ANALYSIS OF INDOOR THERMAL COMFORT IN MECHANICALLY VENTILATED OFFICE BUILDINGS OF MODERATE CLIMATE

A DISSERTATION

Submitted in partial fulfillment of the requirements for the award of the degree of

MASTER OF ARCHITECTURE

By

BETTY LALA

DEPARTMENT OF ARCHITECTURE AND PLANNING
INDIAN INSTITUTE OF TECHNOLOGY, ROORKEE
ROORKEE-247667

JUNE 2014

<u>CANDIDATE'S DECLARATION</u>

I hereby declare that the work, which is being presented in the dissertation, entitled " **Analysis Of Indoor Thermal Comfort In Mechanically Ventilated Office Buildings Of Moderate Climate**" in partial fulfillment of the requirement for the award of the degree of Master of Architecture, submitted to the Department of Architecture and Planning of the Indian Institute of Technology Roorkee, Roorkee is an authentic record of my own work carried out during the period from July 2013 to June 2014, under the supervision and guidance of Dr. P.S Chani, Department of Architecture and Planning, Indian Institute of Technology, Roorkee, India.

The matter embodied in this dissertation has not been submitted by me for the award of any other degree of this or any other institute.

Date:

Place: Roorkee   Ms. Betty Lala

This is to certify that the above statement made by the candidate **Ms. Betty Lala** is correct to the best of my knowledge and belief.

<u>Thesis supervisor:</u>
Dr. P.S Chani
Associate Professor
Department of Architecture and Planning
Indian Institute of Technology, Roorkee
Roorkee, Uttrakhand, India-247667

Date:

Place: Roorkee

CERTIFICATE

Certified that report entitled **"Analysis Of Indoor Thermal Comfort In Mechanically Ventilated Office Buildings Of Moderate Climate"** which has been submitted by **Ms. Betty Lala**, for partial fulfillment of the requirement for the award of the post graduate degree in Master of Architecture, in the Department of Architecture and Planning, Indian Institute of Technology Roorkee, Roorkee is the student's own work carried out by her under my supervision and guidance. The matter embodied in this dissertation has not been submitted for the award of any other degree of this or any other institute.

Dr. P. S. Chani
Associate Professor
Department of Architecture and Planning
Indian Institute of Technology, Roorkee
Roorkee, Uttrakhand, India-247667

Date:

Place: Roorkee

ACKNOWLEDGEMENTS

At the end of my thesis, it gives me great pleasure in expressing my gratitude to all those people who have supported me and had their contributions in the success of my study and making this thesis possible and making it an unforgettable experience for me.

First and foremost, I must acknowledge and thank God for His abundant blessings, guidance and protecting me throughout this period. All what I have achieved and become is all because of His grace and love.

I would like to express my special appreciation and thanks to my advisor Dr. P. S. Chani, Associate Professor, Department of Architecture and Planning, Indian Institute of Technology, whose expertise, understanding, and patience, added considerably to my thesis. This thesis would not have been possible without his guidance, support, motivation and help during the course of my dissertation. He has given me freedom during my research, and allowed me to pursue independent work.

In addition, I have been very privileged to have received the opportunity to be a part of the DAAD-IIT Sandwich Program and the chance to collaborate and complete a part of my dissertation in Berlin, Germany. I would like to express my deepest gratitude to my mentor in Technische Universitat Berlin, Prof. Dr.-Ing. Martin Kriegel , head of Hermann Rietschel Institute, Department of Building Energy Systems , for accepting me to be a part of the student exchange program and the opportunity to study under his guidance. The experience and knowledge I gathered in Berlin will always be special. The laboratory experiment in the department at Hermann Rietschel Institute would not have been possible or completed without the help and supervision of Dipl.-Ing. Benjamin Zielke. I appreciate his valuable guidance, scholarly inputs, for lending me his expertise to my scientific and technical problems and consistent encouragement I received throughout the research work.

I would never have been able to finish my dissertation without the guidance of all the professors who have taught me and were a part of my two years in the Department of Architecture and planning, IIT-Roorkee. I thank the Head of the Department, Dr. Pushplata, and M.Arch Co-ordinator Dr. Mahua Mukherjee and all the professors for their advice, encouragement and suhhestions during the course of study.

I cannot imagine my current position without the love and support from my family. I thank my parents for striving hard to provide a good education for me and always encouraging me to study and succeed in life. I would not be able to comprehend their support and all their sacrifices; their prayer has sustained me thus far.

Words cannot express how grateful I am to my best friend, Manas Kala, for being my driving force and whose love and encouragement, undying support, invaluable advices and endless patience has made this whole journey a successful completion.

I would not have been able to finish my dissertation without the friendships I have gained here; for being sources of support, laughter and joy. To Snehal, for being a very good friend. I appreciate the critical remarks and suggestions, for inputs in every submission and being a great companion. To every individual who has helped me in any way through my journey this far, I acknowledge the help, suggestions and support.

Last but not the least, I would like to convey special acknowledgement to my grandparents for their love and prayers. I strongly believe that their prayers played an important role in my life. Not to forget the support, help and encouragement from my to-be in-laws who have been so caring and supportive. I appreciate their best wishes and prayers.

E X E C U T I V E   S U M M A R Y

"The task of the designer is to create the best possible indoor climate. The occupants of the building judges the quality of the design from a physical as well as emotional point of view" (Koenigsberger.1974)

There is no doubt about the fact that sustainability in general and energy efficiency in particular, has finally become a very significant part of the building design process as intent. It has primarily remained an intent and not integrated in the design and operation because of the many gaps that exist related to policy, capacity, skills, and demand, among others. Occupant thermal comfort in buildings represents one such gap because the idea of comfort is limited to maintaining the cooling setpoint based on ASHRAE static comfort model. Furthermore, in spite of the obvious connections, there's been a clear absence of data and studies correlating energy performance and thermal comfort.

"India shows the lowest figures in energy consumption and carbon emissions as compared to many developed countries but these figures are projected to rise by almost seven times of the present level, by the year 2030." (WBCSD, 2008). India is a very vast country with variable climate differing from region to region. With each region having distinctive and diverse climatic conditions, one particular guideline and procedure cannot be accepted and developed as a standard ; each climatic zone has to be studied and researched specifically to develop guidelines regarding energy efficiency or for thermal comfort principles. Research related to thermal comfort studies is mainly concentrated in the west and in some parts of Asia and Africa. This factor and also the lack of analysis and research is perhaps the reason why thermal comfort standards are not yet defined in India. This field is yet to gain momentum in India.

When designing the indoor environments, the thermal comfort standard referred to are based on ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) standards; this only leads to over design or wastage of energy and does not consider the behavior and discomfort of the building occupants and its adverse effect on their health and well-being. On the other hand, the country, having a highly variable

climate from region to region at macro-scale and within a region at microscale,needs variable indoor temperature standards that take into account the outdoor climate.

With the Energy Crisis there is a demand for the promotion of greater saving in energy and efficient use of available energy. In buildings, an increasingly important fraction of the energy is used by air-conditioning systems. However, the energycost of air-conditioning is affected by indoor air temperature standards. Reports show that energy expended on cooling load in commercial buildings accounts for up to 45% of the total electrical consumption in India. (BEE,2007).

The thesis aims to investigate the thermal comfort conditions provided in existing offices in Indian moderate climate with the aim of establishing how thermal environments provided affect the perceived thermal comfort conditions achieved for the occupants.

The area of study is Pune, located on the western margin of the Deccan plateau and falls under the moderate climate of India. The studied area was chosen due to the emerging of the city as a major IT centre, with sprawling software parks mushrooming all over the city. This would provide the chance to survey maximum number of cases to study the conditions existing in office buildings of moderate climatic zone of India. The upcoming projects and growth of IT sector in the city has placed Pune the eighth among the metropolis of India.

A subjective questionnaire / online survey was undertaken during November2013--January 2014, The purview and configuration of the questionnaire is establised on the Indoor Environmental Quality (IEQ) sur¬vey questionnaire from the Centre of the Built Environ¬ment (CBE) at the University of California, Berkeley. Experimental analysis on thermal comfort (TC) inside a model test room was performed in the laboratory of Hermann Rietschel institute, under the Technical University of Berlin, Germany. To allow maximum recordings with most probability and accurate measure of thermal comfort, different cases were studied with changes in time of the day, solar radiation, temperature (indoor, outdoor wall and window), air velocity, humidity factors etc.

Chapter 1 provides a concise narrative of introduction of the thesis topic. The purpose of study with its aim, objective and methodology has been briefly described.

Chapter 2 contains description of literature study. This includes study of Thermal Comfort, its relevance in the field of architecture, the thermal comfort standard and models and various methods to measure and determine thermal comfort. The chapter also includes various aspects of thermal comfort that affects the users perception and how these factors can affect the indoor environment.

Chapter 3 is a review of the Thermal Standards that has been studied and analysed for measuring thermal comfort indices. The standards of ASHRAE, ISO 7730, ISO 8996, SO 9920 etc has been presented in detail.

Chapter 4 gives a brief background of the distinct thermal comfort models used to evaluate and determine. It describes the metholody used to determine the factors of the thermal comfort variables. This includes the theotrtical, emperical and adaptive models.

Chapter 5 presents a brief account of the study area and discusses the need for study in the area selected. Introduction to the location, its climatic characteristics and the current scenario of the region has been provided.

Chapter 6 contains the results of subjective questionnaire / survey undertaken during online, this was based on post-occupancy survey and even though the questions are subjective, it was vital to understand what the current situation inexisting office environment was.

Chapter 7 includes the experimental studies on thermal comfort performed in a laboratory in a model test room of Hermann Rietschel institute, under the Technical University of Berlin, Germany.

Chapter 8 summarises the experimental study and the results of the analysis. The conclusion includes the results of the experiment along with the highlighting the limitaions of thermal comfort standard in India

TABLE OF CONTENTS

List of Figures

List of Tables

List of Graphs

Nomenclature

- Predicted Mean Vote (PMV)
- Percentage People Dissatisfied (PPD)
- Extended Pmv Model (PMVe)
- Actual Mean Vote (AMV)
- Adaptive Predicted Mean Vote (APMv)
- Clothing Insulation (1 Clo¼ 0.155 M2 K/W)
- Air Temperature (Ta)
- Mean Radiant Temperature (Tr)
- Relative Air Velocity (V) m/s
- Water Vapor Pressure In Ambient Air (Pa)
- Skin Temperature (Tsk)
- Core Or Internal Temperature (Tcr)
- Sweat Rate
- Skin Wettedness (W)
- Thermal Conductance (K)
- Dry Bulb Temperature (DBT)
- Effective Temperature (ET)
- Relative Humidity (RH)
- Standard Effective Temperature (SET)
- Wet Bulb Temperature (WBT)
- Unit Of Metabolic Rate (MET)
- Draught Rate (DR)
- Percentage Dissatisfied (PD)
- Heat Exchange by radiation (W/m2)
- Sick Building Syndrome (SBS)

CHAPTER 1 – INTRODUCTION

1.1 Need for Study

"*Architecture is a physical, emotional and intellectual experience. It facilitates man's bodily comfort, emotionally attaches him in to it, and, as a work of art, through symbolic communication leads to him towards a higher realm of contemplation*" (Kulatilake,1994)

We can comprehend from here that architecture should be experienced in all senses that covers both physical (tangible) and psychological (subjective) experience. Our human mind will ascertain it in psychological terms and the human body will encounter it in physical terms. In the physical experience, the temperature (warmth or cold) of a space contributes more than just a dimensional experience. That is called the 'Thermal Comfort' of a space.

