of building thermal mass. Also, from temperature profile, it was also observed that during night time outdoor average minimum temperature not falls below 25˚C that is not sufficient to cool the high mass of the stone wall, even if the building was night vented. As Givoni [**14**] [**124**] discussed for experimental results in Israel, for the effective night ventilation to cool high thermal mass inside the building, the minimum outdoor temperature should fall below 20˚C. The high thermal mass stone building was found very effective to narrow down the indoor fluctuations vis-à-vis outdoor ambient changes during summer and winter season as shown in Figure 6-5.

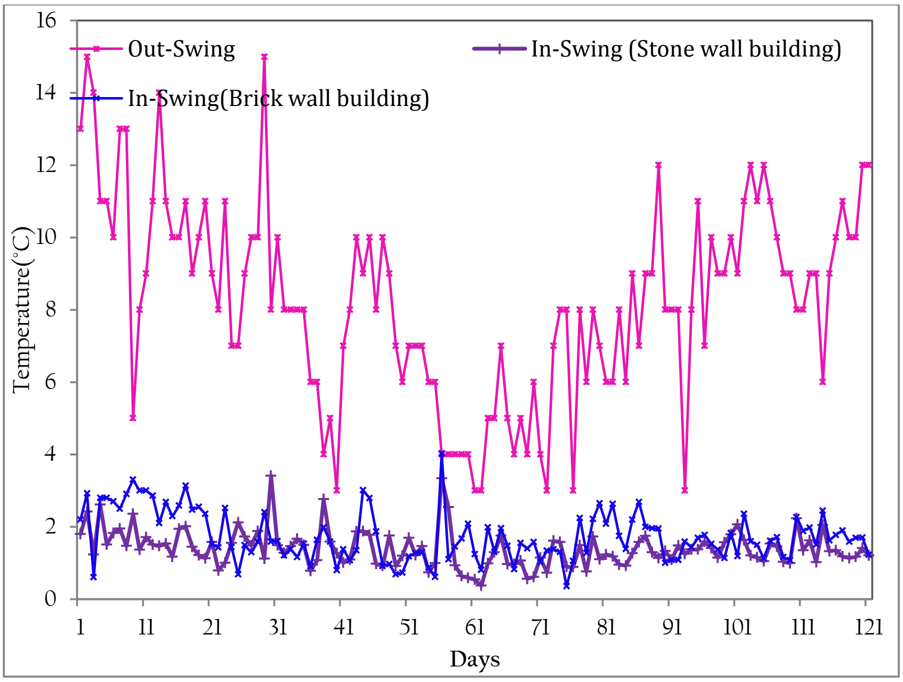


(a)

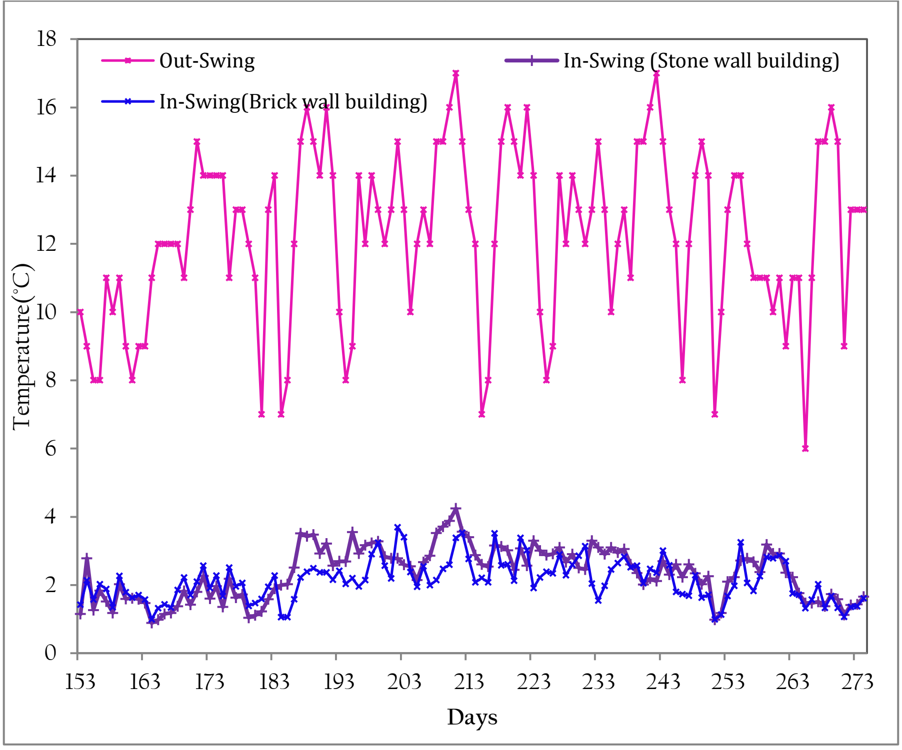


(b)

Figure 6-4 Indoor and outdoor temperature profile for monitored stone wall residential buildings (a) during summer and (b) during winter season



(a)



(b)

Figure 6-5 Indoor and outdoor temperature swings for residential buildings during (a) summer and (b) winter monitored period

b) Winter performance analysis

Winter season in a composite climate of India spans more than four months from November to February. The condition during this season is very cold and harsh as ambient temperatures fall below a minimum of 4°C during peak winter days. Thermal monitoring of stone wall building was carried out from 1

November 2015–29 February 2016 for the entire winter season. The average outdoor temperature during this period varied from 15˚C–25.4˚C with a mean swing of 8˚C–17˚C. During the same period, average indoor temperature varied from18˚C–27˚C with a mean swing of 2˚C–4˚C. It can be seen from Table 6.7 that the average indoor air temperature is about 2˚C–3˚C above the outdoor average temperature during peak winter days due to solar penetration through windows. This elevation is most pronounced during peak winter month viz. December and January and decreases afterward due to lower solar elevation. Also, high thermal mass in building envelope results in constant indoor air temperature patterns despite the varying ambient fluctuations. Also, management of the windows, as an adaptive action taken by the occupants, helps in achieving the indoor comfort conditions as per their needs. A detailed description of measured indoor and outdoor average temperature, indoor and outdoor swing and thermal lag obtained during different sub-periods in the summer and winter season for the stone wall residential building is summarized in Table 6.7.

Table 6.7 Description of day average temperatures, diurnal swing and thermal time lag for stone wall residential building

Season	Sub-period	Day average temperature(˚C)		Temperature swing (˚C)		Thermal time lag (hr.)
		Indoor	Outdoor	Indoor	Outdoor	
Summer season	1	34.6	32.7	1-3	5-15	3-4
	2	34.4	32.8	2-4	7-15	4-5
	3	32.9	30.3	1-3	3-10	4-5
	4	31.0	28.6	1-2	4-9	3-4
	5	30.1	28.7	1-2	3-8	3-4
	6	32.8	30.1	1-2	3-12	4-5
	7	34.8	31.7	1-4	9-12	4-5
	8	33.4	29.9	1-2	6-12	4-5
Winter season	9	27.8	25.3	1-3	8-12	3-4
	10	24.4	21.3	2-4	7-15	3-4
	11	22.1	18.8	3-4	8-17	4-5
	12	18.8	15.9	2-3	7-16	4-5
	13	22.0	18.5	3-4	9-17	3-4
	14	18.8	15.8	1-3	7-14	4-5
	15	22.3	18.7	1-3	6-13	4-5
	16	24.5	22.7	2-4	6-16	3-4

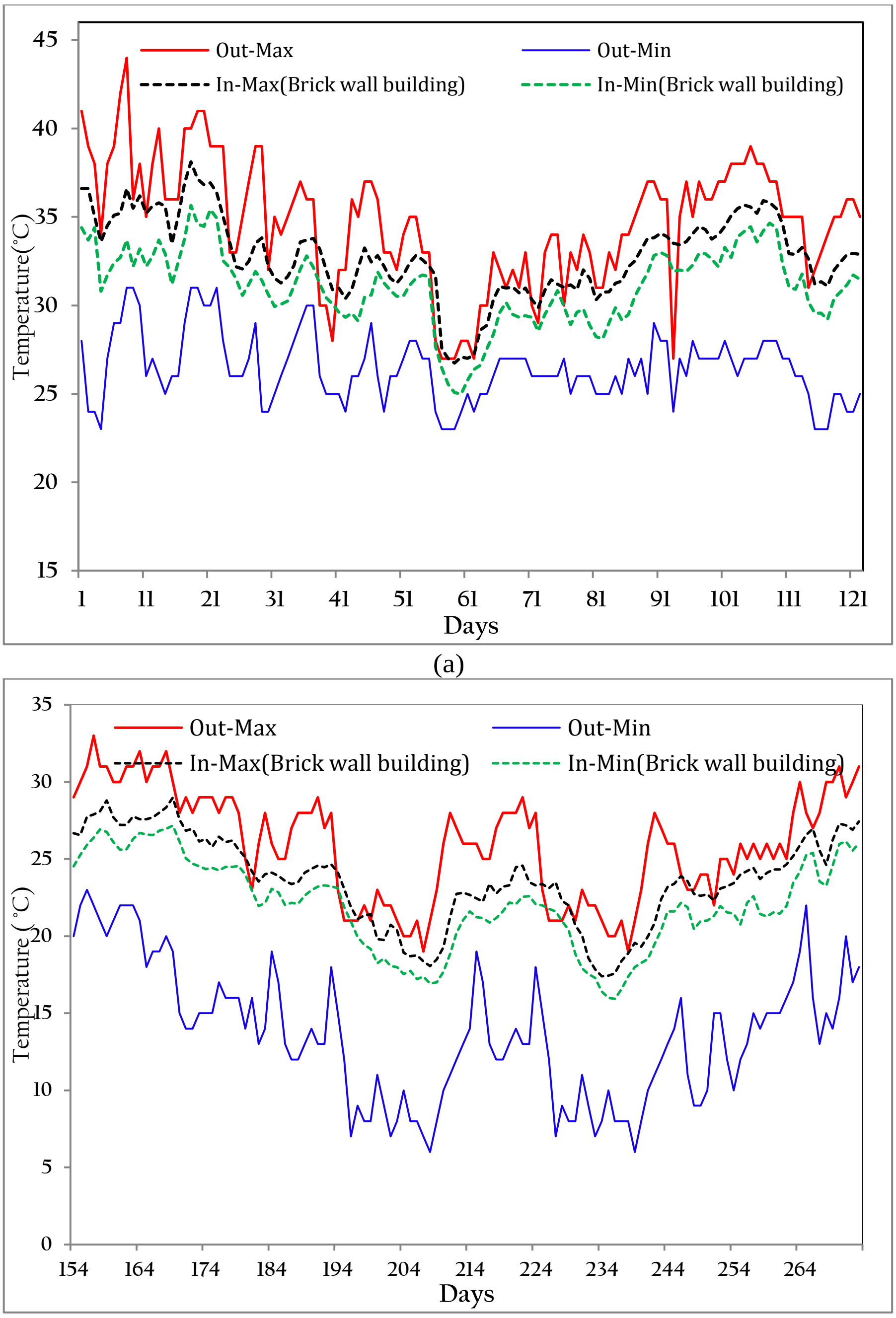
6.6.2 Brick wall residential building

a) Summer performance analysis

During summer monitoring, an increasing trend of indoor temperature closely following the outdoor temperature was observed as shown in Figure 6-6 (a). The average indoor temperature swing of about 2˚C–4˚C with a thermal time lag of 3–5hr has been seen during summer monitoring period for brick wall building. However, stone wall building was found having somewhat lower indoor temperature swing and high time lag in comparison to brick wall building. This may be due to high heat storage capacity of stone material than the brick material in the external wall.

b) Winter performance analysis

During this period, outdoor maximum varies from 14˚C–33˚C and minimum vary from 3˚C–20˚C with an average outdoor swing of 8˚C–17˚C. It was observed that indoor maximum temperature ranges from 20˚C–27˚C and minimum ranges from 16˚C–21˚C with a mean indoor temperature swing of 2˚C–3˚C from temperature profile of brick wall building during for the same period. A detailed analysis of measured indoor and outdoor average temperature, indoor and outdoor swing and thermal lag achieved during different sub-periods in summer and winter season for brick wall building is summarized in Table 6.8. It can be seen from Table 6.8 that during the winter, the average indoor temperature is well above the outdoor average due to sufficient heat storage in the high mass of building envelope and direct solar gain through windows or fenestration.



(a)

(b)

Figure 6-6 Indoor and outdoor temperature profile for monitored brick wall residential buildings (a) during summer and (b) during winter season

Table 6.8 Description of day average temperatures, diurnal swing and thermal time lag for brick wall residential building

Season	Sub-period	Day average temperature(˚C)		Temperature swing (˚C)		Thermal time lag (hr.)
		Indoor	Outdoor	Indoor	Outdoor	
Summer season	1	33.1	32.7	1-3	5-15	3-4
	2	33.9	32.8	2-4	7-15	4-5
	3	31.4	30.3	1-3	3-10	4-5
	4	28.9	28.6	1-2	4-9	3-4
	5	28.7	28.7	1-2	3-82	3-4
	6	30.2	30.1	1-2	3-12	3-4
	7	32.8	31.7	1-4	9-12	4-5
	8	31.2	29.9	1-2	6-12	4-5
Winter season	9	27.0	25.3	1-3	8-12	3-4
	10	25.2	21.3	2-4	7-15	3-4
	11	22.9	18.8	3-4	8-17	3-5
	12	19.3	15.9	2-3	7-16	4-5
	13	22.3	18.5	3-4	9-17	3-5
	14	18.9	15.8	1-3	7-14	3-4
	15	22.5	18.7	1-3	6-13	3-4
	16	24.4	22.7	2-4	6-16	4-5

6.7 Seasonal thermal monitoring conditions for office buildings

Typically, office buildings have a deeper plan, more perimeter glazing, and different management than residential buildings [**160**]. In addition, adaptation behaviors like opening/closing of windows, on /off fans and heating or cooling equipment's vary substantially between residential and office environments. In the present study, two office buildings situated at Malaviya National Institute of Technology, having different construction material type were chosen for long-term thermal monitoring during summer and winter season.