According to Andris Auliciems and Steven V. Szokolay, "*we need to be mindful of the broad principle that, within a changing environment, survivability is greater among the adaptable than the adapted.."* If the architectural design is to serve the future end users of a building, it must look toprovide a favourable and comfortable thermal environment. Therefore, the first step of a good thermal design must be to establish what is the range of thermal conditions of comfort, and we must go beyond this primary interest and establish conditions that will also allow conditions to become refreshing and also stimulating, without causing any or much ill effects to the occupants in that space. Hence, the need to be conscious of both the possible risk and threat of extremes and also the need to examine conditions that are suitable for thermal comfort.

"All architecture is shelter, all great architecture is the design of space that contains, cuddles, exalts or stimulates the persons in that space" (Johnson, 1990). This should be the purpose and the ultimate objective of architecture. Architecture is for people. Therefore, architect should provide the people with sufficient physical (definite) and psychological (analytical) comfort and satisfaction in outdoor and indoor spaces.

1.2 Aims and Objectives

The thesis aims to investigate the thermal comfort conditions provided in existing offices in Indian moderate climate with the aim of establishing how thermal environments provided affect the perceived thermal comfort conditions achieved for the occupants.

Intention of this study is to :

1. Identify the existing thermal environment for indoor thermal comfort in artificially ventilated office buildings with reference to moderate climate

2. To analyze the factors of temperature, air velocity, humidity etc inside the office affecting the thermal comfort of users, through laboratory experiment.

3. To conduct field surveys to analyse the perception of indoor thermal environment existing in mechanically ventilated office buildings.

4. To establish whether ASHRAE Standard 55 and other established international comfort standards apply in the study area of moderate climate of India.

1.3 Scope and Limitation

1. The scope of the study is limited to evaluating and understanding the thermal comfort of employees in office buildings, in a moderate climate.

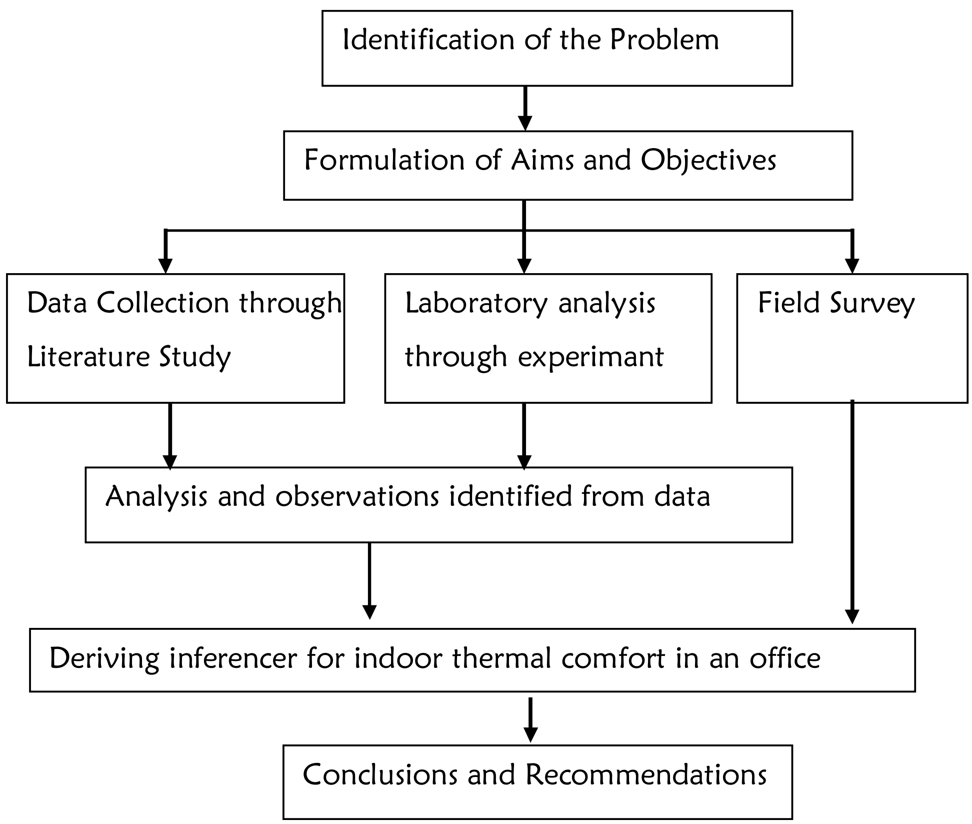
2. Laboratory based experiment used as the mode of analysis.

3.Based solely on the indoor thermal comfort factor and does not involve sustainability criterions, cost factors or other variables affecting such as energy, operation, maintenance etc.

1.4 Methodology

The Need for study was considered and analysed ; based on that aims and objectives of the research are defined. Data collection is conducted through existing data resources and survey. The research study is an experimental and laboratory-based experimental study. The objective to understand the existing thermal conditions in office buildings is done by first surveying of occupants and employees working in mechanically ventilated office, and then setting up a model test room in a laboratory and manipulating the factors of temperature, air humidity and air speed. Therefore, after the theoretical background and hypothesis for the study, research work is carried for the selected setting. A Field survey was conducted online to find out the thermal comfort perception of the users

.



CHAPTER 2 – LITERATURE STUDY

2.1 Architecture and thermal Comfort

"The task of the designer is to create the best possible indoor climate. The occupants of the building judges the quality of the design from a physical as well as emotional point of view" (Koenigsberger.1974)

An indoor environment is required to be thermally comfortable and healthy as the residence period inside a building has been gradually escalating. The utilization of air-conditioning systems and HVAC devices has been rapidly increasing in current years and the demand for artificially ventilated systems have elevated around the world. Due to this reason, energy utilization of buildings and decrease in resources of developed countries has also amplified drastically. The essential purpose of every built structure and heating and air-conditioning systems installed in a building is to provide an atmosphere that is suitable and pleasing, one that does not affect wellbeing or functioning of the inhabitants.

"The experience of a space is depended on what the user expects from that particular space or user needs or aspirations. The architect's role is to realize the aspirations of the user and create a building that responds positively to those needs ". (Sri Nammuni, 1987).

Thermal comfort is essential for the man to lead a healthy life. Therefore, since the beginning times, man has tried to create thermally comfortable environments. Thermal comfort is highly subjective sensation. It is a cognitive indicator, which cannot be easily converted in to physical tangible parameters. However, thermal comfort can be defined more qualitatively as the range of climatic conditions which most of the people feel comfortable, neither cold nor warm.

It is defined in the ISO 7730(1994) as "*The condition of mind that which expresses satisfaction with the thermal environment*"*(ASHRAE). "The main reason for mechanically conditioning office buildings is to create comfortable thermal conditions for occupants ". (ASHRAE, 1992; 2001; Brager, Fountain, Benton, Arens & Bauman, 1994; Schiller, 1990).*

In today's time, it is not acceptable to simply provide protection from extreme cold and heat – we also anticipate fresh air, healthy surroundings, adequate lighting and excellent thermal comfort, i.e. constant supply of adequate air temperature and air flow velocity, all year round. "Thermal *comfort considers both physical factors in the building environment, as well as human factors such as clothing insulation and metabolic heat, or a person's activity level."* (Health and Safety Executive). Therefore, understanding the importance of indoor environmental qualities like temperature, humidity etc with respect to architecture is vital.

People working in unpleasant indoor environments (uncomfortably hot and cold surroundings) are more probable to behave and perform precariously, causing serious threat because their ability to make decisions and/or execute physical manual tasks depreciates. People may, for instance, presume short cuts to take the easy way out to get out of a cold surrounding, or employees may get negligent and prefer not to wear personal protective gear appropriately in hot environments, thus escalating the hazards. Also the chance for an employee's capability to pay attention and concentrate on a given assignment may start to dwindle and hence increasing the risk of mistakes happening.

Many research that has been conducted, have concluded and emphasized the importance of providing improved good quality indoor air quality and thermal comfort to office employees to keep them healthy and promote their . "*Because people spend up to 90% of their time indoors, and much of it in their workplaces, the physical environment in offices should be carefully designed and managed. The physical conditions that occupants experience are important determinants of satisfaction, comfort, well-being, and effectiveness*" (Workstation Design for Organizational Productivity, 2004) .

2.2 Concept of thermal Comfort

*"Man has always striven to create a thermally comfortable environment. This is reflected in building traditions around the world - from ancient history to present day. Today, creating a thermally comfortable environment is still one of the most important parameters to be considered when designing buildings." (*Climate variations and the Evaluation of Thermal Comfort Study on the Change of Physiological Signals ,Kim, Hyung - Chul , Keum, Jong - Soo). Thermal comfort is principally a mental state and condition of the body that responds to its environment and this is different from the equations for heat and energy balances. Thus, thermal comfort is a subjective way to describe and identify if the surrounding setting is unperturbed and comfortable or not. An indoor environment that is perfect can be defined and summarized as:

- The inhabitant feels moderatelyneither hot nor cold i.e., thermally neutral and does not desire the environment to be any colder or warmer.
- At any particular time, the inhabitant is not exposed to any distinct unwanted cooling or heating at any particular part of their body.

According to ASHRAE Standard 55, thermal comfort is defined as," *that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation." (ASHRAE 2005)*. Although the state of mind (mental, emotional and physical) is difficult to measure and evaluate, researchers have successfully performed experiments to predict thermal comfort and generate adaptive models. In the recent times, analysis, research and studies have successfully been developed using computer simulation methods, computer models, mathematical derivations and physical measurements to estimate thermal comfort.

Thermal environmental elements like air temperature of the room, relative humidity (RH), air speed and individual aspects of level of clothing and metabolic rate (activity) affect condition of comfort and health of its occupants. The fundamental variables that have considerable influence on the thermal comfort and wellbeing for an occupant inside a workplace can be divided into environmental and personal factors.

- **Environmental factors:**

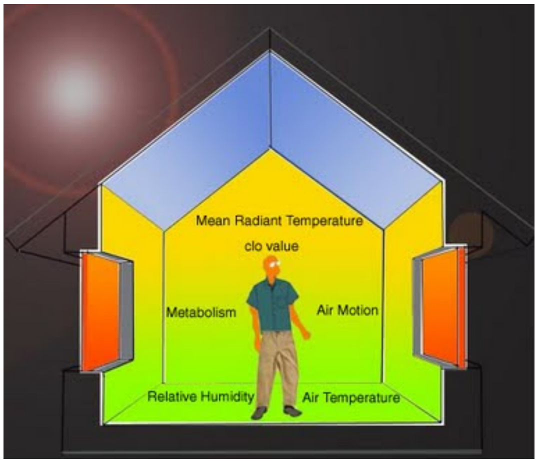


Figure 1: Thermal comfort environment fact
(Source: http://www.design.asu.edu)

1. Air Temperature (measured by the dry bulb temperature (DBT). This factor establishes the temperature of air at a particular point, along with air movement.)

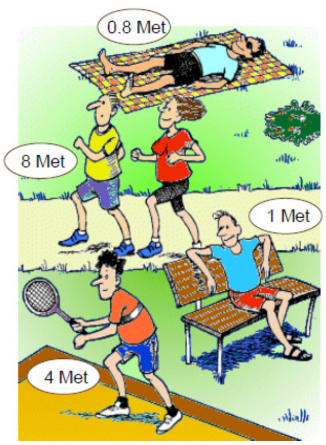
2. Mean Radiant temperature (This determines the heat exchanged between an occupant in a particular space and her/his Surroundings)

3. Humidity ((RH) Humidity of the air have an influence on evaporation rate as well as aspects of comfort like feelings of dryness or stuffiness.)

4. Air Velocity (measured in m/s with an anemometer, affects both evaporative and convective heat transfer from the skin. It is the rate of movement of air.)

- **Personal factors:**

1. Personal Activity And



2. Clothing insulation

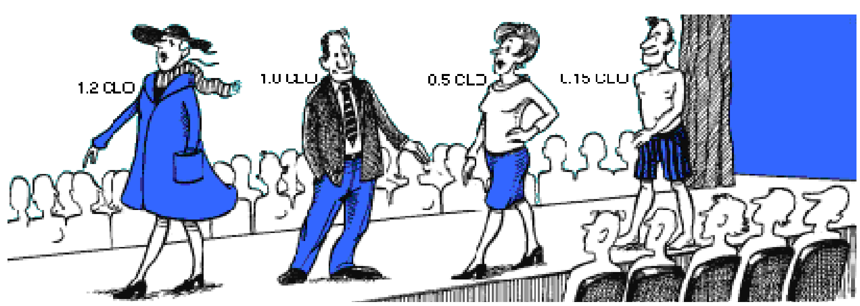


Figure 2: thermal comfort personal factors (Source: http://www.design.asu.edu)

Thermal comfort is an indicator / index that cannot be easily transformed and calculated in to physical parameters. However, thermal comfort can be defined more qualitatively and collectively as the range of climatic conditions in which most of the people feel comfortable, neither cold nor warm in that particular space. *"Two conditions must be fulfilled to maintain thermal comfort. First is the actual combination of skin temperature and the body's core temperature which provides a sensation of thermal neutrality. Second is the fulfillment of the body's energy balance; the heat produced by the metabolism should be equal to the heat lost from the body."* Fanger (1970). Thermally neutral sensations are outlined by the temperature, skin temperature and activity level.

2.3 ASHRAE Comfort Standard

ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) has provided a general agreed standard to describe and specify comfort requirements within buildings. The revised ASHRAE Standard 55-2010 -Thermal Environmental Conditions for Human Occupancy, outlines the characteristics and demands for a healthy indoor thermal environment. The principle of this standard was developed is to determine the specific combinations of indoor thermal environmental factors and personal factors that will produce thermal environmental conditions acceptable or tolerable to a majority of the occupants within the space. The standards purpose states that it is based on 80% acceptability and is for an average group of people, and not for an individual.

The purpose of this standard is to establish the various combinations of indoor thermal environmental factors along with personal factors that will produce a comfortable condition of thermal environmental that is acceptable to a majority of the occupants within a given space.

2.4 Thermal Comfort measuring indices

The most notable models have been developed by P.O. Fanger (the Fanger Comfort Model) and the J. B. Pierce Foundation (the Pierce Two-Node Model), A few researchers at Kansas State University have also developed and published the KSU Two-Node Model. Fanger's Predicted Mean Vote (PMV) model was developed in the 1970's after laboratory experiments and laboratory studies.

In these studies, participants were dressed in standardized clothing (winter and summer clothing) and completed standardized activities, while exposed to different thermal environments.

Indicators for thermal comfort can be quantified by PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied) parameters. The European standard BS EN ISO 7730 provides methods for predicting thermal sensation and intensity of discomfort (thermal dissatisfaction) of people in their respective thermal environments by:

- *PMV (*Predicted Mean Vote) - PMV forecasts the aggregate result of the votes for a category of occupants dictated to similar environmental circumstances. However it does not project the number of occupants who will be feeling thermally uncomfortable or dissatisfied (PPD).

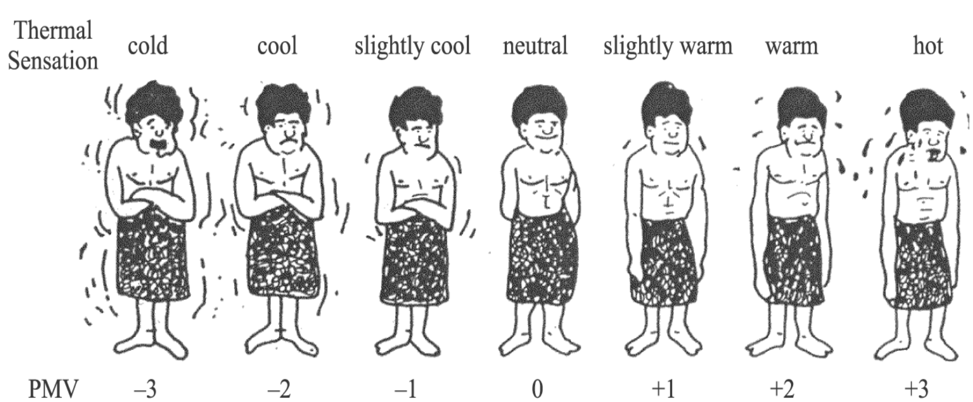


Figure 3: Predicted Mean Vote (Source: http://www.emeraldinsight.cor

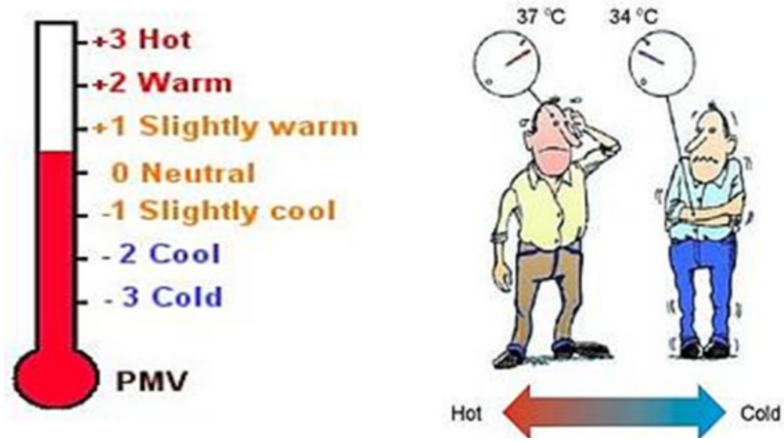


Figure 4: PMV scale index (Source: http://atjenese.wordpress.com)

- PPD (Predicted Percentage Of Dissatisfied) - PPD forecasts the number of people in that environment whose satisfaction fall beyond the range of comfort, therefore ascertaining the number of occupants who are thermally uncomfortable and dissatisfied by feeling either extreme hot or intense cold.

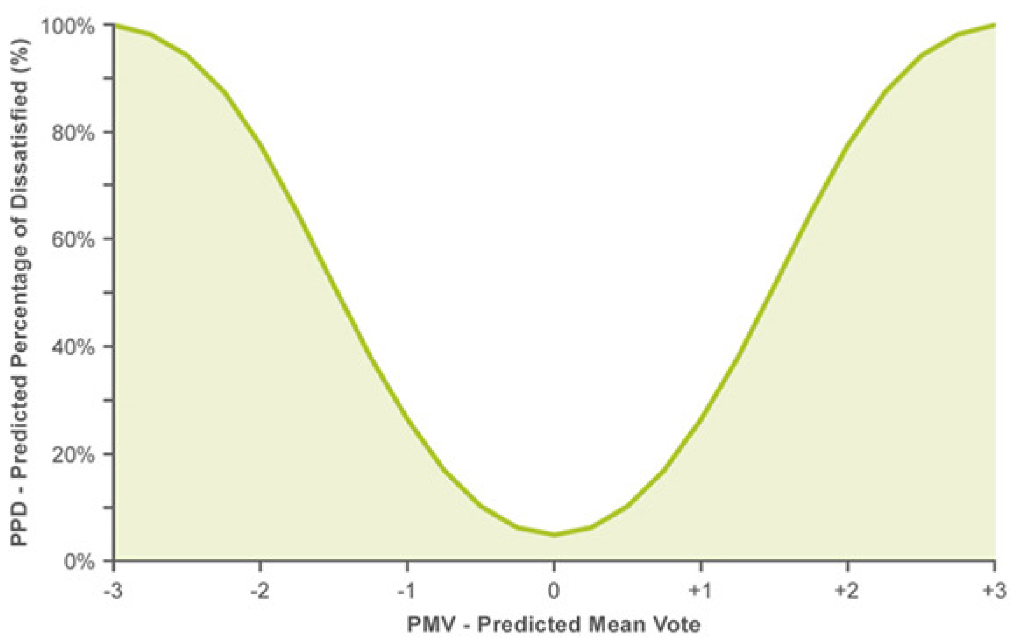


Figure 5: Predicted Percentage of Dissatisfied (PPD) as a function of PMV (Predicted Mean Vote) (Source: http://danieloverbey.blogspot.in/)

2.5 Subjective scales for measuring Thermal Comfort

The common approach to measure thermal comfort in a field work is subjectively i.e., an assessment scale approach where in comfort is measured as a representation of "neutral" or "acceptable" and "comfortable" on subjective scales such as the Bedford's scale or Fanger's scale of comfort level.

Table 1: Subjective Scales(Source: Chenko 1974)

1.	Much too warm	1	Unacceptable
2.	Too warm	2	Unacceptable
3.	Comfortably warm	3	Acceptable
4	Comfortable	4	Acceptable
5.	Comfortably Cool	5	Acceptable
6.	Cool	6	Unacceptable
7.	Much too cool	7	Unacceptable

Table 2: Subjectives Scales (Source: Fnagers 1972)

1.	Hot	+3	Unacceptable
2.	Warm	+2	Unacceptable
3.	Slightly warm	+1	Acceptable
4.	Neutral	0	Acceptable
5.	Slightly cool	-1	Acceptable
6.	Cool	-2	Unacceptable
7.	Cold	-3	Unacceptable

"Despite the apparent semantic differences between the ASHRAE scale of thermal sensation and the Bedford comfort scale, these two scales have been found to behave more-or-less the same in most practical situations" (McIntyre, 1978a; de Dear, 1985).

From the above table, it is evident that "neutral" is usually synonymous with "comfortable", "acceptable," and "preferred" for calculating and predicting comfort.

2.6 Criteria for thermal Comfort

One of the elementary objectives of buildings besides providing protection and shelter is to cater its inhabitants a complacent and satisfying environment. And to create an acceptable comfortable thermal environment, the heating and cooling may require extra cost and be energy demanding which will be a challenge for the architect as well the user to balance between energy savings, cost –effective factors and occupant comfort. The specifications that characterize a thermal environment are namely: air temperature, air humidity, air velocity and personal factors (clothing together with activity level).