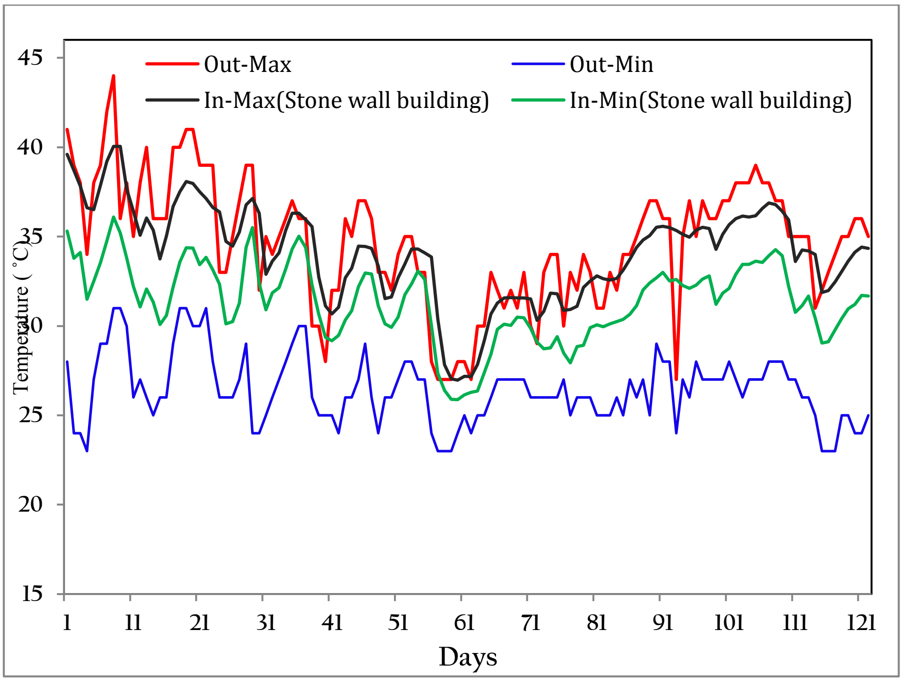
6.7.1 Stonewall office building

a) Summer performance analysis

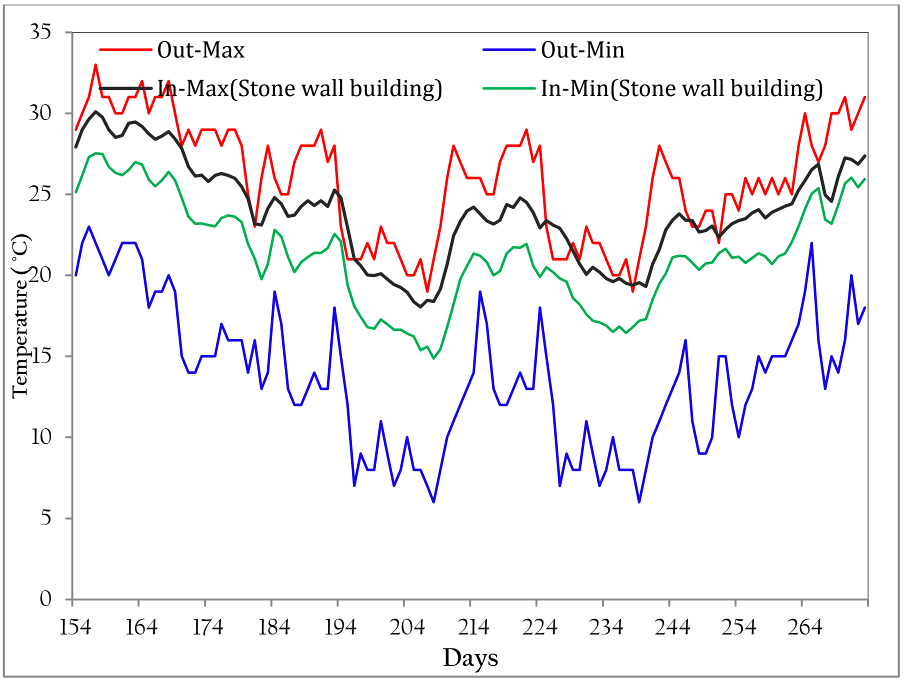
Figure 6-7 (a) represent the temperatures profile for indoor and outdoor temperatures for the monitored period of the summer and winter seasons. The maximum indoor temperature observed during the sub-period of 1–15 June 2015 was about 40.1˚C in the stone wall office building. The average outdoor temperature swing was seen about 5˚C–15˚C while average indoor temperature swing was found to be about 2˚C–4˚C which is higher than residential buildings. Also, the indoor mean temperature was found to be 2˚C– 3˚C higher than the outdoor average temperature during peak summer days. This was due to high heat storage capacity of building material and no night ventilation available to these buildings to flush out the stored heat in thermal mass due to management and security issues. Since the functionality of office buildings are different from residential buildings regarding occupancy and window opening behavior, the indoor temperature observed was higher than residential dwellings in spite of same construction types.

b) Winter performance analysis

In peak winter months of December and January, there is the decreasing trend of outdoor temperature as well as indoor temperature (Figure 6-7 (b)).. Table 6.9 summarized the measured indoor and outdoor average temperature, indoor and outdoor swing and thermal time lag achieved during different sub-periods in the summer and winter season for stone wall office building.



(a)



(b)

Figure 6-7Indoor and outdoor temperature profile for monitored stone wall office buildings (a) during summer and (b) during winter season

Table 6.9 Description of day average temperatures, diurnal swing and thermal time lag for stone wall office building

Season	**Sub-period**	**Day average temperature(˚C)**		**Temperature swing (˚C)**		**Thermal time lag (hr.)**
		Indoor	Outdoor	Indoor	Outdoor	
Summer season	1	37.4	32.7	3-4	5-15	3-5
	2	36.3	32.8	3-4	7-15	3-4
	3	33.7	30.3	2-3	3-10	3-4
	4	31.7	28.6	1-3	4-9	3-4
	5	30.6	28.7	2-3	3-8	2-3
	6	33.4	30.1	1-2	3-12	3-5
	7	35.6	31.7	2-3	9-12	4-5
	8	34.1	29.9	2-3	6-12	3-5
Winter season	9	27.9	25.3	2-3	8-12	3-4
	10	24.3	21.3	2-4	7-15	3-4
	11	21.5	18.8	2-4	8-17	2-4
	12	17.5	15.9	1-3	7-16	3-5
	13	21.3	18.5	3-4	9-17	3-4
	14	19.9	15.8	1-3	7-14	3-4
	15	23.0	18.7	1-3	6-13	3-5
	16	25.6	22.7	2-4	6-16	3-4

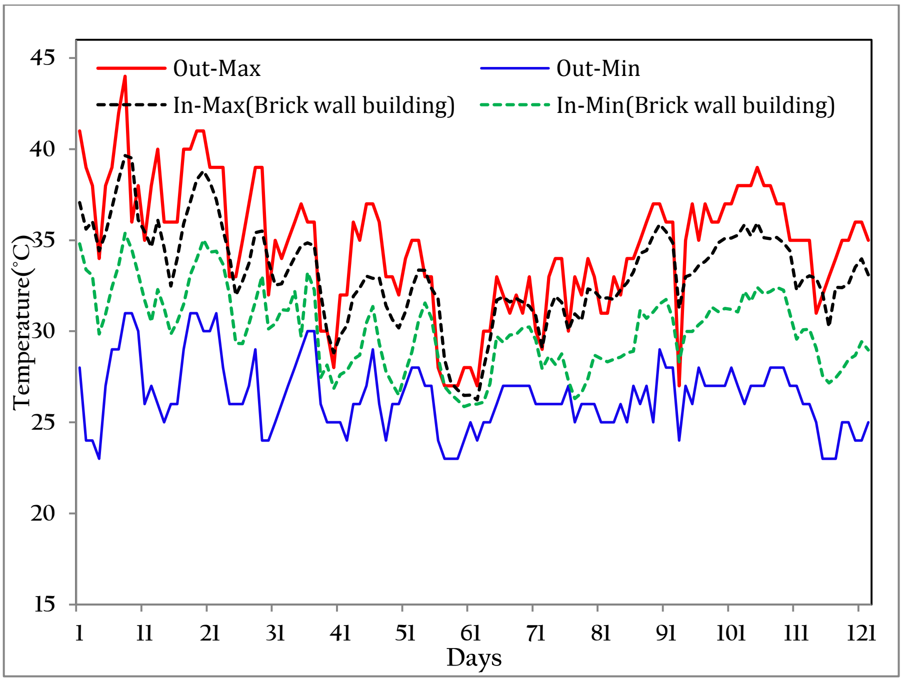
6.7.2 Brick wall office building

a) Summer performance analysis

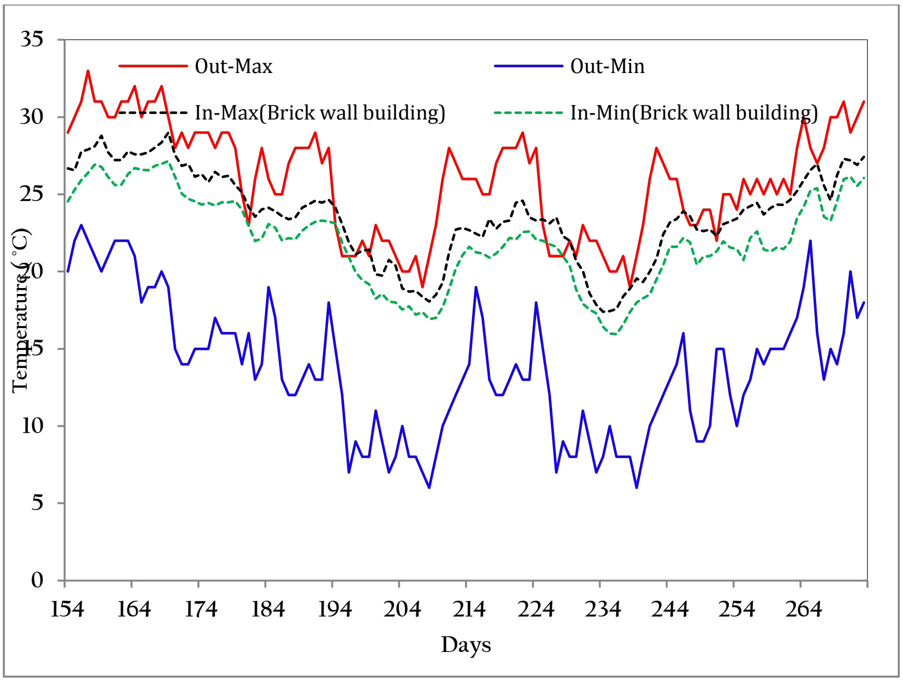
Figure 6-8 (a) represent the temperatures profile for indoor and outdoor temperatures for the monitored period of the summer and winter seasons in brick wall office buildings.. However, there was not much difference was observed between average indoor swings for both type of construction and also thermal time lag was nearly same for this period. Table 6.10 depicts the measured indoor and outdoor average temperature, indoor and outdoor swing and thermal time lag during summer and winter monitoring period.

b) Winter performance analysis

Figure 6-8 (b) represents the temperatures profile for indoor and outdoor temperatures for the monitored period of the winter seasons in brick wall office buildings. During peak winter period the average indoor temperature was sufficiently higher (2˚C–3˚C) than outdoor average temperature. This is due to the efficient heat storage in building envelope through solar gains and internal gains due to lightning and equipment. Also, the average indoor temperature swing was found slightly lower than stone brick wall office buildings as depicted in Table 6.10.



(a)



(b)

Figure 6-8 Indoor and outdoor temperature profile for monitored brick wall office buildings (a) during summer and (b) during winter season

Table 6.10Description of day average temperatures, diurnal swing and thermal time lag for brick wall office building

Season	Sub-period	Day average temperature(˚C)		Temperature swing (˚C)		Thermal time lag (hr.)
		Indoor	Outdoor	Indoor	Outdoor	
Summer season	1	36.1	32.7	3-4	5-15	3-5
	2	35.2	32.8	3-4	7-15	3-4
	3	32.3	30.3	2-3	3-10	3-4
	4	30.5	28.6	1-3	4-9	3-4
	5	30.6	28.7	2-3	3-8	2-3
	6	33.1	30.1	1-2	3-12	3-5
	7	34.5	31.7	2-3	9-12	4-5
	8	33.0	29.9	2-3	6-12	3-5
Winter season	9	27.3	25.3	2-3	8-12	3-4
	10	24.5	21.3	2-3	7-15	3-4
	11	20.8	18.8	1-3	8-17	2-4
	12	16.9	15.9	1-3	7-16	3-5
	13	21.5	18.5	3-4	9-17	3-4
	14	18.9	15.8	1-3	7-14	3-4
	15	21.9	18.7	1-3	6-13	3-5
	16	24.6	22.7	2-4	6-16	3-4

6.8 Methods for development of correlations for indoor temperatures

Indoor temperature predictions, for a particular building but different climatic conditions, based exclusively on outdoor climatic parameters, were shown to be possible both for non-occupied and occupied unconditioned buildings [**121**] [**124**]. The constants in these formulas do indirectly take into account the thermo-physical characteristics of the envelope through the indoor temperature.

These predictions are developed through simple equations by multiple regressions techniques, which relate indoor daily maximum, average, minimum and other independent variables. However, these correlations are proposed with limited statistical analysis, relying on the correlation of coefficient (R^2) during generation and validation period. No further statistics analysis has been carried out to test the significance of correlations or parameters by using ‘F–statistics’ analysis or ‘t–statistics’ analysis. In the present study, a detailed statistical analysis has been carried out for statistical significance of developed correlations using ‘F–statistics’ and ‘t–statistics’ analysis. However, correlations are developed for the monitored high mass buildings according to the procedure described in [**111**] [**118**] [**120**] for summer and winter season, separately.

One of the advantages of using these correlations is to predict the indoor conditions for buildings in different climates provided buildings should have similar construction details and management [**111**]. Also, these correlations incorporate some behavioral adaptive actions taken by occupants in different seasons in naturally ventilated buildings to make their living conditions comfortable which is otherwise so challenging and complex phenomenon to include in simulation tools [**27**] [**120**].

6.8.1 Variables used in mathematical correlations

The measured data of each season then divided into parts; the first part was used to generate correlations based on the measured data (generation) and the second part was used for validation of the correlations by independently measured data. In the summer season, the mathematical correlations were generated based on experimentally measured temperatures of June 2015 and August 2015 months and validation for developed formulae was based on independently measured temperatures of July 2015 and September 2015. While for winter season the mathematical correlations were generated for the period of November 2015 and January 2016 and validation were carried out for the data of December 2015 and February 2016. Independent measured indoor data of at least 28 days in each month has been used for development of formulae and validation.

The indoor daily maximum and average temperatures were also affected by the average outdoor temperature during previous several days, in addition to the effects of the current day's average and maximum. Consequently, an arbitrary term Rn_{avg}, the average of 3 last days, was introduced in the predictive formulae. Also, it was observed from, the aspect of the relationship, that average period temperature (GT_{avg}) has pronounced effect on indoor temperatures. In dealing with the minimum indoor temperature, it was found that the minimum indoor temperature of the given day is affected by the drop (T_{drop}) in previous day's maximum temperature ($T_{max(n-1)}$) to the present day minimum temperature ($T_{min(n)}$) and is shown in equation (6.1).

$$\mathbf{T_{drop} = T_{max(n-1)} - T_{min(n)}} \tag{6.1}$$

Effect of these parameters on predicting the indoor temperature in high mass buildings has been referred from the previous studies conducted by Givoni and Kruger [**175**].

Independent variables used in the development of mathematical correlations are:

Outdoor maximum temperature	(T_{max})
Outdoor daily average temperature	(T_{avg})
Outdoor minimum temperature	(T_{min})
Period's outdoor average	(GT_{avg})
Diurnal swing, (T_{max}–T_{min})	(S_{wg})
Running average of previous 3-days	(Rn_{avg})
Temperature drop	(T_{drop})
Window use,	(W)

Fully open: “2”
Partially open: “1”
Close: “0”

Adaptive actions, viz. "occupancy," "use of fan" and "window opening behavior" were evaluated to consider their effect on occupants. These adaptive behaviors have played a significant role to adjust the indoor temperature to achieve comfort during the summer and winter season. However, during analysis, it is found that "occupancy" and "use of fan" did not improve the correlation significantly (R^2 value), so not included in predictive formulas but window opening, has shown significant effect so included in the development of formulae.

6.8.2 Mathematical correlations for high mass residential buildings with adaptive actions

Since the functionality of high mass building in this region is different for summer and winter season, as described above, thus the separate mathematical correlations are developed. Multiple regression techniques are used to establish the correlations for predicting the indoor temperatures. Statistical analysis has been carried out based on R^2 value, 'F–statistics,' and 't–statistics' analysis to determine the accuracy and robustness of the obtained correlations for different seasons. The coefficient of determination, R^2 is achieved in the output from the linear estimation function which determines the relationship between the independent variables and the dependent variable [**177**]. F-statistic, obtained in the output array is used to determine whether the results of R^2 value occurred by chance. If the F value is higher than the critical level of F then, the high F value occurred by chance is extremely unlikely. Here, the assessment has done by finding the critical level of F in the F table, taking the level of significance value = 0.01. The t–statistics is calculated to determine whether each parameter of concern is useful in estimating the dependent variable. The critical value of 't' is given by the TINV function, TINV (0.01, df).