Table 3: Factors of Thermal Comfort with Impact

	Factors	**Description**	**Impacts on Thermal Comfort**
Human Factor	Physiology	• Metabolic Rate • Age • Gender • Weight	• Body Thermoregulatory • Acclimatization • Clothing Adjustment • Activity (metabolic) Adjustment
Human Factor	Psychology	• Behavior • Control • Expectation • Perception	• Behavioral Adjustment • Background and Experience • Acceptability • Perseverance
Macro Environment	Climatology	• Geographical • Location • Climate	• Prevailing Wind • Humidity • Outdoor temperature • Solar Radiation • Precipitation
Micro Environment	Design	• Building Form • Orientation • Openings • Vegetation	• Building Mass (Heat Transfer) • Porosity and Shading • Room Dimension • Building Layout

2.7 Methods of Thermal Comfort Analysis Research

1. Model Based Approach
2. Human Based Approach
3. Space Based Approach

2.7.1. Model Based Approach –The physical conditions of the indoor environment is simulated using a virtual model (Computer modeling) based on certain assumptions and standards.

2.7.2. Human Based Approach - Direct investigation based on the occupants of the building by conducting controlled experiments in thermal chamber or by conducting field surveys

2.7.3. Space Based Approach – The indoor spaces are analyzed for thermal comfort .The aspects considered are :

- Building Design – Passive strategies via layout , form , envelope orientation and insulations
- Building service system – Mechanical devices used to achieve comfort

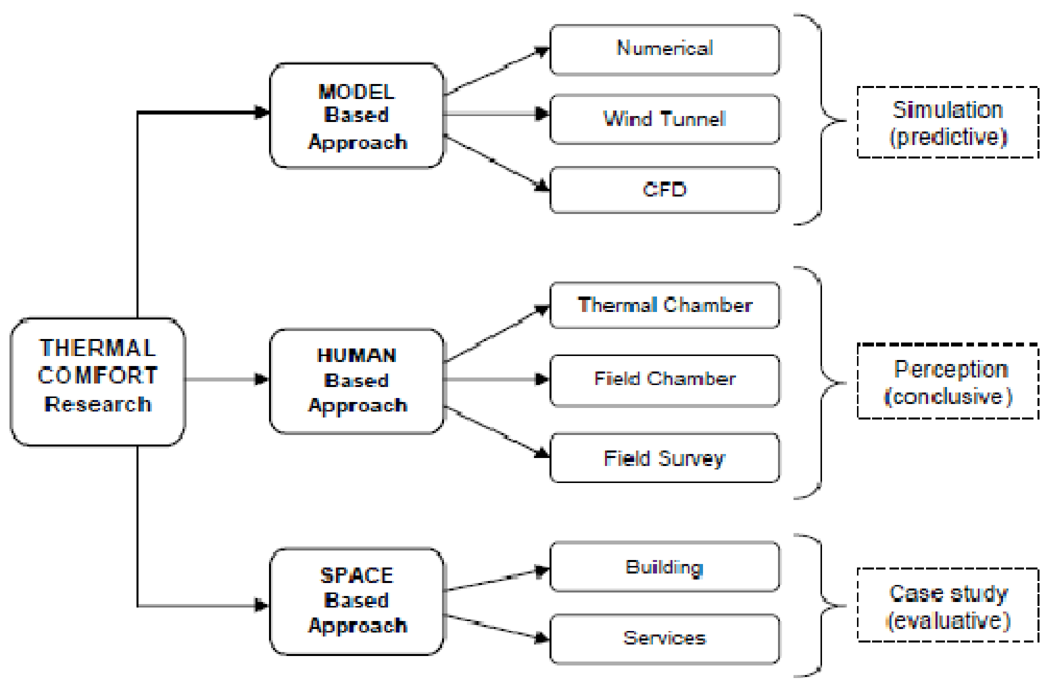


Figure 6: Methods of Thermal Comfort Analysis Research (Source: Hardy, 1971)

2.8 Recommended Criteria for Thermal Operation in Mechanically Ventilated Buildings

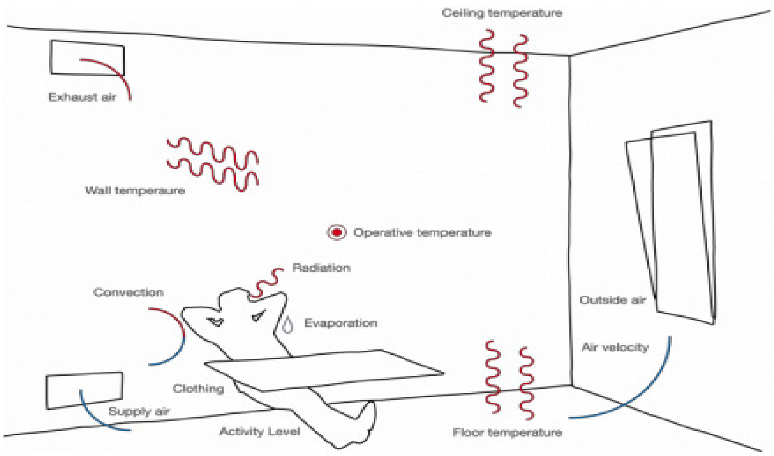
Substantial physical indices of thermal comfort is predicated on environmental parameters, example air temperature, relative humidity and air speed, along with personal factors like clothing insulation, metabolic heat (level of activity), acclimatization of the body to different conditions, age and gender, state of fitness and wellbeing, and even factors of ethnicity and even food and drink. The EN ISO 7730 standards states that "*the criteria for the designing of a thermal environment should be based on parameters of PMV (Predicted Mean Vote) and PPD (Predicted Percentage Of Dissatisfied), while assuming the activity level and including the clothing values for summer and winter season".*

Using the assumptions of activity level and clothing factor with assumed relative humidity and varying air velocities, a range of comfortable temperature range can be well-established. In mechanically ventilated office space, the operative temperature will be the highest contributor to the amount of energy consumed within the building. Therefore, according to EN15251 Standard, artificially ventilated buildings have been categorized into summer and winter operative temperatures and recommended PMV and PPD also provided along with the maximum air velocity allowed.

Table 4: Categories of thermal environment along with PMV and PPD (Sourec: ISO EN 7730, 2005)

Cate-gory	Thermal state of the body as a whole		Operative temperature °C		Max. mean air velocity m/s	
	PPD %	PMV	Summer (0,5 clo) Cooling	Winter(1 clo) Heating	Summer(0,5 clo) Cooling	Winter(1 clo) Heating
A	< 6	-0.2 < PMV < + 0.2	23,5 – 25,5	21,0 – 23,0	0,18	0,15
B	< 10	-0.5 < PMV < + 0.5	23,0 – 26,0	20,0 – 24,0	0,22	0,18
C	< 15	0.7 < PMV < + 0.7	22,0 – 27,0	19,0 – 25,0	0,25	0,21

2.9 Parameters to be measured



While calibrating and surveying the indoor thermal climate, it is essential to summon into mind that man does not sense the degree of heat or room temperature, instead it is the energy loss from the body that he can address to and feel.

Figure 7: thermal comfort parametrs (Source:www.educate-sustainability.eu)

The various factors can be classified into environmental and personal parameters. They are as follows:

Environmental Parameters

- Air Temperature
- Mean Radiant Temperature
- Air Velocity
- Relative Humidity

• **Personal Variables**

- Activity Level
- Clothing Insulation

• **Secondary Factors**

- Non-Uniformity Of The Environment
- Adaptation
- Age
- Outdoor Climate

2.9. Environmental Parameters

2.9.1 Air Temperature

Air temperature is a measure of the heat, i.e. the temperature of the air at a point. The average air temperature is the numerical average of the air temperature at the ankle level, the waist level, and the head level. These levels are 0.1, 0.6, and 1.1 m for seated occupants and 0.1, 1.1, and 1.7 m for standing occupants. Radiant heat may not be reflected in the air temperature, but is the impact of cold or hot objects in the area. It is the temperature of air surrounding the body.

2.9.2 Humidity

The relative humidity of air needs to be controlled to ensure the thermal comfort for its occupants. EN ISO 7730 clearly shows that humidity range of 30% to 70%RH id recommended, mainly due to IAQ(Indoor Air Quality). Low humidity is associated with irritation in skin, eyes while higher humidity levels can lead to microbial growth and poor indoor air quality.

2.9.3 Air Velocity

Moving air has a cooling effect on human skin. Therefore, air velocity can be used to increase indoor temperature during summer days. The air speed however has to be in consideration so not to cause draft sensation, in turn causing thermal discomfort. This describes the speed of air moving across the worker and may help cool the worker if it is cooler than the environment. Air velocity is an important factor in thermal comfort because people are sensitive to it.

2.9.4 Mean Radiant Temperature

The Mean Radiant Temperature of an environment is defined as that uniform temperature of an imaginary black enclosure which would result in the same heat loss by radiation from the person as the actual enclosure. What we experience and feel relating to thermal comfort in an indoor environment is related to the influence of both the air temperature and the temperature of surfaces within that space.

2.10 Local thermal discomfort

Thermal dissatisfaction can also be caused by unwanted cooling or heating of one particular part of the body. This is known as local discomfort. It is mainly people at light sedentary activity who are sensitive to local discomfort. These will have a thermal sensation for the whole body close to neutral. At higher levels of activity, people are less thermally sensitive and consequently the risk of local discomfort is lower.

Generally, local thermal discomfort can be grouped under one of the following four headings:

1. Local convective cooling of the body caused by draught
2. Cooling or heating of parts of the body by radiation, known as a radiation asymmetry problem.
3. Cold feet and a warm head at the same time, caused by large vertical air temperature differences.
4. Hot or cold feet, caused by uncomfortable floor temperature.

2.10.1 Draught

Draughts are the most common complaint when talking about indoor climate in air conditioned Buildings. Man can not feel air velocity, so what people actually complain about is an unwanted local cooling of the body. People are most sensitive to draught in the unclothed parts of the body, i.e., face, hands and lower legs. The amount of heat loss from the skin caused by draughts is dependent on the average air velocity, as well as the turbulence in the airflow and the temperature of the air.

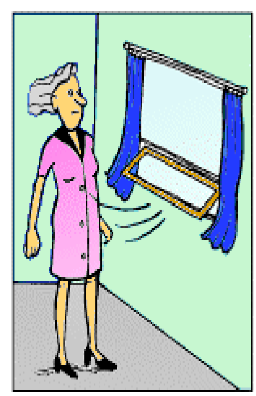


Figure 8: unwanted coolin due to draught (http://www.scientificassoc es.8m.com/)

2.10.2 Radiation Asymmetry

Being surrounded by surfaces that have large temperature differences may be become a cause of discomfort, even when the indoor air temperature and air humidity is controlled within the comfort zone. Radiation asymmetry is caused by warm ceilings, cool walls / windows, cool ceiling or warm walls / windows.