The mathematical correlations for the indoor temperatures of stone and brick wall construction residential buildings for different seasons are generated by multiple regressions techniques from measured data and are depicted in Table 6.11 and Table 6.12. The results illustrated in tables showed that high Pearson's correlation coefficient, 'r' (CC) ≥ 0.90 between the measured temperatures and the computed temperatures, for the generation and the validation periods. Figure 6-9 (a, b, c) shows the matching of measured and calculated daily indoor temperatures viz. maximum, minimum and average temperatures for stone wall residential building in summer and winter season.

6.8.3 Statistical analysis of the developed correlations

The correlation coefficient (R^2 value) is calculated more than 0.90 for all the developed mathematical correlations for summer and winter season, respectively. However, to justify the high value of R^2, further analysis has been carried out for 'F–statistics,' and 't–statistics' (Table 6.13 and Table 6.14). Results show a higher value of F-statistics and at p value=0.01 for all developed correlations, which suggests that the high value of R^2 for established correlations, were not by chance. However, some slope coefficient or parameters in developed correlations are found to be not useful in estimating the dependent parameters. It is observed that R^2 value, F value, and the t-statistics are functions of different variables and depend on the quantity of data used in relations. Also, adaptive behavior and management of buildings play a vital role in modifying the indoor conditions which are tough to model. A long-term monitoring of similar buildings under different climatic conditions should be conducted to reduce error and increase more accuracy in developed correlations [**191**] [**192**].

The use of these correlations, such as those presented here, is meant for indoor temperature predictions of a mass buildings, with a given geometry and building materials, concerning different periods of the year or even exposed to various climatic conditions [**111**].

Table 6.11 Mathematical correlations for stone wall residential building

Season	Daily temperature correlation	R², F-statistic, p value	Pearson coefficient (r)	
			$CC_{gen.}$	$CC_{valid.}$
Summer season	$\mathbf{Maximum(T_{in}) = 1.68 + 0.63 \times T_{avg} - 0.066 \times GT_{avg} + 0.43 \times Rn_{avg} - 0.161 \times S_{wg}}$	$R^2 = 0.93, F\ statistic = 137, S.E. = 0.69\ ^{\circ}C, p < 0.01)$	0.96	0.93
	$\mathbf{Minimum(T_{in}) = 0.98 + 0.43 \times T_{min} + 0.39 \times T_{drop} + 0.49 \times T_{avg} + 0.35 \times \mathit{W}}$	$(R^2 = 0.93, F\ statistic = 196, S.E. = 0.69\ ^{\circ}C, p < 0.01)$	0.94	0.93
	$\mathbf{Average(T_{in}) = 3.14 + 0.62 \times T_{avg} - 0.20 \times GT_{avg} + 0.50 \times Rn_{avg} + 0.13 \times S_{wg}}$	$(R^2 = 0.91, F\ statistic = 153, S.E. = 0.72\ ^{\circ}C, p < 0.01)$	0.95	0.92
Winter season	$\mathbf{Maximum(T_{in}) = 6.4 + 0.12 \times T_{avg} + 0.44 \times GT_{avg} + 0.51 \times Rn_{Avg} + 0.38 \times S_{wg} - 0.09 \times W}$	$R^2 = 0.97, F\ statistic = 286, S.E. = 0.6\ ^{\circ}C, p < 0.01)$	0.98	0.95
	$\mathbf{Minimum(T_{in}) = 5.50 + 0.16 \times T_{min} + 0.48 \times T_{avg} + 0.10 \times GT_{avg} + 0.15 \times T_{drop} + 1.1 \times W}$	$(R^2 = 0.94, F\ statistic = 171, S.E. = 0.86\ ^{\circ}C, p < 0.01)$	0.97	0.92
	$\mathbf{Average(T_{in}) = 4.85 + 0.42 \times T_{avg} - 0.08 \times GT_{avg} + 0.49 \times Rn_{Avg} + 0.10 \times S_{wg} + 0.41 \times W}$	$(R^2 = 0.96, F\ statistic = 281, S.E. = 0.67\ ^{\circ}C, p < 0.01)$	0.98	0.96

Table 6.12 Mathematical correlations for brick wall residential building

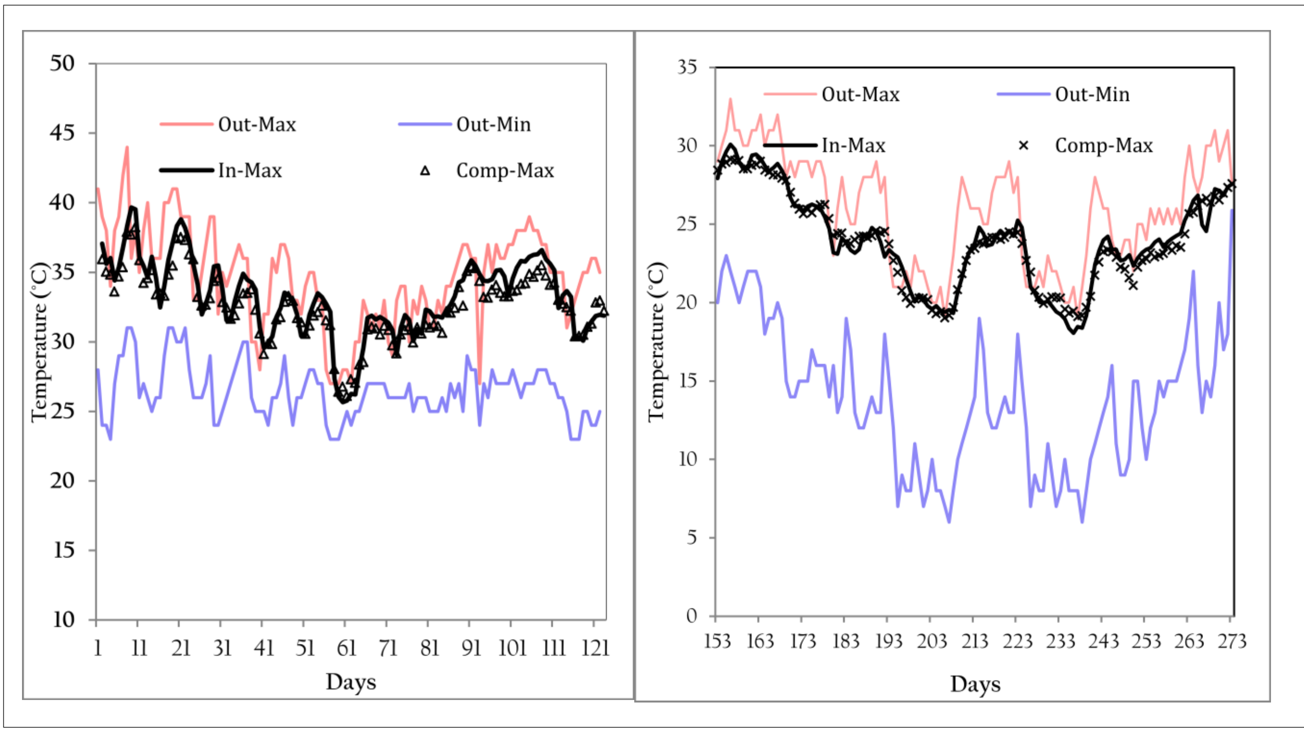
Season	Daily temperature correlation	R2, F-statistic	Pearson coefficient (r)	
			$CC_{gen.}$	$CC_{valid\cdot}$
Summer season	$\mathbf{Maximum(T_{in}) = 1.83 + 0.45 \times T_{avg} + 0.114 \times GT_{avg} + 0.39 \times RnAvg - 0.072 \times S_{wg}}$	$R^2 = 0.92, F\ statistic = 347, S.E. = 0.75\ ^\circ C, p < 0.01)$	0.96	0.92
	$\mathbf{Minimum(T_{in}) = 4.07 + 0.82 \times T_{min} + 0.44 \times T_{drop} + 0.23 \times W}$	$(R^2 = 0.94, F\ statistic = 171, S.E. = 0.86\ ^\circ C, p < 0.01)$	0.97	0.92
	$\mathbf{Average(T_{in}) = 5.42 + 0.41 \times T_{avg} - 0.043 \times GT_{avg} + 0.44 \times Rn_{Avg} + 0.12 \times S_{wg}}$	$(R^2 = 0.90, F\ statistic = 132, S.E. = 0.72\ ^\circ C, p < 0.01)$	0.95	0.93
Winter season	$\mathbf{Maximum(T_{in}) = 5.61 + 0.23 \times T_{avg} + 1.09 \times GT_{avg} + 0.68 \times Rn_{Avg} + 0.35 \times S_{wg} - 0.3 \times W}$	$R^2 = 0.93, F\ statistic = 113, S.E. = 0.90^\circ C, p < 0.01)$	0.97	0.94
	$\mathbf{Minimum(T_{in}) = 6.39 + 0.33 \times T_{min} + 0.24 \times T_{avg} + 0.050 \times GT_{avg} + 0.37 \times T_{drop} + 1.97 \times W}$	$(R^2 = 0.9, F\ statistic = 102, S.E. = 1.06\ ^\circ C, p < 0.01)$	0.95	0.92
	$\mathbf{Average(T_{in}) = 5.01 + 0.36 \times T_{avg} - 0.31 \times GT_{avg} + 0.68 \times Rn_{Avg} + 0.23 \times S_{wg} + 1.2 \times W}$	$(R^2 = 0.95, F\ statistic = 190, S.E. = 0.81\ ^\circ C, p < 0.01)$	0.97	0.92

Table 6.13 Statistical analysis ('R^2', 'F–statistics,' and 't–statistics') for developed correlations for stone wall residential buildings

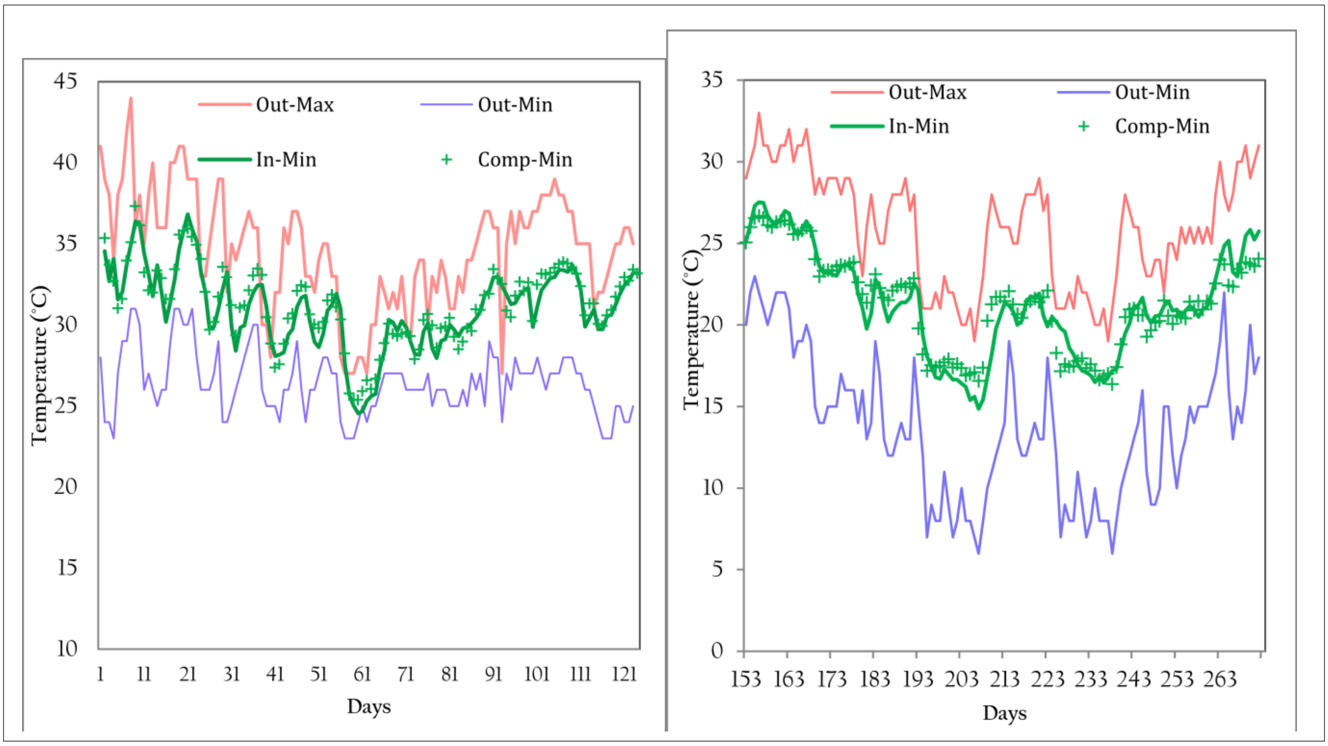
Construction type	Season	Daily Formulae	F-Statistics, p-value	F-Statistics critical value	t- Statistics critical value(TINV)	Variable	t- Statistics (Absolute values), p-value	Standard error (˚C)
Stone wall	Summer	Maximum	137, 3.4×10^{-30}	3.36	2.66	T_{avg}	$9.24, 7.6 \times 10^{-13}$	0.06
						GT_{avg}	0.47,0.63	0.13
						Rn_{avg}	$4.99, 6.2 \times 10^{-6}$	0.09
						S_{wg}	2.34,0.02	0.07
		Minimum	196, 3.1×10^{-32}	3.66	2.66	T_{min}	$4.27, 7.4 \times 10^{-5}$	0.05
						T_{avg}	$5.41, 1.3 \times 10^{-6}$	0.08
						T_{drop}	$9.22, 7.9 \times 10^{-13}$	0.04
						W	$2.78, 4 \times 10^{-3}$	0.03
		Average	153, 1.7×10^{-29}	3.36	2.66	T_{avg}	$9.92, 5.9 \times 10^{-14}$	0.06
						GT_{avg}	1.05,0.11	0.12
						Rn_{avg}	$6.49, 2.3 \times 10^{-8}$	0.07
						S_{wg}	2.73,0.002	0.09
	Winter	Maximum	286, 1.4×10^{-37}	3.36	2.66	T_{avg}	$3.29, 1 \times 10^{-3}$	0.03
						GT_{avg}	$2.56, 2 \times 10^{-2}$	0.30
						Rn_{avg}	$8.02, 8.9 \times 10^{-11}$	0.06
						S_{wg}	$4.57, 2.8 \times 10^{-5}$	0.08
						W	1.01,0.3	0.09
		Minimum	171, 3.4×10^{-32}	3.36	2.66	T_{min}	$2.89, 3 \times 10^{-3}$	0.40
						T_{avg}	1.95, 0.05	0.20
						GT_{avg}	0.79, 0.43	0.13
						T_{drop}	$2.95, 4 \times 10^{-4}$	0.06
						W	$3.57, 7.7 \times 10^{-5}$	0.37
		Average	281, 7.3×10^{-38}	3.36	2.66	T_{avg}	$4.43, 4.5 \times 10^{-5}$	0.09
						GT_{avg}	0.8,0.42	0.10
						Rn_{avg}	$6.73, 1.0 \times 10^{-8}$	0.07
						S_{wg}	$3.47, 1.6 \times 10^{-4}$	0.04
						W	1.57,0.2	0.31

Table 6.14 Statistical analysis (‘R^2’, ‘F–statistics,' and ‘t–statistics’) for developed correlations for brick wall residential buildings

Construction type	Season	Daily Formulae	F-Statistics, p-value	F-Statistics critical value	t- Statistics critical value(TINV)	Variable	t- Statistics (Absolute values), p-value	Standard error (˚C)
Brick wall	Summer	Maximum	347, 4.5 $\times10^{-32}$	3.36	2.66	T_{avg}	$8.0,7.6\times10^{-11}$	0.05
						GT_{avg}	$2.92,3.1\times10^{-2}$	0.11
						Rn_{avg}	$5.42, 1.3\times10^{-4}$	0.06
						S_{wg}	1.11,0.25	0.06
		Minimum	171, 1.6×10^{-29}	3.66	2.66	T_{min}	$14.83,3.2\times10^{-21}$	0.05
						T_{drop}	$7.64,2.6\times10^{-10}$	0.05
						W	$5.04,4.9\times10^{-6}$	0.04
		Average	132, $1.0\times10-^{29}$	3.36	2.66	T_{avg}	$7.22,1.5\times10^{-9}$	0.05
						GT_{avg}	0.38,0.7	0.11
						Rn_{avg}	$6.39,3.4\times10^{-8}$	0.07
						S_{wg}	2.64,0.01	0.05
	Winter	Maximum	113, 1.6×10^{-29}	3.36	2.66	T_{avg}	$4.33,6.4\times10^{-5}$	0.05
						GT_{avg}	2.62,0.01	0.4
						Rn_{avg}	$7.09,2.8\times10^{-9}$	0.09
						S_{wg}	2.81,0.006	0.12
						W	2.25,0.02	0.13
		Minimum	102, 1.23×10^{-26}	3.36	2.66	T_{min}	2.53,0.01	0.21
						T_{avg}	0.9, 0.42	0.3
						GT_{avg}	0.3, 0.77	0.15
						T_{drop}	$3.11,2\times10^{-3}$	0.11
						W	$4.3,7.6\times10^{-5}$	0.13
		Average	190, 2.1×10^{-33}	3.36	2.66	T_{avg}	$3.16,2\times10^{-3}$	0.11
						GT_{avg}	2.62,0.01	0.11
						Rn_{avg}	$7.95,1.0\times10^{-10}$	0.08
						S_{wg}	$4.73,1.5\times10^{-5}$	0.04
						W	$3.23,2.3\times10^{-3}$	0.37



(a)



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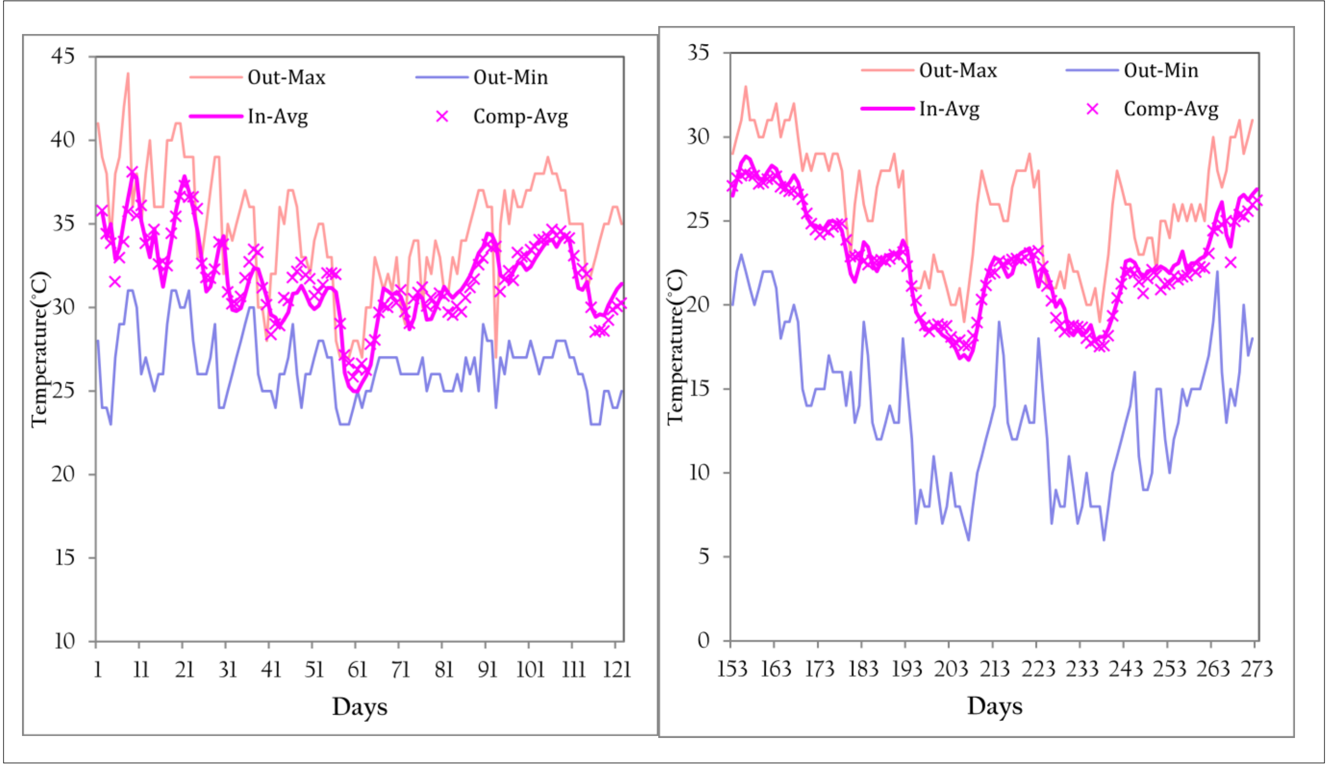


(c)

Figure 6-9 Matching between the measured and the computed (a) maximum,(b) minimum and (c) average indoor temperature for stone wall residential buildings in summer(left) and winter season(right)

6.8.4 Mathematical correlations for high mass office buildings with adaptive actions

Table 6.15 and Table 6.16 represent the developed correlations to predict the daily indoor maximum, average and minimum temperatures for high mass office buildings during summer and winter season, respectively. The high value of Pearson's correlation coefficient 'r' during generation and validation period suggests that the relationships between predicted and measured temperatures are strong. Also, F value is significantly higher than critical values at p-value =0.01 for all cases, which further robust the findings that values predicted are not by chance (Table 6.17 and Table 6.18).

Table 6.15 Mathematical correlations for stone wall office building

Season	Daily temperature correlation	R2, F-statistic, p value	Pearson Correlation (r)	
			$\mathrm{CC_{gen}}$	$\mathrm{CC_{valid}}$
Summer season	$\mathbf{Maximum(T_{in}) = 8.83 + 0.36 \times T_{avg} - 0.07 \times GT_{avg} + 0.50 \times Rn_{avg} - 0.21 \times S_{wg} - 0.74 \times W}$	$(R^2 = 0.90, F\ statistic = 84.4, S.E. = 1.0\ ^{\circ}C, p < 0.01)$	0.95	0.92
	$\mathbf{Minimum(T_{in}) = 2.68 + 0.16 \times T_{min} + 0.36 \times T_{drop} + 0.54 \times T_{avg} + 0.20 \times GT_{avg} - 0.05 \times W}$	$(R^2 = 0.93, F\ statistic = 142, S.E. = 0.78^{\circ}C, p < 0.01)$	0.96	0.94
	$\mathbf{Average(T_{in}) = 0.79 + 0.38 \times T_{avg} + 0.08 \times GT_{avg} + 0.54 \times Rn_{avg} + 0.23 \times S_{wg} - 0.007 \times W}$	$(R^2 = 0.90, F\ statistic = 102, S.E. = 0.95\ ^{\circ}C, p < 0.01)$	0.96	0.95
Winter season	$\mathbf{Maximum(T_{in}) = 7.4 + 0.30 \times T_{avg} - 0.012 \times GT_{avg} + 0.41 \times Rn_{Avg} + 0.07 \times S_{wg} + 1.18 \times W}$	$R^2 = 0.89, F\ statistic = 60.7, S.E. = 0.57\ ^{\circ}C, p < 0.01)$	0.98	0.95
	$\mathbf{Minimum(T_{in}) = 7.2 + 0.21 \times T_{min} + 0.28 \times T_{avg} + 0.16 \times GT_{avg} + 0.15 \times T_{drop} + 1.9 \times W}$	$(R^2 = 0.94, F\ statistic = 88.9, S.E. = 1.3\ ^{\circ}C, p < 0.01)$	0.94	0.92
	$\mathbf{Average(T_{in}) = 6.81 + 0.33 \times T_{avg} + 0.08 \times GT_{avg} + 0.39 \times Rn_{Avg} + 0.05 \times S_{wg} + 1.3 \times W}$	$(R^2 = 0.89, F\ statistic = 86.7, S.E. = 1.2^{\circ}C, p < 0.01)$	0.98	0.93

Table 6.16 Mathematical correlations for brick wall office building

Season	Daily temperature correlation	R2, F-statistic	Pearson Correlation(r)	
			$\mathrm{CC_{gen}}$	$\mathrm{CC_{valid}}$
Summer season	$\mathbf{Maximum(T_{in}) = 6.25 + 0.49 \times T_{max} - 0.12 \times GT_{avg} + 0.53 \times RnAvg + 0.18 \times S_{wg} - 1.3 \times W}$	$R^2 = 0.94, F\ statistic = 143, S.E. = 0.81^{\circ}C, p < 0.01)$	0.97	0.95
	$\mathbf{Minimum(T_{in}) = 5.7 + 0.33 \times T_{min} + 0.42 \times T_{avg} + 0.05 \times GT_{avg} + 0.38 \times T_{drop} - 0.56 \times W}$	$(R^2 = 0.93, F\ statistic = 153, S.E. = 0.73\ ^{\circ}C, p < 0.01)$	0.97	0.93
	$\mathbf{Average(T_{in}) = 3.3 + 0.46 \times T_{avg} - 0.10 \times GT_{avg} + 0.57 \times Rn_{Avg} + 0.17 \times S_{wg} - 0.63 \times W}$	$(R^2 = 0.94, F\ statistic = 165, S.E. = 0.76^{\circ}C, p < 0.01)$	0.97	0.93
Winter season	$\mathbf{Maximum(T_{in}) = 6.9 + 0.33 \times T_{avg} + 0.19 \times GT_{avg} + 0.57 \times Rn_{Avg} + 0.08 \times S_{wg} + 1.27 \times W}$	$R^2 = 0.94, F\ statistic = 158, S.E. = 0.82\ ^{\circ}C, p < 0.01)$	0.96	0.91
	$\mathbf{Minimum(T_{in}) = 6.72 + 0.36 \times T_{min} + 0.12 \times T_{avg} + 0.17 \times GT_{avg} + 0.26 \times T_{drop} + 1.87 \times W}$	$(R^2 = 0.92, F\ statistic = 142, S.E. = 0.94\ ^{\circ}C, p < 0.01)$	0.93	0.90
	$\mathbf{Average(T_{in}) = 6.05 + 0.35 \times T_{avg} - 0.14 \times GT_{avg} + 0.51 \times Rn_{Avg} + 0.08 \times S_{wg} + 1.24 \times W}$	$(R^2 = 0.94, F\ statistic = 189, S.E. = 0.83^{\circ}C, p < 0.01)$	0.97	0.92

Table 6.17 Statistical analysis ('R^2', 'F–statistics', and 't–statistics') for developed correlations for stone wall office buildings

Construction type	Season	Daily Formulae	F-Statistics, p-value	F-Statistics critical value	t- Statistics critical value(TINV)	Variable	t- Statistics (Absolute values), p-value	Standard error (˚C)
Stone wall	Summer	Maximum	84.4, 2.8×10^{-24}	3.36	2.66	T_{avg}	$4.60,2.5\times10^{-5}$	0.07
						GT_{avg}	0.40,0.68	0.17
						Rn_{avg}	$4.76, 1.5\times10^{-5}$	0.10
						S_{wg}	$3.24,2.1\times10^{-4}$	0.06
						W	$2.58,1.0\times10^{-2}$	0.03
		Minimum	142, 3.3×10^{-30}	3.66	2.66	T_{min}	1.38,0.45	0.11
						T_{avg}	$5.16,3.4\times10^{-6}$	0.10
						GT_{avg}	1.78,0.09	0.11
						T_{drop}	$7.15,2.1\times10^{-9}$	0.05
						W	0.14,0.88	0.03
		Average	102, 1.4×10^{-26}	3.36	2.66	T_{avg}	$5.08,4.6\times10^{-6}$	0.07
						GT_{avg}	1.49,0.06	0.16
						Rn_{avg}	$5.36,1.6\times10^{-6}$	0.07
						S_{wg}	$3.83,3.2\times10^{-3}$	0.09
						W	0.014,0.98	0.48
	Winter	Maximum	60.7, 6.1×10^{-21}	3.36	2.66	T_{avg}	$2.84,6.0\times10^{-3}$	0.11
						GT_{avg}	1.76,0.12	0.12
						Rn_{avg}	$6.59,1.9\times10^{-8}$	0.08
						S_{wg}	1.85,0.11	0.08
						W	$3.33,1.0\times10^{-3}$	0.40
		Minimum	87.6, 6.2×10^{-25}	3.36	2.66	T_{min}	0.87,0.38	0.24
						T_{avg}	0.81, 0.42	0.34
						GT_{avg}	1.66, 0.15	0.18
						T_{drop}	1.10,0.27	0.13
						W	$3.47,1.2\times10^{-4}$	0.53
		Average	86.7, 7.8×10^{-25}	3.36	2.66	T_{avg}	$2.96,5\times10^{-3}$	0.16
						GT_{avg}	0.04,0.96	0.18
						Rn_{avg}	$2.99,4.7\times10^{-3}$	0.12
						S_{wg}	0.73,0.46	0.68
						W	2.62,0.01	0.56

Table 6.18 Statistical analysis (‘R^2’, ‘F–statistics’, and ‘t–statistics’) for developed correlations for brick wall office buildings

Construction type	Season	Daily Formulae	F-Statistics, p-value	F-Statistics critical value	t- Statistics critical value(TINV)	Variable	t- Statistics (Absolute values), p-value	Standard error (˚C)
Brick wall	Summer	Maximum	143, 6.5×10^{-30}	3.36	2.66	T_{avg}	$7.7,2.6\times10^{-10}$	0.06
						GT_{avg}	1.9,0.30	0.13
						Rn_{avg}	$6.08, 1.2\times10^{-7}$	0.06
						S_{wg}	$3.5,9\times10^{-3}$	0.05
						W	$3.11,2\times10^{-3}$	0.41
		Minimum	153, 5×10^{-31}	3.66	2.66	T_{min}	$14.83,3.2\times10^{-21}$	0.05
						T_{avg}	$4.29,7.3\times10^{-5}$	0.09
						GT_{avg}	0.47,0.63	0.11
						T_{drop}	$7.94,1.1\times10^{-10}$	0.05
						W	$2.49,1.4\times10^{-2}$	0.37
		Average	164, 8.2×10^{-32}	3.36	2.66	T_{avg}	$7.60,3.85\times10^{-10}$	0.05
						GT_{avg}	0.78,0.43	0.13
						Rn_{avg}	$7.05,3.1\times10^{-9}$	0.07
						S_{wg}	$3.53,8\times10^{-4}$	0.05
						W	$2.60,1\times10^{-2}$	0.39
	Winter	Maximum	158, 5.1×10^{-29}	3.36	2.66	T_{avg}	$2.84,6\times10^{-3}$	0.11
						GT_{avg}	1.86,0.01	0.12
						Rn_{avg}	$6.58,1.9\times10^{-8}$	0.08
						S_{wg}	$2.58,2 \times10^{-3}$	0.05
						W	$3.33,1\times10^{-3}$	0.38
		Minimum	142, $3. 5\times10^{-30}$	3.36	2.66	T_{min}	2.89,0.01	0.19
						T_{avg}	0.43, 0.66	0.26
						GT_{avg}	1.76, 0.24	0.13
						T_{drop}	$2.70,2\times10^{-3}$	0.10
						W	$4.5,3.1\times10^{-5}$	0.41
		Average	189, 2.2×10^{-33}	3.36	2.66	T_{avg}	$3.0,3\times10^{-3}$	0.11
						GT_{avg}	1.1,0.27	0.12
						Rn_{avg}	$5.79,3.4\times10^{-7}$	0.08
						S_{wg}	$2.6,1.1\times10^{-2}$	0.05
						W	$3.27,1\times10^{-3}$	0.38