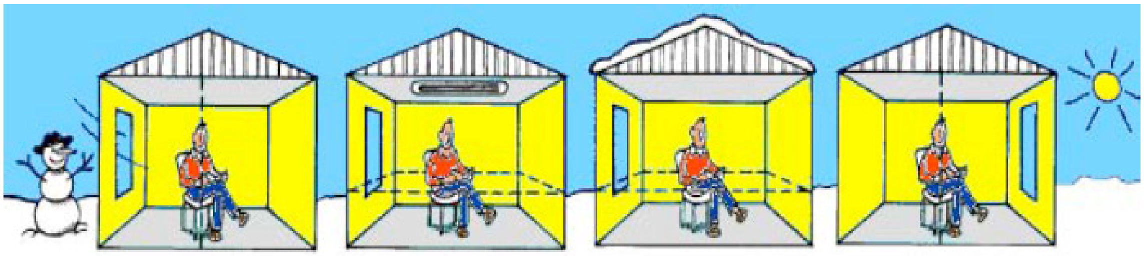
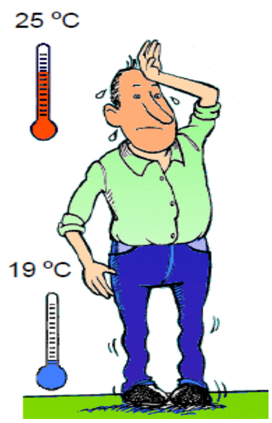


Figure 9: Radiation Asymmetry (Source: (http://www.scientificassociates.8m.com/)

I

recommended, mainly due to IAQ (Indoor Air Quality). Low humidity may be associated with irritation of skin and eyes, while at higher humidity levels; it may lead to microbial growth and poor indoor air quality. So the standard recommends that the temperature difference in opposite directions (asymmetry) in the vertical plane shall be less than 5°C (9°F), and in the horizontal plane, less than 10°C.



2.10.3 Vertical Air Temperature Difference

A high vertical air temperature difference between head and ankles can cause discomfort. The Vertical Air Temperature difference is expressed as the difference between the Air Temperature at ankle level and the Air Temperature at neck level.

Figure 10: Vertical ait temperature differnce (source: http://www.scientificassociates.8m.com/)

2.10.4 Floor Temperature

If the floor is too warm or too cool, the occupants could feel uncomfortable owing to thermal sensation of their feet. Due to the direct contact between feet and floor, local discomfort of the feet can often be caused by too high or too low a floor temperature. The ISO 7730 standard sets comfort levels at sedentary activity to 10% dissatisfied. This leads to acceptable Floor Temperatures ranging from 19°C to 29°C.

Figure 11: Fllor tempertaure (Source :http://www.scientificassociates.8m.com)

CHAPTER 3 – THERMAL COMFORT STANDARDS

There are several organizations whose standards have an influence internationally and contribute to the advancement and observation of thermal comfort and the utilization of that knowledge. The essential and most accepted standard for thermal conditions is ISO 7730 which is established on a model of whole body thermal comfort, namely the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) indices .

Table 5: International and national standards for general thermal comfort in moderate

1.	ISO Standards	1. ISO 11399:1995 *Ergonomics of the thermal environment*—principles and application of relevant international standards 2. ISO 7730:2005 *Ergonomics of the thermal environment*—analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria 3. ISO 9920:2007 *Ergonomics of the thermal environment*—estimation of thermal insulation and water vapor resistance of a clothing ensemble 4. ISO 7726:1998 *Ergonomics of the thermal environment*—instruments for measuring physical quantities 5. ISO 10551:1995 *Ergonomics of the thermal environment*—assessment of the influence of the thermal environment using subjective judgment scales
2.	ASHRAE Standard	6. ANSI/ASHRAE 55-2004 - Thermal environmental conditions for human occupancy
3.	Spanish Standards	7. NTP 74: Thermal comfort 8. NTP 501: Thermal environment: local thermal discomfort 9. NTP 242: Ergonomics: ergonomic office workplaces analysis

3.1 ISO Standards

A thermal comfort standard for ISO (International Standards Organization) is proposed by a working group, committee or others and is supported by a document, explaining the requirement and the scope of the proposed standard. The proposed ISO standards should be valid, reliable, sensitive and useable with sufficient scope for practica l application. All standards are reviewed every five years.

These documents or standards specify comfort zones in which a major percentage of occupants and users with given personal parameters in an enclosed space will regard the environment as acceptable and comfortable. Standards concerning with thermal comfort related subjects are produced by ISO/TC 159 SC5 WG1.

***3.1.1 BS EN ISO 7730:2005 Ergonomics of the thermal environment** - Determination of the PMV and PPD indices and specification of the conditions for thermal comfort*

This standard is based on Fanger's equation of energy balance (Fanger's, 1972). The variables considered are, metabolic rate, external work, thermal resistance of clothing, ratio of surface area clothed, air and mean radiant temperature, relative air humidity and air velocity. In this standard, the PMV (Predicted Mean Vote) and PPD (Predicted Percentage Dissatisfied) indices are described and acceptable conditions for thermal comfort are described. The PMV predicts the mean value of the votes of a large group of people on the ISO thermal sensation scale (+3 = hot; +2 = warm; +1 = slightly warm; 0 = neutral; -1 = slightly cool; -2 = cool; -3 = cold). The PPD predicts the percentage of a large group of people likely to feel 'too warm' or 'too cool'.

An index is provided in this standard involving the various factors of air temperature, air velocity and turbulence intensity, all given in the form of an equation. It is mainly applicable for situations in which sedentary people are wearing light clothing with a whole-body thermal sensation close to neutral. ISO 7730 can be considered in terms of to whom it applies and over what range of environmental conditions. The PMV/PPD index was developed after analysis and study on North American and European people. The standard accepts that deviations may likely occur due to the difference in ethnic and national-geographic differences and for people who are sick or physically disabled.

3.1.2 ISO 8996:2004 Ergonomics of the thermal environment— *Determination of metabolic heat production*

This ISO standard describes six different methods for estimating the metabolic heat production, which is an essential requirement in the use of ISO 7730 and therefore, the assessment of thermal comfort. The methods are divided into three different levels according to accuracy.

1. Level I provide tables of estimates of metabolic rate for various kinds of activity and occupation. This is a rough estimation and inaccurate information where the risk of error is great.

2. Level II presents tables of estimated metabolic rate based upon group assessment, specific activities, and measurement of heart rate. This is a high error risk estimate with an accuracy of ± 15%.

3. Level III is the most accurate measure (± 5%). It includes a method of estimating metabolic rate by analysis of expired 'air' from the lungs (indirect calorimetry). The units are presented as Watts per square metre of the body surface of a standard person.

3.1.3 ISO 9920:2007 Ergonomics of the thermal environment— *Estimation of thermal insulation and water vapor resistance of a clothing ensemble*

ISO 9920 provides a detailed database of the thermal properties of clothing and garments, after extensive studies and research. The properties of the standards are based upon the measurements done on heated manikins where basic thermal insulation is measured. The essential question of the standards validity and accuracy is therefore determining whether the measurements received from experiments done on the manikins represent the actual properties of clothing as worn by people. This standard like the ISO 8996 is not so reliable due to its inaccurate and validity issues. Therefore the predictions of discomfort may vary from person due to the metabolic rate estimate and clothing insulation approximation.

3.1.4 ISO 7726: Thermal environments –

Instruments and methods for measuring physical quantities

The ISO standard 7726 provides a set of specification of instruments for particularly measuring the thermal environment in a place. These environmental measures are used in the process of calculating and measuring thermal comfort assessment. The required accuracy of the measures is provided as well as the various operating range and also the response time of the measuring instruments is provided. Descriptions of numerous instruments, several principles of the measurement along with their practical safety measures are described.

3.1.5 ISO 10551: Ergonomics of the thermal environment –

Assessment of the influence of the thermal environment using subjective judgment scales

If the thermal comfort is a psychological phenomenon, then the measurement of the factors associated with it is also using subjective judgments. Where the particular population of interest is available to supplement the analysis of ISO 7730, subjective assessment scales can be used to consider and calculate thermal comfort. The use of judgmental subjective scale for providing data that can be compared and found reliable on aspects of thermal comfort is covered in this standard. ISO 10551 presents the associated principles and methodology behind the use of subjective scales and judgment. The five different types of scale that are presented in this standard are: a) perceptual, b) affective, c) preference, d) acceptance, and e) tolerance.

3.1.6 ISO 14415: Ergonomics of the thermal environment:

The application of International Standards for people with special requirements

This standard which is still under development, considers the thermal comfort requirements for people especially with disabilities, illness, ladies who are pregnant, the senior group (aged), and other persons with special requirements. The standard considers the effects of their special needs like sensory impairment or paralysis, body shape, impairment of body and metabolic rate. The standard presents guidance for hot, moderate, and cold environments and the applicability of current international standards are considered along.

3.1.7 ISO 11399 Ergonomics of the thermal environment:

The principles and application of relevant international standards.

The purposed of this standard is basically to provide information which will allow the practical use and corrective and effective way to use the international standards that is related to the ergonomics of thermal environment.

3.1.8 ISO 13731 Ergonomics of the thermal environment:

Vocabulary and symbols.

This standard has been prepared for the purpose of listing definitions, symbols and units of measures for thermal environment. The aim is to provide a reference of vocabulary and symbols that are / will be used in writing future standards or other publications on the ergonomics of the thermal environment.

3.2 CEN 15251: Indoor environmental input parameters for design and assessment of energy performance of buildings- addressing indoor air quality, thermal environment, lighting and acoustics

The CEN standard defines minimum requirements for ventilation, minimum and maximum indoor temperatures that can be used for calculation of energy, its assessment and also certification. This European standard specifies the thermal environment parameters for indoor, that will have an impact on the performance of the building in terms of energy, its consumption and calculation. The aim is to contribute to the calculation of building energy use along with the occupants comfort and well being. The purpose of this standard is to bring together the information that exists about air quality, thermal and visual com fort and acoustics. It also recognizes the occupant's expectations towards thermal environment in a naturally and mechanically ventilated building. It is different than prescribed standards because it makes a difference between mechanically ventilated systems and naturally ventilated systems. For buildings without mechanical ventilation /cooling, alternative methods are proposed.

3.3 ASHRAE Thermal Comfort Standard

ANSI/ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) Standard 55 is the standard in North-America that deals with thermal comfort. Standard 55-2010, “Thermal Environmental Conditions for Human Occupancy,” is a revision of Standard 55-2004. The standard specifies the many conditions in which the occupants will find the environment thermally acceptable and comfortable.

3.3.1 PURPOSE

The purpose of this standard is to specify the various combinations of indoor thermal environmental factors along with personal factors that will produce a comfortable condition of thermal environmental that is acceptable to a majority of the occupants within a given space.

3.3.2. SCOPE

- The environmental factors addressed in this standard are temperature, thermal radiation, humidity, and air speed; while the personal factors are level of activity and clothing insulation (summer or winter).
- It is proposed that all of the above criteria in this standard should be applied together for thermal comfort analysis, since measuring comfort in the indoor environment is complex and corresponds to the relation of all of the factors.
- This standard does not address the factors of indoor air quality, acoustics, and illumination or other physical, chemical, or biological space contaminants that may affect comfort or health.