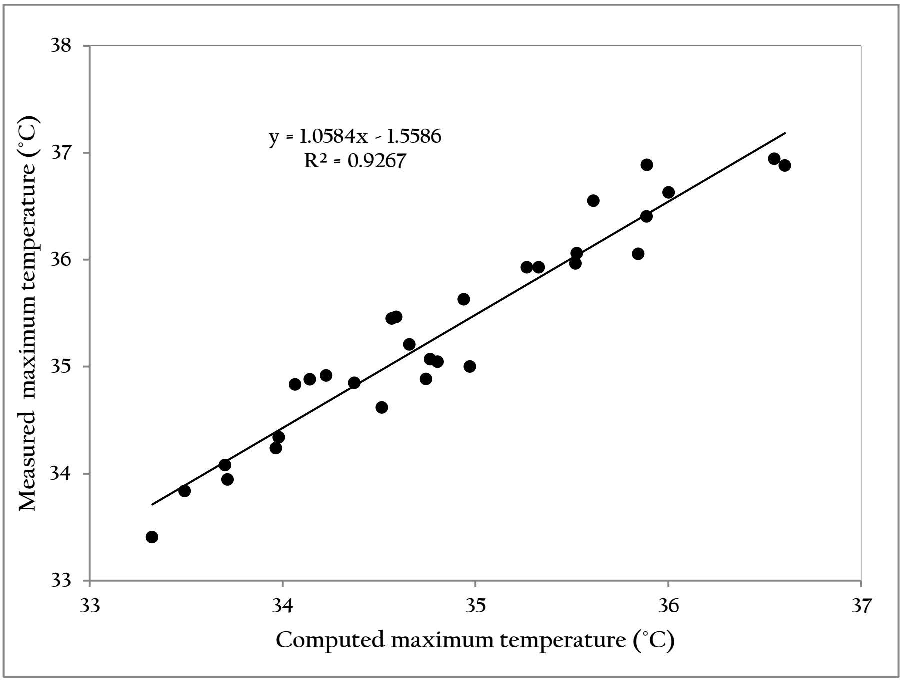
6.8.5 Field validation of developed mathematical correlations

A partial monitoring has been carried out for other thermal mass buildings in existing dwellings of this climatic region to check the robustness and validation of developed correlations. The partial monitoring was conducted for two residential and two office buildings other than monitored thermal mass buildings. The monitored buildings were having similar thermal mass, construction material, and management of building as used for long-term monitoring buildings. The monitoring has carried out for 30 days during peak summer and winter season viz. in June 2015 and December 2015 months, using Hobo U-12 loggers.

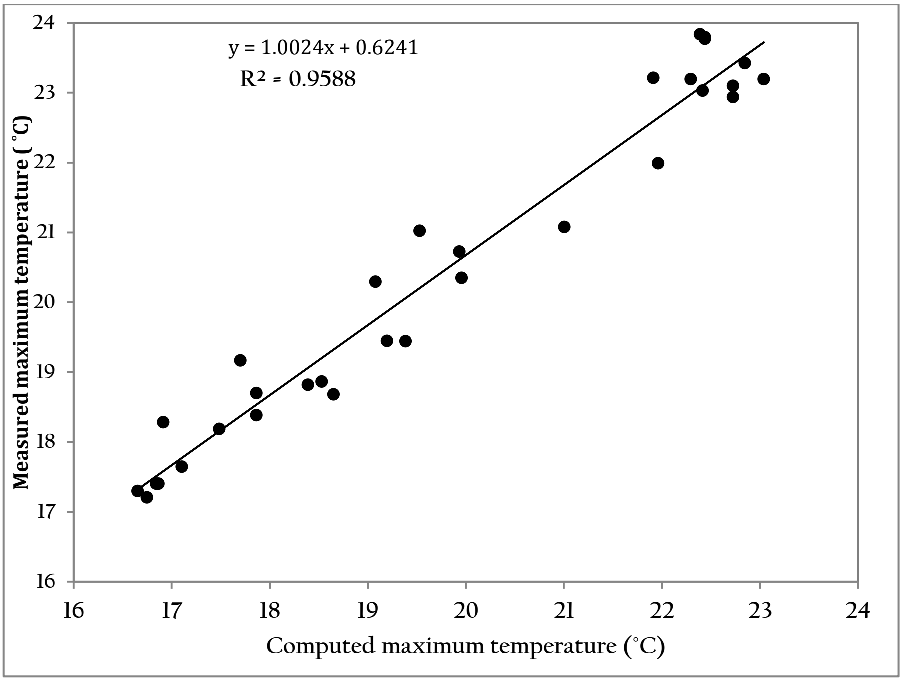
ASHRAE 14–2002 [**193**] recommends using the linear regression analysis to assess the accuracy and correlation between measured and predicted data from the model. The correlation coefficient (R^2) between predicted temperature versus measured temperatures of more than 0.90 and the linear slope of more than 1 are sufficient comparing with the recommendation of ASHRAE 14–2002 (R^2 of 0.90 or greater and slope between 0.75 and 1.25) [**110**]. Results depict that relationship works well in other stone and brick wall buildings for the region as shown in Table 6.19 and good correlation has been obtained between measured and computed temperatures as illustrated in Figure 6-10.

Table 6.19 Matching between measured and predicted values(R^2) during validation period

Building type	**Construction type**	**Daily temperature**	**R^2 statistics**	**Pearson's correlation(r)**	
				June	December
Residential buildings	Stone wall construction	Maximum	0.92	0.98	0.95
		Minimum	0.91	0.95	0.93
		Average	0.92	0.96	0.93
	Brick wall construction	Maximum	0.92	0.96	0.92
		Minimum	0.89	0.91	0.89
		Average	0.89	0.93	0.89
Office buildings	Stone wall construction	Maximum	0.92	0.96	0.92
		Minimum	0.93	0.97	0.91
		Average	0.90	0.93	0.89
	Brick wall construction	Maximum	0.91	0.93	0.90
		Minimum	0.90	0.93	0.91
		Average	0.89	0.93	0.87



(a)



(b)

Figure 6-10 Field validation for stone wall residential building during (a) June 2015 (b) December 2015 month, respectively

6.9 Proposed thermal mass boundaries for naturally ventilated residential and office buildings

Givoni [**25**] introduced his BBCCs which were devoted to predicting the indoor conditions of the building according to the outdoor prevailing climatic conditions as shown in Figure 1-2. The boundary line, defining the ambient conditions on the psychrometric chart below which night ventilated high mass buildings can provide indoor thermal comfort to occupants, was developed by Givoni, primarily from fieldwork conducted in Europe and Israel [**14**] [**29**]. The boundary is based on the relationship between indoor maximum temperature and average vapor pressure. The dependence on vapor pressure (moisture content of the air) recognizes that the diurnal temperature swing decreases as humidity ratio rise.

In the proceeding sections, detailed discussions about the thermal performance of high mass naturally ventilated office, and residential buildings are carried out. Also, existing bio-climatic design chart like Givoni's building bio-climatic chart uses ASHRAE Standard 55–2013 comfort zone to assess the potential of various passive design strategies for a particular climate.

In the previous chapter, new comfort zones at different airspeed range, particularly for this climatic region, was developed to capture region specific expectation and adaptations, especially for naturally ventilated buildings. Furthermore to that part, this study focuses on proposing new envelopes for the use of high thermal mass in buildings, modified over existing bio-climatic design charts, to produce indoor comfort, especially for naturally ventilated residential and office buildings of this particular region.

6.9.1 Proposed high thermal mass boundary for residential buildings

Givoni [**14**] proposed a boundary defining "the outdoor maximum temperature below which indoor comfort can be maintained in a well-designed building as a function of vapor pressure." The limit is based on the relationship between indoor maximum temperature and average vapor pressure. Further, the proposed high thermal boundaries were up to a maximum ambient temperature of 36˚C and 38˚C for developed and developing countries, suggesting developing countries inhabitants can be comfortable at higher temperature limits.

In reviewing the distribution of temperature ranges of many regions in the world, Givoni [**14**] found a quantitative relationship between the vapor pressure (vp) and the diurnal ranges characterizing the different regions. Adopting the similar approach and based on measured average monthly outdoor swing and average monthly vapor pressure during the peak summer season (May- Sept), following quantitative relation have been developed for composite climate of Jaipur as depicted in equation (6.2).

$$\mathbf{S_{wg} = 37.8 - 1.9 \times vp(mm\ of\ Hg)} \qquad (\mathbf{6.2})$$

Where, S_{wg} is average outdoor temperature swing, and vp is average vapor pressure in mm of Hg.

In peak summer months (Apr-June) of Jaipur, average vapor pressure was found to be 8 mm of Hg, resulting in a maximum temperature swing of 20˚C. So, while defining the climatic boundary for the use of high thermal mass in buildings, actual diurnal swing during peak summer days have been considered for this climatic region.

Also, during the experimental investigation, the monitored high mass residential buildings showed an average indoor temperature diurnal swing of 15%–25% of outdoor daily temperature swing during peak summer days as presented in Figure 6-4 and Table 6.7. Also, the average indoor temperature in high mass buildings; was observed about 1ºC–2ºC above the mean outdoor temperature due to high heat storage capacity of materials, solar and internal heat gains.

So, while defining the boundary for climatic applicability of high mass with night ventilation for this climatic region, following assumption has been made.

- Steady state outdoor temperature conditions in peak summer month.
- Average monthly maximum and minimum temperatures are used as the input parameters
- The indoor comfort boundary has been extended by the use of ceiling fans (up to 1 m/s)

Taking into account, the relationships between the ambient vapor pressure and the outdoor range in summer and between the maximum indoor temperature and the outdoor range; a new boundary has been developed for high mass residential buildings under which comfort can be maintained and shown in Figure 6-11.

Procedure to define the oundary for high thermal mass is described below with a typical example:

Following steps have been used to define the climatic boundary of ambient condition for the use of high thermal mass in buildings through BBCC approach

- In setting a climatic boundary for the use of high thermal mass, it is assumed, in peak summer month having average monthly maximum, minimum and mean temperature is about 38.4˚C, 20˚C, and 29.2˚C, respectively.
- The average indoor temperature can be elevated, by solar and internal heat gains, up to 30.2˚C (~1˚C above outdoor average).
- Assuming an average indoor temperature swing of 20% (~3.6˚C) of outdoor temperature range in a high thermal mass well-ventilated building in composite climate lowers the indoor maximum and minimum

temperature to 32˚C and 28.4˚C, respectively which is well within the comfort zone.

- So, a new climatic boundary extended up to an average monthly maximum temperature of about 38.4˚C at 2g/kg specific humidity and follows a tilted line up to 35˚C at 20 g/kg of specific humidity which is the upper limit of the comfort zone at still air condition (up to 0.2 m/s) as shown in Figure 6-11.
- However, the comfort zone extends to a limit of 34.5˚C when the ceiling fan is used, and high mass polygon can be shifted to a limit of 40.9˚C as shown in Figure 6-12.

While estimating the climatic boundary for high thermal mass, the relationships between the ambient vapor pressure and the outdoor range and between the maximum indoor temperature and the outdoor range during peak summer days have been considered. Also, the difference between average indoor swing in stone wall building and brick wall building during peak summer period was negligible, suggesting no difference between bio-climatic boundary of thermal mass in buildings for different constructions materials.

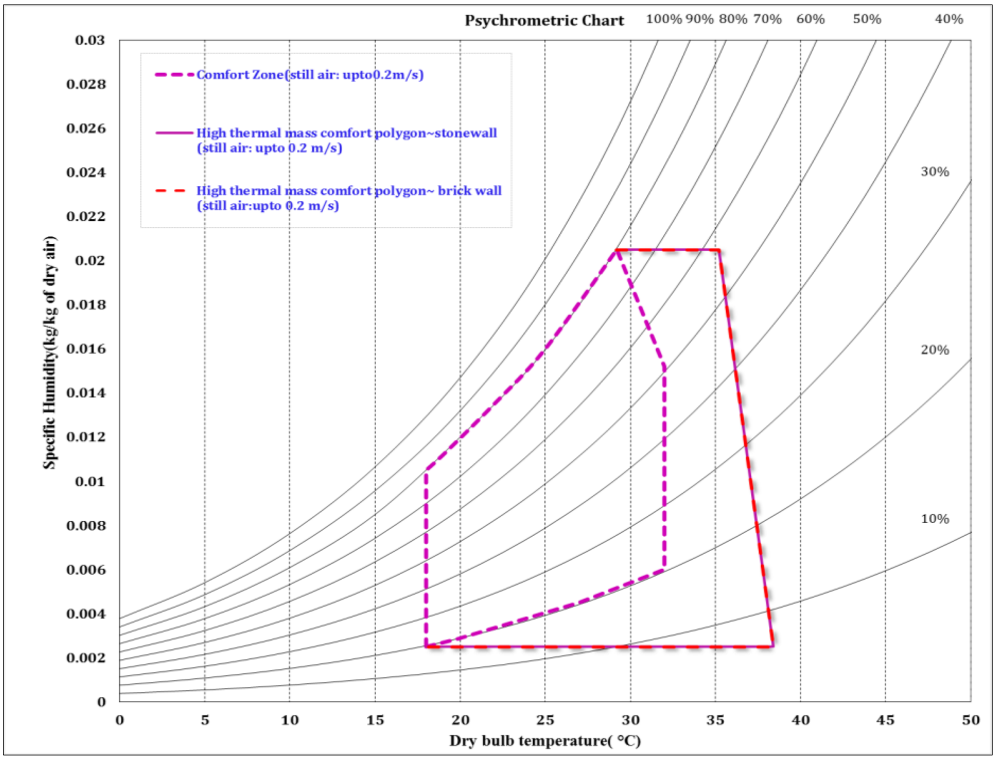


Figure 6-11 Redefined bio-climatic boundary for high mass residential buildings at still air condition (up to 0.2 m/s)

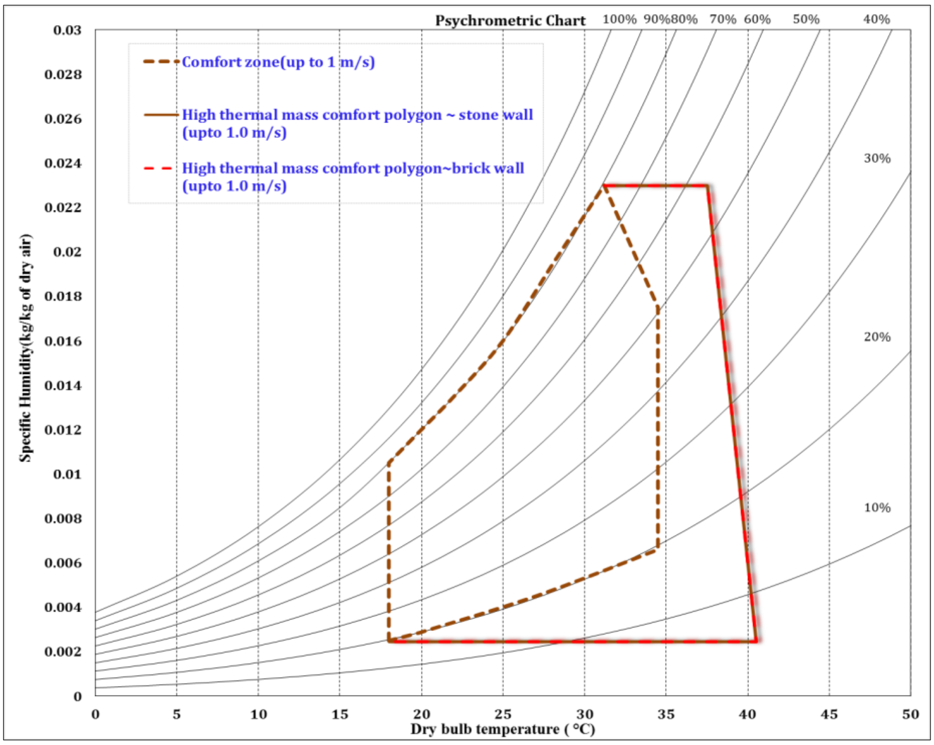


Figure 6-12 Redefined bio-climatic boundary for high mass residential buildings at elevated speed condition using ceiling fan (up to 1 m/s)

6.9.2 Proposed high thermal mass boundary for office buildings

Office buildings considered for present study has the high thermal mass to volume ratio, more glazing area, and different management/schedules than residential buildings. Office buildings were operated between 9 am to 6 pm for both summer and winter season. The adaptive actions like opening/closing of windows, switch on /off fans and regulating speed vary substantially between residential and office environments. Windows were found closed during the night in summer and winter season due to management and security reasons. This restricts the effective ventilation to cool the high thermal mass of office buildings, and sequentially higher indoor temperatures were observed, especially in during peak summer days. Also, during extensive interactions with office occupants, it was revealed that during early morning the windows and fan were used to flush out the indoor heat and lower the indoor temperatures. This leads to higher indoor temperature swings in office buildings in comparison to residential buildings as shown in Table 6.9.

During the experimental investigation, the monitored high mass office buildings showed an average indoor temperature swing of 25%–35% of outdoor temperature swing during peak summer days. Also, the average indoor temperature in office buildings; was observed about 2˚C–3˚C above the average outdoor temperature due to high heat storage capacity of materials, solar and internal heat gains. As the method adopted in above section, bio-climatic boundary for the use of high mass in office buildings extended up to an average monthly maximum temperature of about 37.4˚C and follows a tilted line up to 34˚C at still air condition (up to 0.2 m/s) as shown in Figure 6-13. The bio-climatic boundary for office buildings shifted towards lower ambient conditions due to high internal gain, inefficient night ventilation condition and different management of these buildings which leads to higher indoor temperatures during the summer season. A similar finding has been observed by Lomas et al. [**160**] while defining the climatic boundaries for indirect evaporative cooling for office buildings. They further concluded that boundary was sensitive towards different internal gains and type of construction used in buildings. The bio-climatic boundary for the use of high thermal mass in office buildings extends to an ambient temperature limit of 39.9˚C when the ceiling fan is used (Figure 6-14).

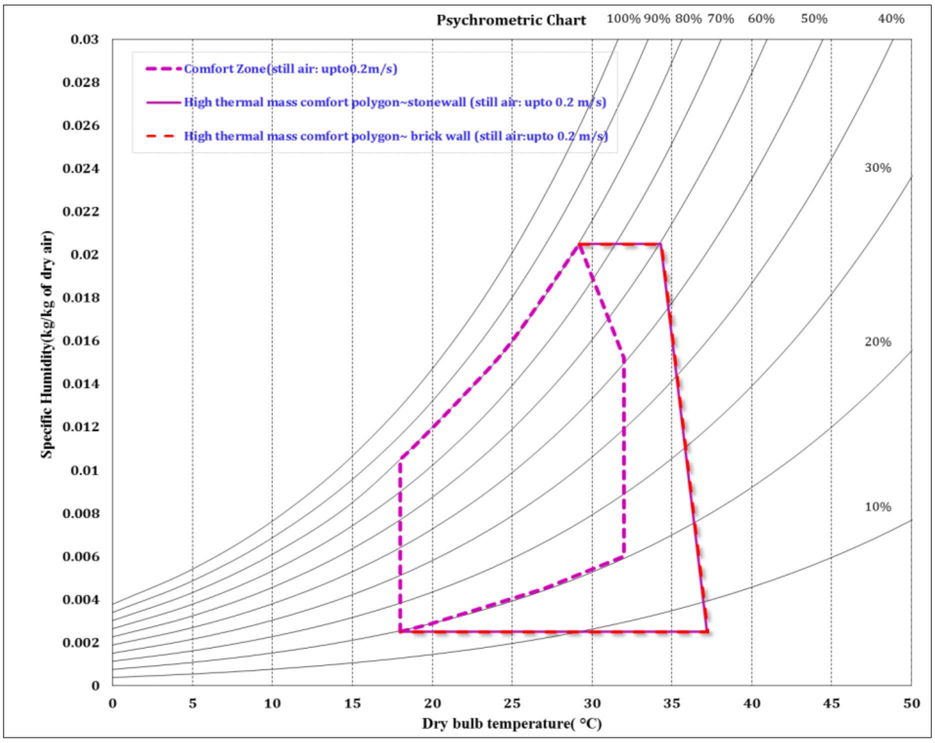


Figure 6-13 Redefined bio-climatic boundary for high mass office buildings at still air condition (up to 0.2 m/s)

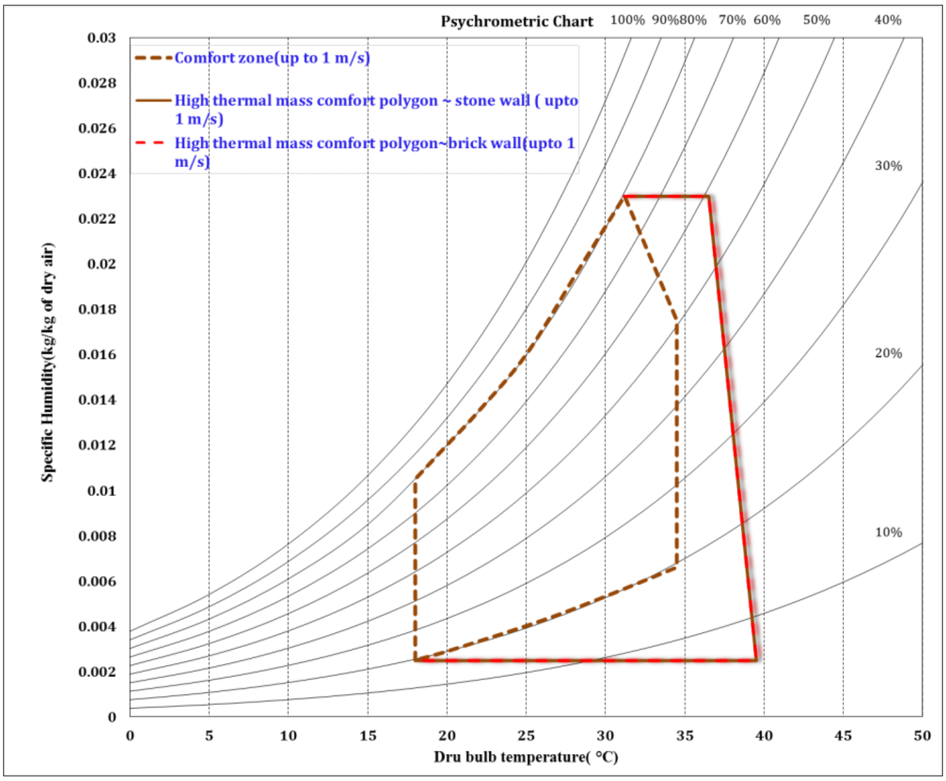


Figure 6-14 Redefined bio-climatic boundary for high mass office buildings at elevated speed condition using ceiling fan (up to 1 m/s)

6.10 Modeling, simulation, and calibration of developed models

In the preceding sections, the climatic boundaries for the use of high thermal mass in naturally ventilated residential and office buildings through building bio-climatic design approach has been developed for this region. However, these boundaries are ambiguous and depend upon building construction type (thermal mass in building envelope), internal gains, and management of buildings (schedules) as found in previous studies [**20**] [**160**]. So, the developed boundaries are further investigated using simulation techniques for different construction type and at various internal gains for naturally ventilated residential and office buildings.

The residential and office building model used for simulation study were developed using experimental stone wall construction building as shown in Figure 6-15. A detailed description of their physical geometry and construction type are shown in Table 6.1 and Table 6.3. The building models were initially developed using Google Sketch Up version 8.0 using all the geometrical parameters from the existing experimental buildings. Later the model is imported to a dynamic thermal simulation tool called E+ (EnergyPlus version

8.3) for refinement and simulation runs. The EnergyPlus program [**194**] combines the best capabilities and features from BLAST and DOE–2 program along with new capabilities to simulate the indoor conditions with fair accuracy.

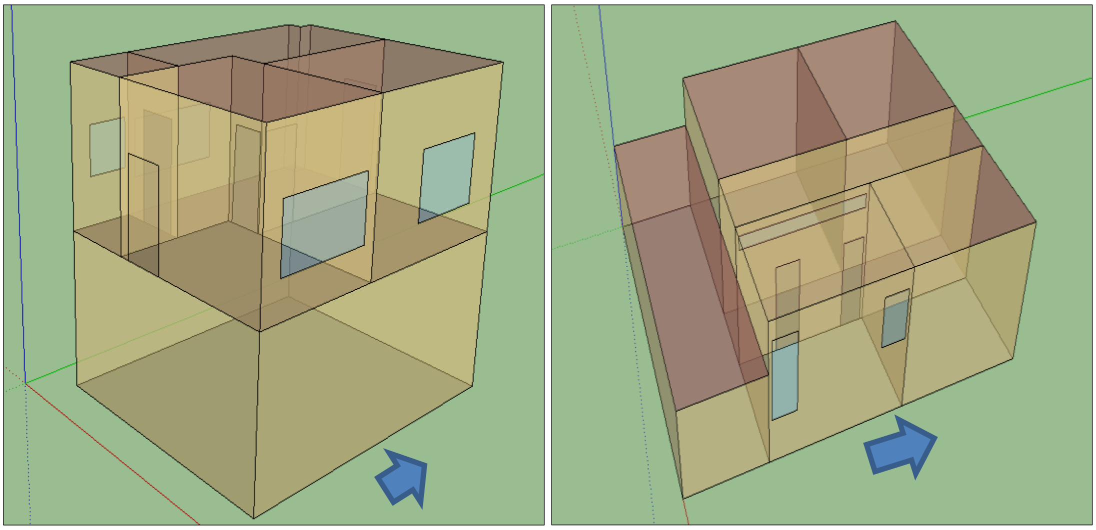


Figure 6-15 3D drawing of developed models for (a) residential building and (b) office building

The models are calibrated using simulation runs for 15 days in the month of June and compared with measured data to assess the "goodness-of-fit" (R^2) as suggested in ASHRAE Guideline 14–2002 [**193**] [**195**]. As per the criteria of ASHRAE Guideline 14–2002, R^2 of 0.9 or greater and slope between 0.75 and 1.25 are sufficient for calibration. Figure 6-16 represents the agreement between simulated and measured data for stone wall residential buildings. In the case of naturally ventilated buildings, opening windows and ventilation flow rate through openings are crucial to calibrate the models. In the present study, an extensive interaction has been carried out with occupants for their adaptive actions (Table 6.5) viz. opening/ closing of windows, night ventilation scenarios, etc. and incorporated in simulation runs. Further, the ventilation rates have been adjusted during simulation runs to calibrate the models and generate a reasonably accurate output to predict the thermal performance of simulated buildings.

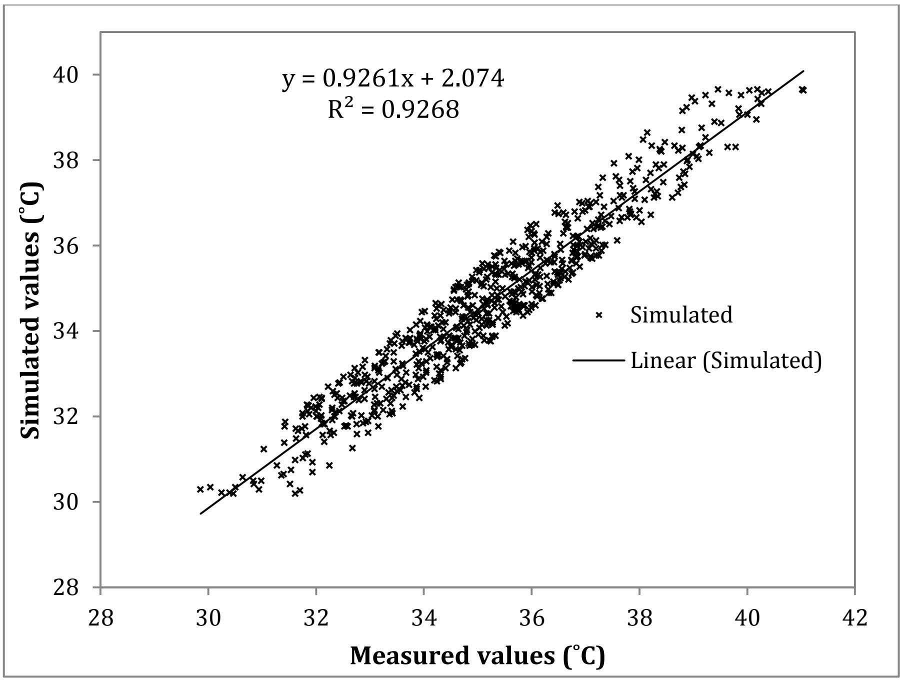


Figure 6-16 Agreement between measured and simulated temperatures for stone wall residential building model for all 360 hrs

6.10.1 Effect of thermal mass and internal gains

Thermal mass can reduce indoor air temperature variation in buildings which is mainly influenced by external climatologically parameters (solar radiation, outdoor temperature) and highly variable internal loads (occupancy, lights, equipment). The calibrated residential and office building models were simulated for two thermal mass scenarios:

1. High thermal mass: with the 0.30m stone wall external wall and 0.15m concrete ceiling with plaster to the interior
2. Low thermal mass: with the 0.12m single brick construction (change in the density of brick from 750kg/m^3 to 500 kg/m^3) and 0.10m concrete ceiling with plaster to the interior.

The internal gains in residential and office building also vary substantially. The office has higher internal gain regarding equipment load, higher occupancy density per unit area and lighting load. Also, the schedules of office buildings are quite different from residential buildings. Occupants of residential buildings are free to adjust their indoor environment according to their need by operating various controls available to them. However, in office buildings occupants have limited adaptive controls to improve their indoor conditions. Thus, the internal gains and schedules were also varied to establish the sensitivity of climatic boundary using a different level of internal gains in the building. The internal gains modelled in the simulation were:

1. Light internal gain: a person having 100W of thermal load per 20m^2 with very low LPD (Lighting Power Density) of about 5W/m^2 and equipment density load of 5W/m^2.
2. High internal gain: a person having 100W of thermal load per 5m^2 area with LPD of about 20W/m^2 and equipment density load of 10W/m^2.