The standard focuses on defining the various ranges of indoor thermal environmental conditions that will be acceptable to a majority of occupants, while accepting the increase va¬riety of design solutions to provide comfort.
The revised Standard 55-2010 modifies and expands the provisions incorporated for evaluating the impacts of elevated air speed in thermal comfort analysis.. The standard also provides a new method for defining and selecting different air speed limits, and alternatives for establishing the margins of comfort at air speeds above 0.15 m/s .

Table 6:Developments of international standards for the ergonomics of the thermal environment.(source:Thermal Environments)

Aims of the Standard	Title of the Document	Status
General presentation of the set of standards in terms of principles and application	Ergonomics of the thermal Environment: principles and application of international standards	ISO EN 11399
Standardization of quantities, symbols and units used in the standards	Ergonomics of the thermal Environment: vocabulary an symbols	ISO 13731
Thermal stress evaluation in hotel environments Analytical method	Hot environments: analytical determination and interpretation of thermal stress using calculation of required sweat	ISO 7933 EN 12515
Diagnostic method	Hot environments: estimation of the heat stress on working man, based on the WBGT index (wet bulb globe temperature)	ISO EN 7243
Comfort evaluation in moderate environments	Moderate thermal environments: determination of the PMV and PPD index and specification of the conditions for thermal comfort	ISO EN 7730
Thermal stress evaluation in cold environments	Evaluation of cold environments: determination of required clothing insulation	ISOTRENV 11079
Data collection standards metabolic rate	Ergonomics: determination of metabolic heat production	ISO 8996
Requirements for measuring instruments	Thermal environments: instruments for measuring physical quantities	ISO 7726

Clothing insulation	Estimation of the thermal insulation and evaporative resistance of a clothing ensemble	ISO EN 9920
Evaluation of thermal strain using physiological measures	Evaluation of thermal strain by physiological measurements	ISO EN 9886
Subjective assessment of the thermal environment	Ergonomics of the thermal environment: Assessment of the influence of the thermal environment using subjective judgment scales	ISO EN 10551
Selection of an appropriate system of medical supervision for different types of thermal exposure	Ergonomics of the thermal environment: medical supervision of individuals exposed to hot or cold environments	ISO DIS 12895
Contact with hot, moderate and cold surfaces	Ergonomics of the thermal environment: methods for assessment of human responses to contact with surfaces	ISO CD 13732
Vehicle environments	Evaluation of the thermal environments in vehicles	NP 14505
People with special requirements	Ergonomics of the thermal environment: the application of international standards for people with special requirements	ISO CD 14415
Assessment of risk in moderate, hot & cold environments	Risk assessment	NP 15265
Work practice in cold environments		NP 15743

3.4 Differences Between CEN and ASHRAE Adaptive Comfort Standards

ASHRAE Standard 55	CEN Standard EN15252
• Geographic / Climatic / Cultural origins of data- Worldwide (RP-884 database)	• Geographic / Climatic / Cultural origins of data- Western Europe (SCATS database)
• Size of the database – ~9000 out of 21,000 votes 36 out of 160 buildings	• Size of the database – Few thousand votes in 26 offices
• Scope of Standards applicability Naturally ventilated buildings without Mechanical cooling	• Scope of Standards applicability Any building in free running mode
• Method of estimating neutrality Regression of observed comfort votes on observed indoor temperatures for each building	• Method of estimating neutrality Regression of observed comfort votes on observed indoor temperatures for each building
• "semantic artifact" correction	• No "semantic artifact" correction
• Representation of outdoor Climate – Mean monthly outdoor air temperature	• Representation of outdoor Climate – Exponentially weighted running mean of daily outdoor air temperature (~week)

Figure 10: Ashare and Cen Standard Differnces (Source: http://w3.bwk.tue.nl/)

CHAPTER 4 – THERMAL COMFORT MODELS

Thermal comfort models- predict comfort responses of individuals exposed to thermal environments under conditions of either rest or exercise. The most notable models have been developed by P.O. Fanger (the Fanger Comfort Model) and the J. B. Pierce Foundation (the Pierce Two-Node Model), A few researchers at Kansas State University have also developed and publised the KSU Two-Node Model. The basic similarity of the three models is that all the three apply an energy balance based and use the energy exchange mechanisms along with experimentally derived physiological parameters to predict the thermal sensation and the physiological response of a person due to their environment. The models differ in the physiological models and in the criteria used to predict thermal sensation. The various thermal comfort models can be categorized as the following:

4.1 Theoretical Comfort Models

4.2 Emperical Models

4.3 Adaptive Models

4.4 Design Strategy Models

4.1 Theoretical Comfort Models

4.1.1 Heat Balance Model - PMV-PPD

Fanger's Predicted Mean Vote (PMV) model was developed in the 1970's after laboratory experiments and climate chamber studies using heat balance equations and empirical studies about skin temperature. In these studies participants were dressed in standardized clothing (winter and summer clothing) and completed standardized activities, while exposed to different thermal environments. Thermal comfort surveys were asked to subjects about their thermal sensation on a seven point scale of extreme cold (-3) to extreme hot (+3).

Figure 11: Fanger's Comfort Scale

PMV represents the 'predicted mean vote' on the thermal sensation scale for a large population of people exposed to a particular combination of air temperature, mean radiant temperature, relative humidity, air speed, metabolic rate, and clothing insulation. PMV is derived from the physics of heat transfer combined with an empirical fit to sensation.

The PMV model is based on extensive American and European experiments involving over a thousand subjects exposed to well-controlled, extensive and rigorous laboratory environments. This approach seeks to capture people's responses to the thermal environment in terms of the physics and physiology of heat transfer

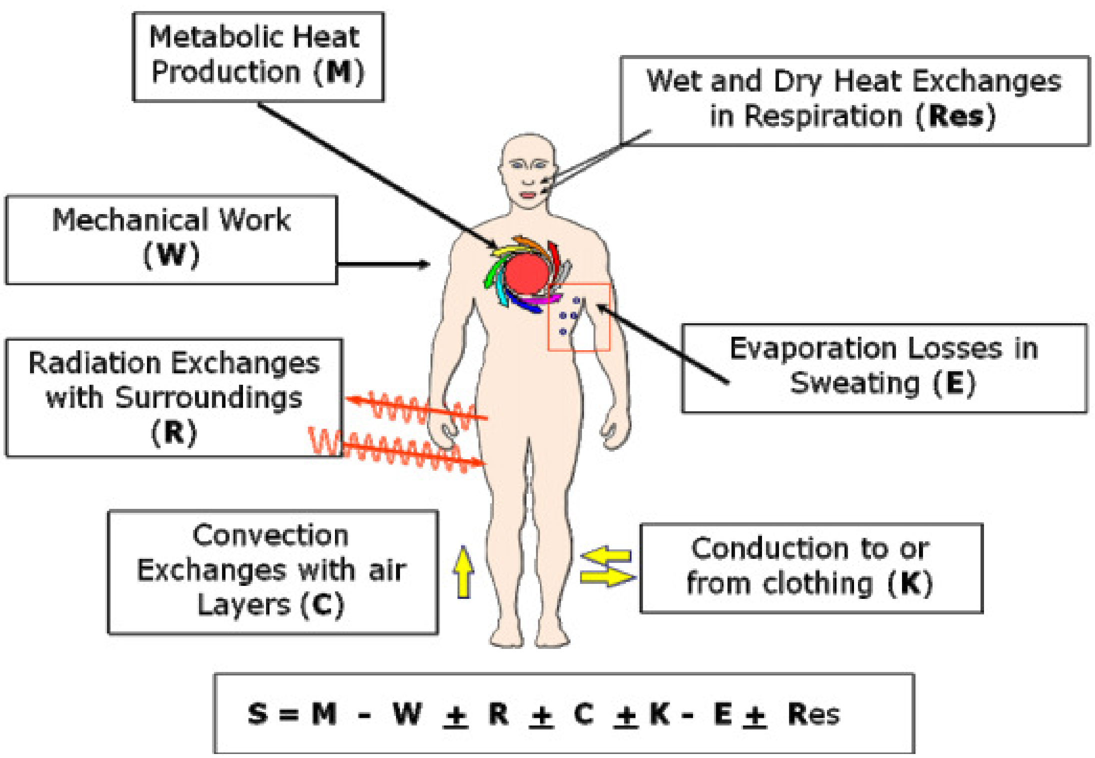


Figure 12: Factors for PMV (Source: ceae.colorado.edu)

$$PMV = (0{,}303e^{-2{,}100*M} + 0{,}028)*[(M-W) - H - E_c - C_{res} - E_{res}]$$

OR

$$PMV = (0.303e^{-0.036M} + 0.028)L$$

where the different terms represent, respectively:

M - the metabolic rate, in Watt per square meter (W/m2);

W - the effective mechanical power, in Watt per square meter (W/m2);

H - the sensitive heat losses;

Ec - the heat exchange by evaporation on the skin;

Cres - heat exchange by convection in breathing;

Eres - the evaporative heat exchange in breathing.

L - thermal load defined as the difference between the internal heat production and the heat loss to the actual environment for a person

As PMV changes away from zero in either the positive or negative direction, PPD increases.

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

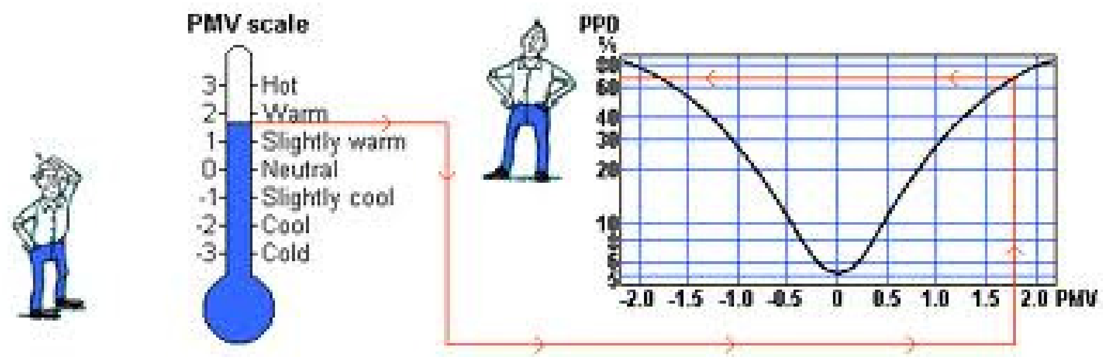


Figure 13: PMV-PPD scale (Source: :http://www.scientificassociates.8m.com)

5.1.2 ET-DISC*

The 2-node model was introduced in 1970 specifically to formulate a new effective temperature scale. ET* stands for New Effective Temperature where "effective temperature" is a temperature index that accounts comfort index or scale that takes into account the temperature of air, its moisture content, and movement. ET*- DISC uses a heat balance model to predict thermal comfort, but the model involves time rather than being steady-state like PMV. It can be calculated using the '2-Node' model, which determines the heat flow between the environment, skin and core body areas on a minute by minute basis. DISC predicts thermal discomfort using skin temperature and skin wettedness.