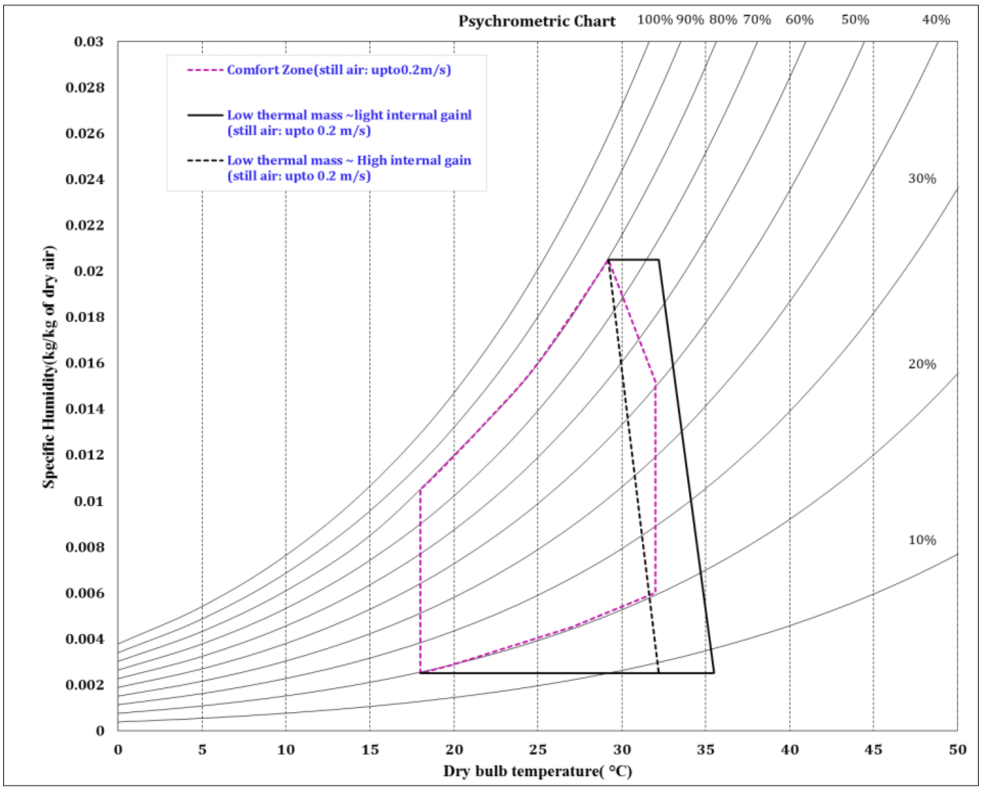
The office buildings were modeled with typical office schedule of 9 am to 6 pm while residential buildings were modeled with a compact schedule for occupancy, lighting, and equipment based on a regular survey conducted during the field study. Also, the night ventilation rate was assumed to be 4 ach^{-1} for office and residential building with a constant infiltration rate of 0.5ach^{-1}.

Simulations were carried out for the whole summer season (1Apr–30Sept) using hourly values of outdoor conditions for Jaipur city as obtained from the weather file of Jaipur city (IND_Jaipur_ISHRAE_2013.epw) [**171**].

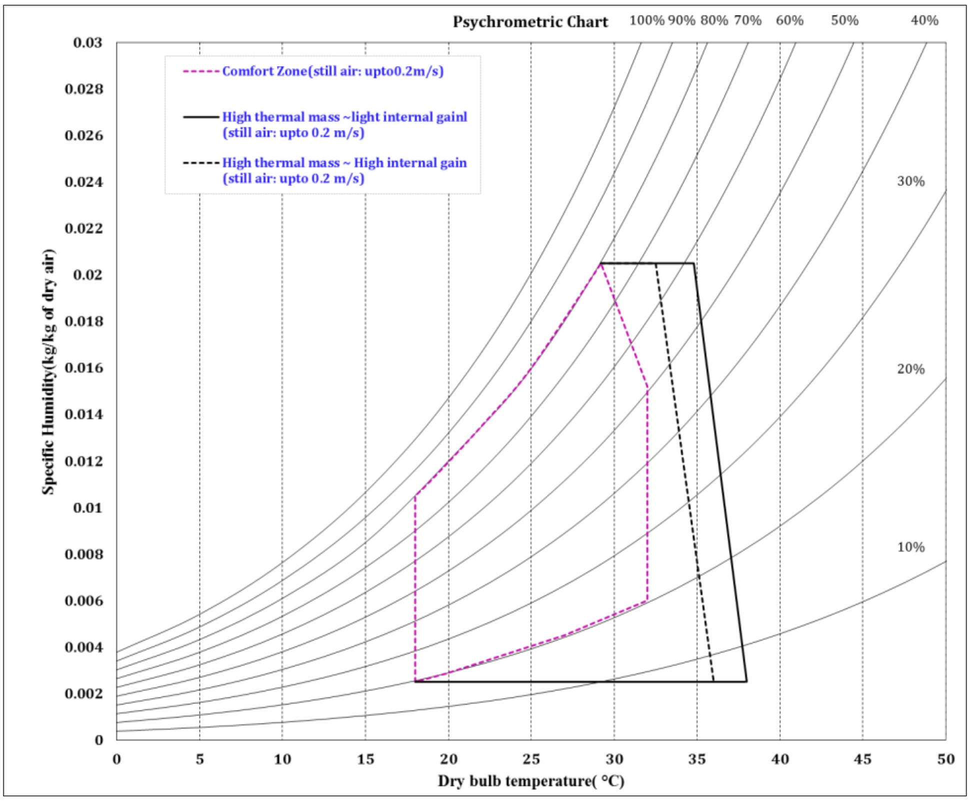
6.10.2 Sensitivity analysis: shifting of boundary for residential buildings

Since for the climate of Jaipur city, summer season spans more than seven months from April to September. Also, thermal mass is most effective during this period due to large diurnal swings in ambient temperature. So all the combination of thermal mass levels with different internal gains were simulated and analyzed for summer period (1 Apr–30 Sept).

Simulation results revealed that low thermal mass building has higher indoor air temperature and large diurnal indoor swings due to low heat storage capacity and corroborates with the findings observed in other studies [**135**] [**124**]. This scenario is more pronounced when there are high internal gains regarding occupancy, lighting and equipment loads. So, it is evident that for low thermal mass buildings climatic boundary exists at lower ambient conditions than high thermal mass buildings. Figure 6-17 (a, b) shows variation in the limit of the low thermal mass residential building at different internal gains. At higher internal gains the climatic boundary further shifts inwards (more than 3˚C) due to high indoor air temperature in peak days which leads to uncomfortable conditions. Table 6.20 describe the maximum ambient temperature limit up to which the thermal mass boundary could yield indoor comfort and corresponding bandwidth of the boundary for different thermal mass and internal gains combinations. However, in the case of high thermal mass, the climatic boundary shows a lower bandwidth in comparison to low thermal mass buildings. The high thermal mass building shows a lower bandwidth of about 2˚C at different internal gains due to the massive structure of the building.



(a)



(b)

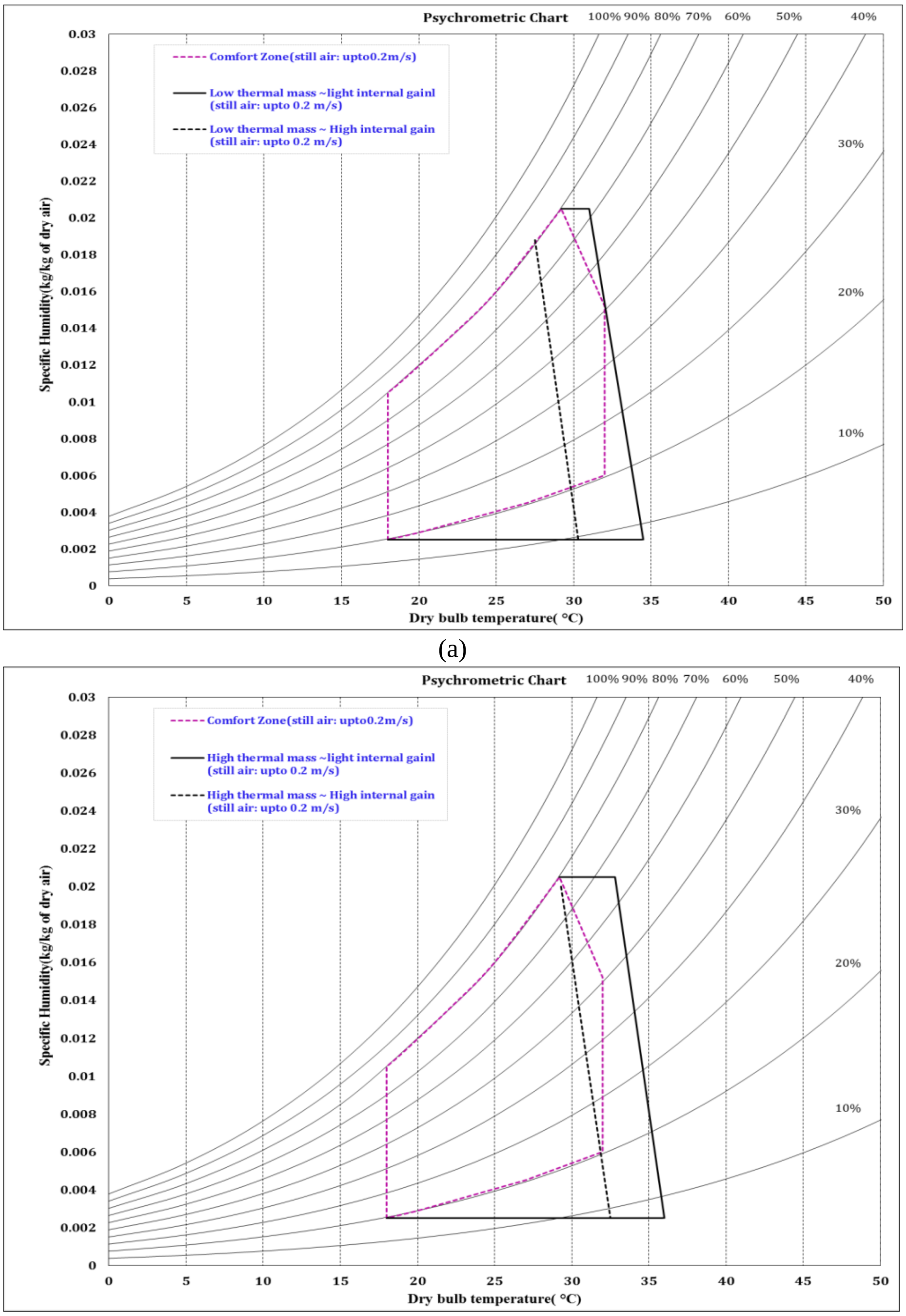
Figure 6-17 Tentative bandwidths of climatic boundary for (a) low thermal mass building and (b) high thermal mass residential buildings at different internal gain

Table 6.20 Maximum temperature limit and bandwidth of climatic boundary for different combinations of thermal mass and internal gains

Type of building	Thermal mass scenario	Internal gains	Maximum temperature limit (˚C)	Bandwidth (˚C)
Residential building	Low thermal mass	Light	35.5	(3.5)
		High	32.0	
	High thermal mass	Light	38.0	(2.0)
		High	36.0	
Office building	Low thermal mass	Light	34.6	(4.3)
		High	30.3	
	High thermal mass	Light	36.0	(3.0)
		High	33.0	

6.10.3 Sensitivity analysis: shifting of the boundary for office buildings

The climatic boundary of high thermal mass is found to be more sensitive for office buildings than residential buildings. This is due to high thermal mass to volume ratio, large glazing area, and a different schedule of office buildings in comparison to residential buildings. Similar to the findings for the residential buildings, the climatic boundary for thermal mass in the office buildings were also showed variation for different combinations of thermal mass and internal gains as shown in Table 6.20. Office buildings showed a higher comfort bandwidth ranging from 3˚C–4.5˚C especially for lightweight construction and high internal gain. Figure 6-18 (a, b) shows variation in the boundary of low thermal mass and high thermal mass office building at different internal gains. Increasing internal gains inside the office building increase the indoor temperatures leads to high discomfort conditions. Also, during peak summer period windows are mostly closed during the day which further adds the heat generated inside the buildings.



(a)

(b)

Figure 6-18 Tentative bandwidths of climatic boundary for (a) low thermal mass building and (b) high thermal mass office buildings at different internal gains

6.11 Summary

This present chapter summarized the results of the experimental investigation for long term thermal monitoring of high thermal mass naturally ventilated buildings during summer and winter season. Mathematical correlations are developed for predicting indoor air temperatures in the monitored high mass buildings. Further statistical analysis has been carried out based on R^2 value, 'F–statistics,' and 't–statistics' analysis to determine the accuracy of the obtained correlation for different seasons for monitored high mass buildings. It is demonstrated that enough good agreement (R^2>0.90) existed between the measured data and the one predicted from formulae during field validation. Results are further extended to develop a new bioclimatic boundary of ambient conditions for the use of high thermal mass in buildings through building bio-climatic design chart using adaptive comfort zones. The boundaries extend up to an average monthly maximum ambient temperature of about 38.4˚C and 37.4˚C for residential and office type buildings, respectively. Calibrated simulation runs were carried out to analyze the sensitivity of developed boundaries for different thermal mass levels and at different internal gains. A bandwidth of more than 3˚C has been observed for high internal gains especially for low thermal mass buildings during simulation study.

CHAPTER 7
CONCLUSIONS

7.1 Thermal adaptations in naturally ventilated buildings

A field study of thermal comfort using adaptive comfort approach was carried out to evaluate the thermal adaptations of subjects residing in naturally ventilated buildings in the composite climatic region of India. The thermal comfort field study was conducted in thirty-two naturally ventilated buildings, collecting a total of 2610 samples spread over an entire period of five years (between April 2011 and July 2016), covering all seasons, age groups, clothing types, and building types. The present study analyzed the thermal sensations and preferences for different environmental parameters, thermal neutrality and the various thermal adaptations prevailing in naturally ventilated buildings for this region. The adaptive use of environmental controls by occupants for thermal comfort is also discussed briefly.

Major findings from this part of the study are as follows:

1. The study observed that the subjects in naturally conditioned spaces were found thermally satisfied for a wide range of indoor temperatures. A total of 82% of the subjects felt thermally comfortable at prevailing indoor conditions. The results of the present study corroborate to the findings of other adaptive comfort studies conducted in naturally ventilated buildings for similar climatic conditions and cultural backgrounds.
2. On an annual basis, the mean comfort temperature, as predicted by Griffith’s method, was found to be 27.9˚C. This is higher than comfort limits defined in National Building Code of India and is comparable to the findings of different studies of adaptive thermal comfort for naturally ventilated buildings in the country.
3. The seasonal analysis revealed that the mean comfort temperature was 30.6˚C in summer and 24˚C in winter. Thus, the seasonal variation of mean comfort temperature was about 6.6˚C.

4. In naturally ventilated buildings in this climate, there is a continuous adaptation in clothing pattern throughout the year; the most preferred clothing level is 0.30 clo for summer and 0.80 clo for winter.
5. In the present study 40% of the total observation, windows were found open. The proportion of window opening reaches to a maximum of 60% when the mean indoor operative temperature peaks at 33.2˚C.
6. The percentage of fans in use increased as the temperature increased, and it reached a maximum of 81% when the mean indoor operative temperatures peaked at 28.5˚C. Use of fans elevated the comfort temperature by about 3˚C in naturally ventilated buildings.
7. Equations for predicting fan and window opening have been developed using the "Logistic Regression" method. The predicted data matched fairly with measured data and can be used to establish algorithms for occupant's control which can be employed in building simulations for energy efficiency in buildings.

7.2 Defining thermal comfort zones for naturally ventilated buildings

It is now a well-known fact, based on the adaptive thermal comfort approach, order of thermal adaptations depends on region-specific adaptations, social, cultural setup, and thermal expectations. Therefore, the results of this adaptive thermal comfort study are further used to define thermal comfort zones on psychrometric chart considering climate specific adaptations, the role of air speed and thermal preferences, especially for naturally ventilated buildings.

1. ASHRAE Standard 55–2013 comfort zones are evaluated considering this climate's specific clothing variability, the role of air speed, regional preferences, and expectations. The results of the present study revealed that these comfort zones need to be modified.
2. The modified comfort zone of this climatic zone reflects that the subjects are comfortable with an indoor operative temperature up to 32˚C and between a relative humidity of 20%–80% in still air conditions of 0–0.2 m/s.

3. The comfort zones further extend up to 34.5˚C and 35˚C between the relative humidity of 20%–80% at a higher indoor air speed of 1 m/s and 1.5 m/s.
4. The defined adaptive comfort zones are further validated using extended thermal comfort data and found to be reliable for this climatic zone.

7.3 Thermal performance and building bio-climatic design chart for high thermal mass buildings

Since this study is motivated to develop a building bio-climatic design chart for one commonly used passive strategy viz. high thermal mass specific to the composite climate of India. The study also developed mathematical correlations for predicting the indoor temperatures vis-à-vis measured outdoor conditions using multiple linear regression method.

Major findings of this part of work are as follows:

1. The study establishes that the locally available high thermal mass construction materials such as stone and brick are efficient during peak summer or winter season for cooling or heating purposes respectively in naturally ventilated buildings for this region.
2. Mathematical correlations are developed for predicting indoor air temperatures in the monitored high thermal mass buildings for summer and winter season separately. It is demonstrated that a reasonably good agreement (R^2>0.90) existed between the measured data and the one predicted from correlations during its validation.
3. Further statistical analysis using ‘F–statistic’ and ‘t–statistic’ established the robustness of developed correlations. Correlations are further field validated to other buildings of similar constructions types.
4. The new bio-climatic boundary of ambient conditions for the use of thermal mass in naturally ventilated buildings is developed. The boundaries extend up to an average monthly maximum temperature of about 38.4˚C and 37.4˚C for residential and office buildings, respectively.

5. Simulation study revealed that boundaries are shifted towards lower ambient temperature limits for low thermal mass construction and high internal gains with a bandwidth of more than 3˚C.

7.4 Scope for further research

Based on the findings of the present study, the scope of future research is suggested here:-

- This study was carried out for the composite climatic zone of India and similar studies for other climatic zones of India should be conducted for assessment of thermal adaptation for different types of buildings to reduce the energy consumption HVAC systems in buildings.
- Use of environmental controls such as windows, fans, doors, blinds/curtains should be analyzed and their effect on indoor thermal comfort and energy consumption should be taken into account during building design phase.
- The potential of other passive strategies like direct evaporative cooling, natural ventilation, direct gain, etc. should be evaluated in the different climatic zone of India to maximize indoor thermal comfort and minimize energy consumption.
- The study further suggests the necessity of exploring the percentage of energy saving while designing the buildings using these customised bio-climatic design charts of passive design along with active cooling systems to make sustainable and energy efficient buildings in India.

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APPENDICS

Appendix 1 Thermal comfort questionnaire used in present study [83]

THERMAL COMFORT QUESTIONNAIRE SURVEY-2013

Survey No. [ ]

Part-A (To be filled by occupant)

Please check mark (√) following:

Building type: [ ] Office [ ] AC [ ] NV [ ] MM [ ] Residential

1. **Occupant name :**_ _
2. **Qualification** : **BTech/ M.Tech/ PhD year of study: 1st /2nd /3rd /4th**
3. **Room No. and floor:** _
4. **Date:** / /2013 **5. Time:** _ _:_ _
6. **Gender** ☐ Male ☐ Female
7. **Weight :** _ _ _ _ _ _ _kg **8. Height:** _ _ _ _ft **9. Age :**_ _ _ _ yr

10. Name of your native place: _

11. Residing years in present city:

☐ One year ☐ two years ☐ three years ☐ more than 3 years

12. Year of service/work on current designation/position:

☐ One year ☐ two years ☐ three years ☐ more than 3 years

13. On the basis of **temperature** how do you feel right now?

Cold	Cool	Slightly Cool	Neutral	Slightly warm	Warm	Hot
☐	☐	☐	☐	☐	☐	☐

14. On the basis of **humidity,** how do you feel right now?

Very dry	Moderately dry	Slightly dry	Neutral	Slightly humid	Moderately Humid	Very humid
☐	☐	☐	☐	☐	☐	☐

15. On the basis of indoor **air movement,** how do you feel right now?

Very still	Moderately still	Slightly still	Acceptable	Slightly Moving	Moderately Moving	Much Moving
☐	☐	☐	☐	☐	☐	☐

16. On the basis of **combined effect of above three,** how do you feel right now?

Very comfortable	Comfortable	Slightly comfortable	Uncomfortable	Very uncomfortable
☐	☐	☐	☐	☐

17. If you could choose to change, how would you prefer the **temperature** to be?

Much cooler	A bit cooler	No change	A bit warmer	Much warmer
☐	☐	☐	☐	☐

18. If you could choose to change, how would you prefer the **humidity** to be:

Moderately dry	Slightly dry	No change	Slightly humid	Moderately Humid
☐	☐	☐	☐	☐

19. If you could choose to change, how would you prefer the air velocity to be:

Moderately still	Slightly still	No change	Slightly Moving	Moderately Moving
☐	☐	☐	☐	☐

20. Sensation of lighting: How do you find the lighting level?

Very Bright	Bright	Slightly Bright	Neither bright nor dim	Slightly Dim	Dim	Very Dim
☐	☐	☐	☐	☐	☐	☐

21. What would you prefer lighting level?

Much dimmer	A bit dimmer	No change	A bit brighter	Much brighter
☐	☐	☐	☐	☐

22. How do you find the air quality?

Excellent	Good	Slightly good	Neither good nor bad	Slightly bad	Bad	Very bad
☐	☐	☐	☐	☐	☐	☐

23. In the last one hour what are the changes made by you (if no changes please check mark)

	Window	Door	Fan	Evaporative cooler	Air conditioner
Open/On (√)					
Close/Off (√)					

24. Your activity in last 15 minutes (Please tick):

Activity	(√)	Duration (hours)	Activity	(√)	Duration (hours)
Sleeping	☐	☐	Standing (working)	☐	☐
Sitting (passive work)	☐	☐	Walking indoors	☐	☐
Sitting (active work)	☐	☐	Walking outdoors	☐	☐
Standing relaxed	☐	☐	Others (Specify)…………………………..		

25. What are you wearing now? (select from list)

1	Baniyan		13	Tights	
2	T-shirt		14	Pyjamas	
3	Short sleeve shirt (Poly/cotton)		15	Lower (thermal inner)	
4	Long sleeves shirt (Poly/cotton)		16	Dhoti	
5	Cotton sari, blouse		17	Jeans	
6	Polyester sari & blouse		18	Trousers/long skirt (Poly/cotton)	
7	Cotton salwar kameez		19	Shorts/short skirt (Poly/cotton)	
8	Polyester salwar & kameez		20	Long gown	
9	Jacket/woolen jacket		21	Scarf/Woolen Cap/hat	
10	Pullover/Sweater/ upcollar		22	Sandals	
11	Thermal tops		23	Slipper	
12	Suit		24	Socks & shoes	

26. Do you feel local thermal discomfort at any part of your body (please tick):

Neck/Head	☐	Arms	☐
Back	☐	Feet	☐
Chest	☐	Palms	☐

27. Do you use **air conditioner/heater at home?**

Yes / No If yes (no. of years):

27. Do you use **A/C or heater in car?**

Yes / No If yes (no. of years):

Part-B (To be filled by Surveyor)

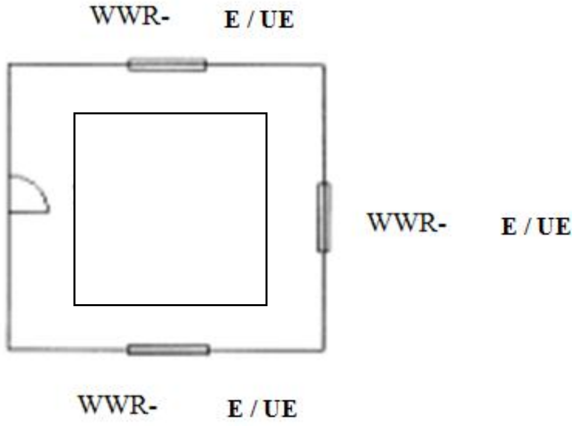
MEASUREMENTS AT OCCUPANT LOCATION

Date: _ _/ _ _ /_ _ _ _ **Time: _ _:_ _**

1. **Kind of office:-**
   a) Individual office room ☐
   b) Shared / open plan office ☐

2. **Nature of building**
   a) Glazed building ☐
   b) Traditional building ☐
   c) Green/Certified building ☐
   d) Any other:-

3. Please mark position of **Person-‘X’**, **Fan-'F’, AC**-‘A’ and **‘H’-for any heat source** with respective location in the given sample)



‘E’-Exposed wall, ‘UE’-Unexposed wall,
‘WWR’-Window wall ratio

4. Level of physical **activity**: (Please tick)
   ☐ Reclining
   ☐ Seated Quite
   ☐ Office, School
   ☐ Standing Relaxed
   ☐ Light Activity, Standing
   ☐ Medium Activity, Standing
   ☐ High Activity

5. **Air draft hitting to the occupant:** Yes / No

6. **Glazing type:**
   Single pane glass ☐
   Single Tinted ☐
   Single reflective ☐
   Double pane ☐
   Special Glass Low–SHGC, low-e ☐
   Others ☐

7. **Roof:** ☐ Exposed ☐ Unexposed

8. **Control conditions during survey:-**

	Open (√)	Close (√)		On (√)	Off (√)
External door			Fan		
Balcony door			Lights		
Window			Evaporative cooler		
Blind/ curtain			Air conditioner		

9. Air conditioning system in the surveyed room: Please check mark the (√) the following:

System	Split-AC/Heater	Window-AC/heater	Central air conditioning	Evaporative coolers	Central Evap. cooler	Fan operated /Any Others
Type of cooling/heating system used						
Height of Cooling /heating system (ft)						
How long use of particular type (years)						

10. Distance of window from working station

☐ 0.5m ☐ 1m ☐ 1.5m ☐ Not near window

11. Thermostat setting – _ _ _ _ _°C **12. No of occupants:**

13. Lighting level: Lux …………

14. Seasonal Conditions

☐ winter ☐ Spring ☐ Summer ☐ Fall

15. Sky conditions: ☐ Clear ☐ Mixed ☐ Cloud

16. Environment conditions:

Sr. no	Environment variables	I (close to person)
I	Outdoor temperature-°C	
II	Room air temperature -°C	
III	Relative humidity -%	
IV	Mean radiant temperature °C	
V	Air velocity -m/s	

17. Level of CO2 ☐ ppm

18. Qualification of surveyed person- ☐ Metric ☐ G ☐ PG

19. Approximate annual income (lac)- ☐ 2-5 ☐ 5-10 ☐ more than 10

Thank you so much for cooperation. Your views and observations are very valuable to us. If anything remains left from our approach we look forward your valuable suggestions.

Symbols-
G-Graduate, PG-Postgraduate

……………
Signature (optional)

Appendix 2: Clothing insulation and activity level checklist used in present study

Clothing ensembles

(Source: ASHRAE Fundamental, 2009 [**42**] and Indraganti, 2010 [**80**])

S.No.	Clothing ensembles	Clothing insulation (Clo)	S.No.	Clothing ensembles	Clothing insulation (Clo)
1	Baniyan	0.04	13	Tights	0.15
2	T-shirt	0.08	14	Pyjamas	0.42
3	Short sleeve shirt (Poly/cotton)	0.19	15	Lower (thermal inner)	0.15
4	Long sleeve shirt (Poly/cotton)	0.25	16	Dhoti	0.15
5	Cotton sari, blouse	0.54	17	Jeans	0.24
6	Polyester sari & blouse	0.61	18	Trousers/long skirt (Poly/cotton)	0.24
7	Cotton Salwar & Kameez	0.44	19	Shorts/short skirt (Poly/cotton)	0.15
8	Polyester Salwar & Kameez	0.53	20	Long gown	0.29
9	Jacket/woolen jacket	0.25	21	Scarf/Woolen Cap/hat	0.03
10	Pullover/Sweater/ upcollar	0.36	22	Sandals	0.02
11	Thermal tops	0.20	23	Slipper	0.03
12	Suit	0.44	24	Socks & shoes	0.05

Activity checklist and corresponding metabolic rate

(Source: Indraganti, 2010 [**80**])

S.No.	Metabolic activity	Metabolic rate (met)	S.No.	Metabolic activity	Metabolic rate (met)
1	Reclining/lying down	0.8	5	Standing-working	2.0
2	Sitting-passive work	1.0	6	Walking indoors	1.7
3	Sitting-active work	1.2	7	Walking outdoors	1.7
4	Standing relaxed	1.2	8	Others	

Appendix 3 Photographs of some selected naturally ventilated buildings surveyed in present study

Location: Jaipur, Rajasthan (India)

(A) Gargi Hostel-MNIT (B) Boys Residential Hostel-2-MNIT (C) and (D) Multi storied Residential Apartment- MNIT (E) Auribindo Hostel-MNIT (F) Library-MNIT (G) Boys Residential Hostel 3 - MNIT (H) Dean Academic Offices- MNIT

Table: Conventional construction materials used in buildings and their properties

Material (Outer to inner layer)	Roof thickness (mm)		Wall thickness (mm)		Floor thickness (mm)
	#	*	#	*	*
Gypsum plaster	12.7		12.7	15	12.7
Sand and gravel	25.4		-	-	25.4
Concrete slab medium density	101.6	150	-	-	101.6
Brick	-		203.2	230	-
Gypsum plaster	12.7		12.7	12.5	12.7
Cork/burnt clay tiles	-	50	-	-	6
Assembly U-value (W/m^2 ^{o}C)	3.760	3.62	1.782	3.026	3.057

*Note: # represents a study carried out by Kumar and Suman (2013) and * corresponds to study performed by Dhaka et al. (2012) at the composite climate of India.*

BRIEF BIO-DATA OF AUTHOR

Mr Sanjay is a Research scholar in Centre for Energy and Environment, Malaviya National Institute of Technology (MNIT), Jaipur. He has received his B.Tech. degree in Mechanical Engineering from YMCA University, Faridabad in 2009. He has received his Master’s degree from Thapar University, Patiala in Thermal Engineering in 2012 and then joined Ph.D. program in July 2013 under supervision of Prof. Jyotirmay Mathur and Dr. Sanjay Mathur, Centre for Energy and Environment, MNIT, Jaipur. His research interests are Thermal comfort, Passive Cooling/Heating, Heat Transfer and Solar Thermal Application.