*5.1.3 SET**

SET is the temperature of an environment in which air and mean radiant temperature equal to each other, relative humidity of 50% in still air, and in which a person with a standard level of clothing insulation would have the same amount of heat loss as the the person who is in the actual environment with the similar clothing insulation under consideration. Activity level is assumed to be the same in both the environments. SET calculation involves: For a given level of activity, clothing, and air speed - psychrometric chart--lines of constant SET. It has also been suggested that SET links directly to sensation rather than air temperature.

5.1.4 TSENS, DISC

TSENS, the first index, represents the model's prediction of a vote on the seven point thermal sensation scale. DISC, the second index, predicts a vote on a scale of thermal discomfort.

The 2-Node model has undergone many iterations and refinements. In the most recent iteration, a new temperature index, PMV*, that incorporates skin wettedness into the PMV equation using SET* or ET* to characterize the environment.

.

5.2. Empirical Models

5.2.1 PD

PD known as “predicted percent dissatisfied due to draft", is an index of persons expressing thermal discomfort because of drafts – unwanted air movement causing discomfort. A 'draft' is unwanted local cooling. The inputs to PD include air temperature, air velocity, and turbulence intensity. The draft risk (or PD) equation is:

$$PD=3.413(34-Ta)(v-0.05)0.622+0.369vTu(34-Ta)(v-0.05)0.622$$

where the different terms represent, respectively:
Tu is the turbulence intensity expressed as a percent.
V is the air velocity (in meters per second) and
Ta is the air temperature in degrees Celsius.

5.2.2 PS

The PS equation predicts the air velocity that will be chosen by a person exposed to a certain air temperature when the person has control of the air velocity source. The PS equation is

$$PS=1.13SQRT(Top)-0.24Top+2.7SQRT(v)-0.99v$$

where the different terms represent, respectively:
Top is operative temperature (in degrees Celsius) and
v is the air velocity in meters per second.

5.2.3 TS

TS is an equation that predicts thermal sensation vote using a linear function of air temperature and partial vapour pressure. The TS equation is:

$$TS=0.245Ta+0.248p-6.475$$

where the different terms represent, respectively:
Ta is the air temperature in degrees Celsius and
p is the partial vapour pressure in kilo-pascals.

4.3. Adaptive model

It has taken about 26 years world wide extensive observations since the first adaptive approach model suggested by Humphreys to be recognized by ASHRAE 55 . Researchers in thermal comfort field studies have found many times that people are not static receptor of their thermal environment as formulated inPMV approach but rather they are active and could significantly enhance the indoor comfort through the control of their local surroundings or acclimatize to the indoor and outdoor climate. The principalof the adaptive approach is that the indoor neutral temperature is highly correlated with the outdoor temperature and hence it can better predict neutral temperature of occupants in naturally ventilated buildings compared to the PMV model. The most world wide established adaptive model specified for thermal comfort in naturally ventilatedbuildings was proposed by de Dear and Brager recognised as the adaptive comfort standard in ASHRAE55 since 2004.

Humphreys and Auliciemes investigated the thermal neutrality of the human body. It was defined as the temperature at which the person feels thermally neutral "comfortable". Their studies were based on laboratory and field works in which people were thermally investigated under different conditions. The results of their experiments were statistically analyzed by using regression analysis. . Humphreys showed that 95% of the neutral temperature is associated with the variation of outdoor mean temperature.

4.4. Design strategy Models

There are some models designed to give advises for climate responsive buildings. They mostly have very simple comfort zone and some advices.

4.4.1. Building bioclimatic charts

Bioclimatic charts facilitate the analysis of the climate characteristics of a given location from the viewpoint of human comfort, as they present, on a psychrometric chart, the concurrent combination of temperature and humidity at any given time. They can also specify building design guidelines to maximize indoor comfort conditions when the building's interior is not mechanically conditioned.

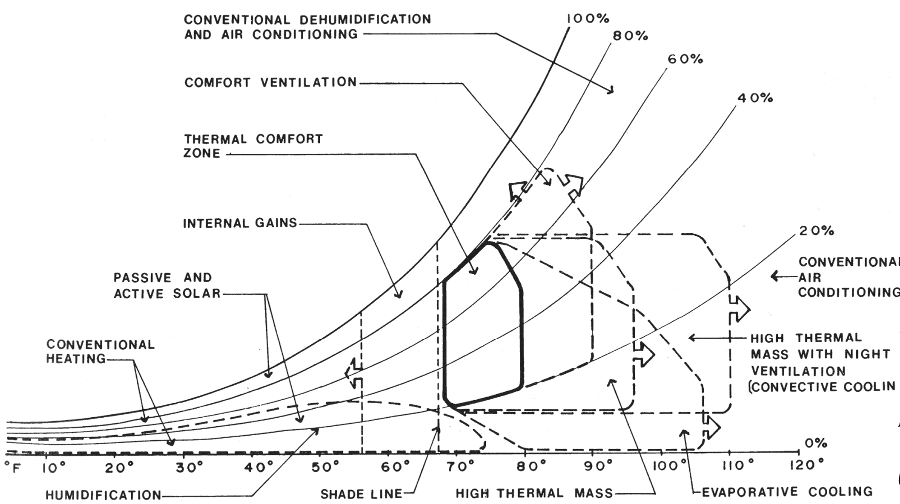


Figure 14: bioclimatic chart

(Source: dada.cca.edu)

4.4.2. Olgyay bioclimatic chart

Olgyays bioclimatic chart, was one of the first attempts at an environmentally conscious building design. It was developed in the 1950s to incorporate the outdoor climate into building design. The chart indicates the zones of human comfort in relation to ambient temperature and humidity, mean radiant temperature (MRT), wind speed, solar radiation and evaporative cooling.
On thechart, dry bulb temperature is the ordinate and relative humidity is the abscissa. The comfort zone is in the centre, with winter and summer ranges indicated separately (taking seasonal adaptation into account). The lower boundary of the zone is also the limit above which shading is necessary.

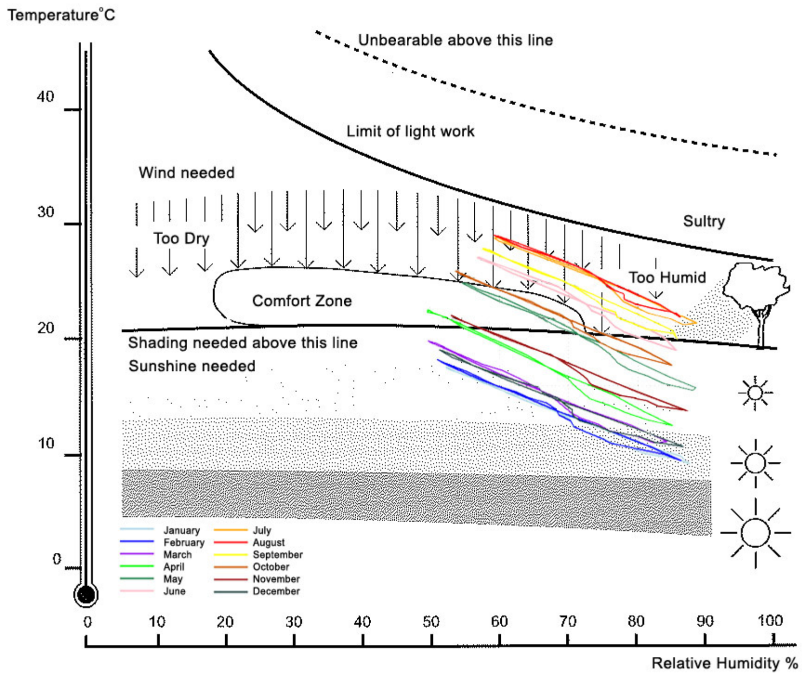


Figure 15: Olgyay bioclimatic chart (Source: www.shadyattia.net)

4.4.3. Givoni bioclimatic chart

Givoni's bioclimatic chart, aimed at predicting the indoor conditions of the building according to the outdoor prevailing conditions. He based his study on the linear relationship between the temperature amplitude and vapour pressure of the outdoor air in various regions. The chart combines different temperature amplitude and vapour pressure of the ambient air plotted on the psychrometric chart and correlated with specific boundaries of the passive cooling techniques overlaid on the chart. These techniques include evaporative cooling, thermal mass, natural ventilation cooling and passive heating.

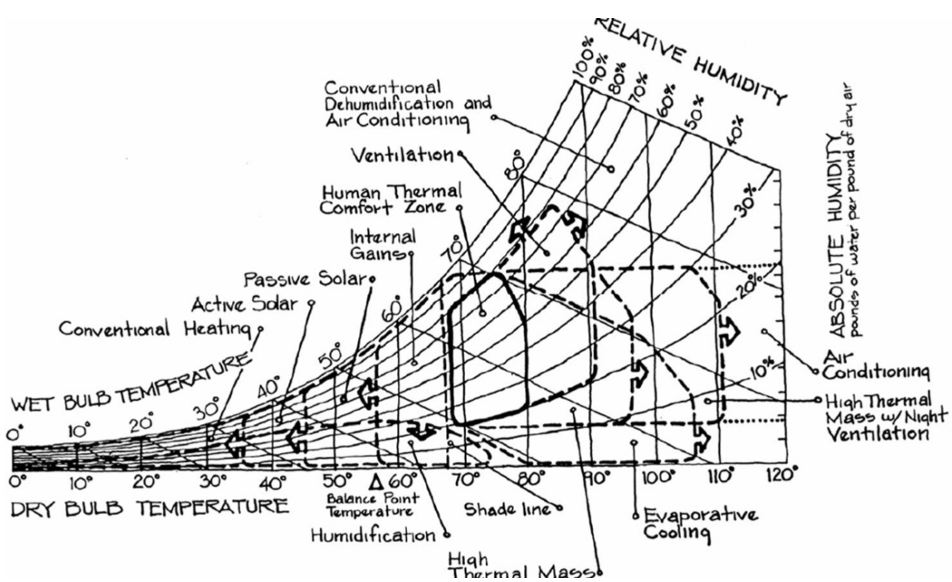


Figure 16: Givoni Bioclimatic chart (Source: http://www.archinology.com)

CHAPTER 5 – STUDY AREA REVIEW

5.1 Climatic Zones of India: Moderate Climate

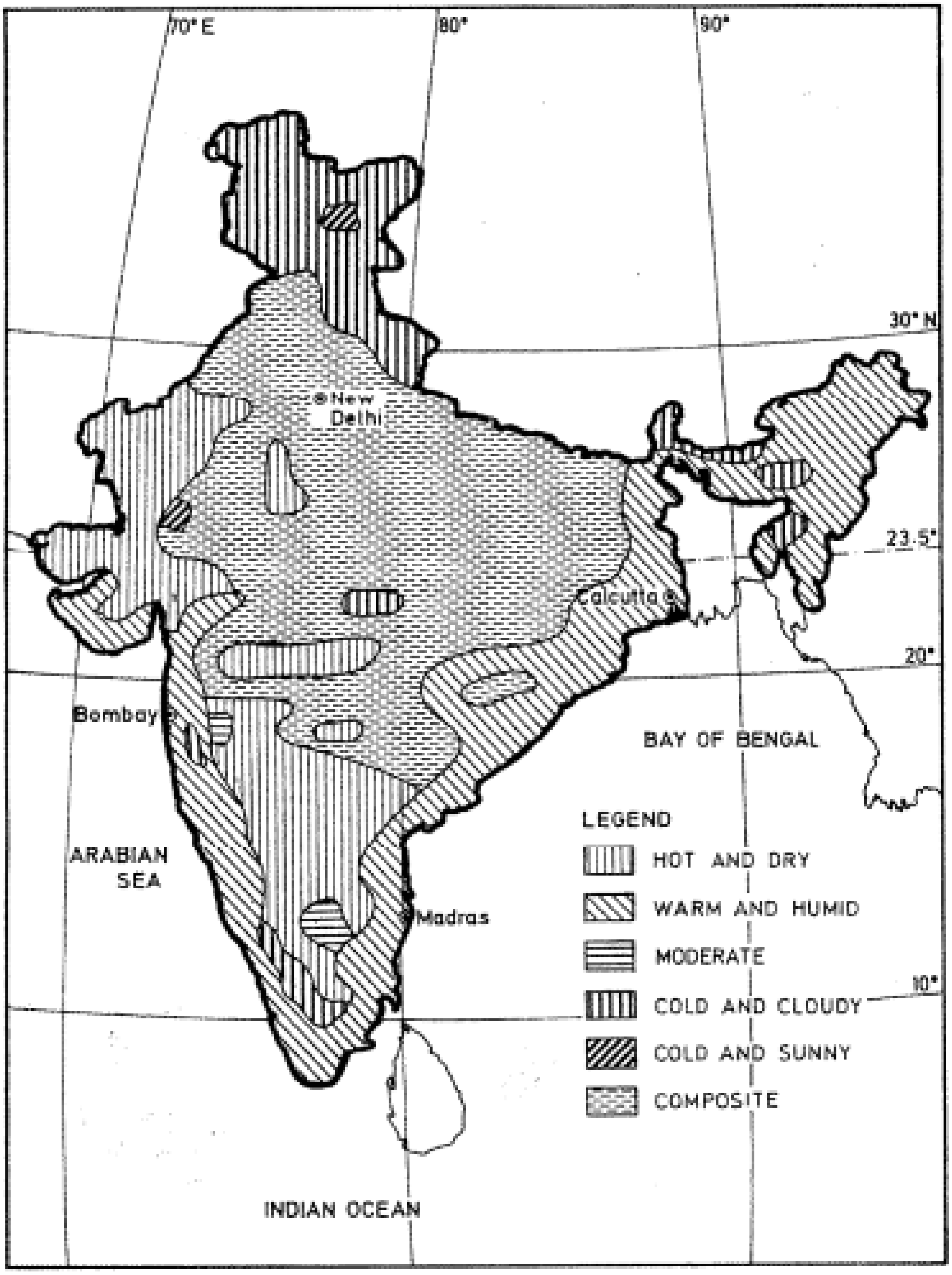
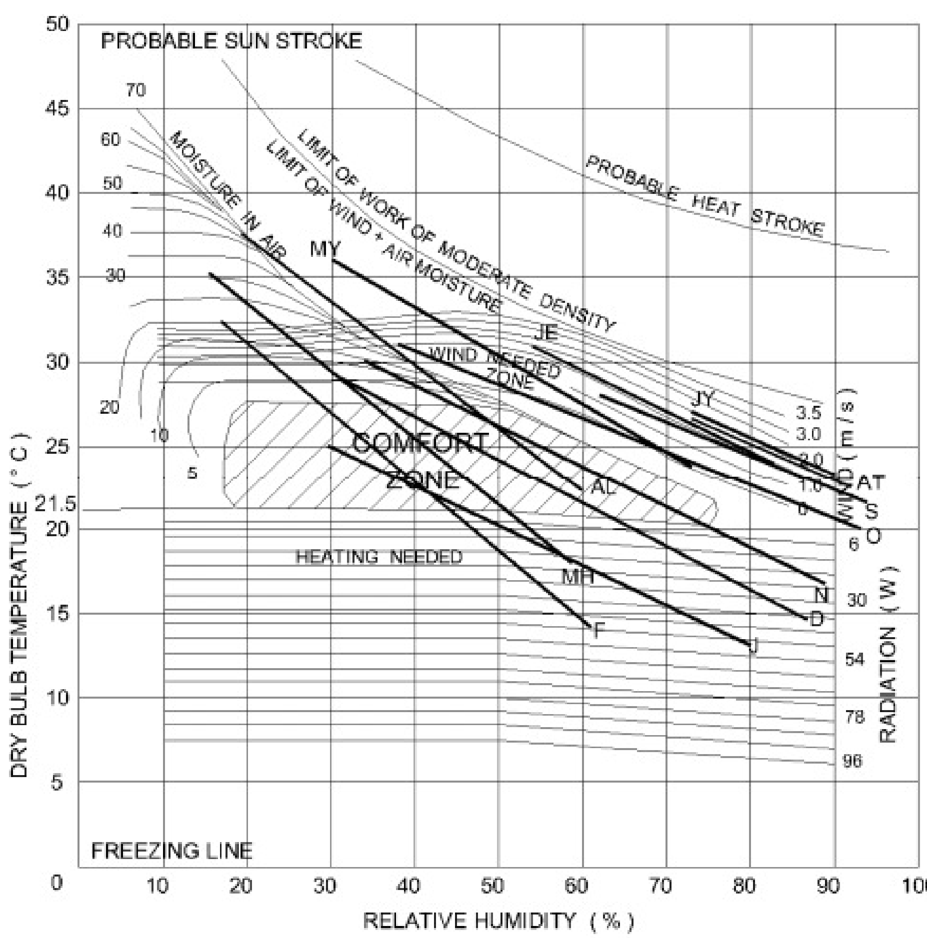


Figure 17: Climatic Zones of India (Source: http://mnre.gov.in)

Within India it is possible to define climatic zones according to its varied distinct region and identical characteristic feature. They can be normally classified and identified into six basic categories namely; Hot and Dry, Warm and Humid, Moderate, Cold and unny, Cold and Cloudy and Composite.

The cities of Pune and Bangalore are examples of cities that fall under the Moderate climatic zone, commonly situated on mountaineous or high-plateau terrains; having moderately abounding flora and fauna. This region enjoys a general comfortable climate, one that is neither too hot or extremely cold.The solar radiation in this belt is approximately the same during the whole of the year. Since these places are located at comparatively greater altitudes, they encounter lesser temperatures than the cold, hot and dry regions. During summers, the temperature may vary 30 – 34 ºC during the daytime and 17 – 24 ºC during night. During winters, the temperature may vary between 27 to 33 ºC during the day and 16 to 18 ºC during night. In terms of relative humidity of air, it is low during the period of winters and summers, varying from 20 – 55%, but during the monsoon season, it may touch 55 – 90%.



J=January, F=February, MH=March, AL=April, My=May, JE=June, JY=July, AT=August, S=September, O=October, N=November, D=December

Figure 17: Bioclimatic chart of Pune (Source: http://mnre.gov.in)

5.2 Introduction to Pune

Figure 19: Location of Pune (Source: http://punecorporation.org)

Pune is located on the leeward side of the Sahyadri mountain range, situated on the western margin of the Deccan plateau and falls between 18° 32"North latitude and 73° 51"East longitude. The city is gradually becoming a cosmopolitan city and is now an important and significant commercial centre. The upcoming projects and growth of IT sector in the city has placed it the eighth among the metropolis of India. Employment is mainly seen in the sector of information technology and software related fields (30 % of the total employed populatace) superseded by production and manufacturing business (25 %) and industry and commerce trade (22 %).

The area of study was therefore chosen because of the growth and sprawling offices and sortware industry and the city emerging as a major IT centre. This would aptly represent the developemnt in real estate development of offices and provide the chance to survey maximum and study the conditions existing in office buildings of moderate climatic zone of India.

5.3 Climatic characteristics Of Pune

Table 7: Climatic data of Pune (Source: http://en.wikipedia.org)

Climate data for Pune [hide]													
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Record high °C (°F)	33.8 (92.8)	36.2 (97.2)	39.8 (103.6)	42.3 (108.1)	41.7 (107.1)	39.8 (103.6)	33.7 (92.7)	31.6 (88.9)	35.3 (95.5)	36.7 (98.1)	34.0 (93.2)	32.8 (91)	42.3 (108.1)
Average high °C (°F)	29.9 (85.8)	31.9 (89.4)	35.4 (95.7)	37.7 (99.9)	36.9 (98.4)	31.7 (89.1)	28.4 (83.1)	27.4 (81.3)	29.4 (84.9)	31.4 (88.5)	30.1 (86.2)	28.9 (84)	31.59 (88.86)
Daily mean °C (°F)	20.5 (68.9)	22.0 (71.6)	25.6 (78.1)	28.8 (83.8)	29.7 (85.5)	27.4 (81.3)	25.3 (77.5)	24.5 (76.1)	25.1 (77.2)	25.0 (77)	22.3 (72.1)	20.2 (68.4)	24.7 (76.46)
Average low °C (°F)	11.0 (51.8)	12.1 (53.8)	15.8 (60.4)	19.9 (67.8)	22.4 (72.3)	22.9 (73.2)	22.2 (72)	21.6 (70.9)	20.8 (69.4)	18.5 (65.3)	14.4 (57.9)	11.5 (52.7)	17.76 (63.96)
Record low °C (°F)	4.8 (40.6)	5.2 (41.4)	8.4 (47.1)	12.3 (54.1)	14.7 (58.5)	16.8 (62.2)	19.5 (67.1)	17.8 (64)	16.0 (60.8)	10.0 (50)	6.0 (42.8)	4.5 (40.1)	4.5 (40.1)
Precipitation mm (inches)	0 (0)	3 (0.12)	2 (0.08)	11 (0.43)	40 (1.57)	138 (5.43)	163 (6.42)	129 (5.08)	155 (6.1)	68 (2.68)	28 (1.1)	4 (0.16)	741 (29.17)
Avg. precipitation days	0.1	0.3	0.3	1.1	3.3	10.9	17.0	16.2	10.9	5.0	2.4	0.3	67.8
% humidity	56	46	36	36	48	70	79	82	78	64	58	58	59.3
Mean monthly sunshine hours	291.4	282.8	300.7	303.0	316.2	186.0	120.9	111.6	177.0	248.0	270.0	288.3	2,895.9
Source: NOAA (1971–1990)[32]													

Typical summer months are from March to May, with maximum temperatures ranging from 30 to 38 °C (86 to 100 °F). The monsoon lasts from June to October, with moderate rainfall and temperatures ranging from 22 to 28 °C (72 to 82 °F). Most of the 722 mm (28.43 in) of annual rainfall in the city fall between June and September, and July is the wettest month of the year. Hailstorms are also common in this region.The daytime temperature during winters hovers around 28 °C (82 °F) while night temperature is below 10 °C (50 °F) for most of December and January, often dropping to 5 to 6 °C (41 to 43 °F).

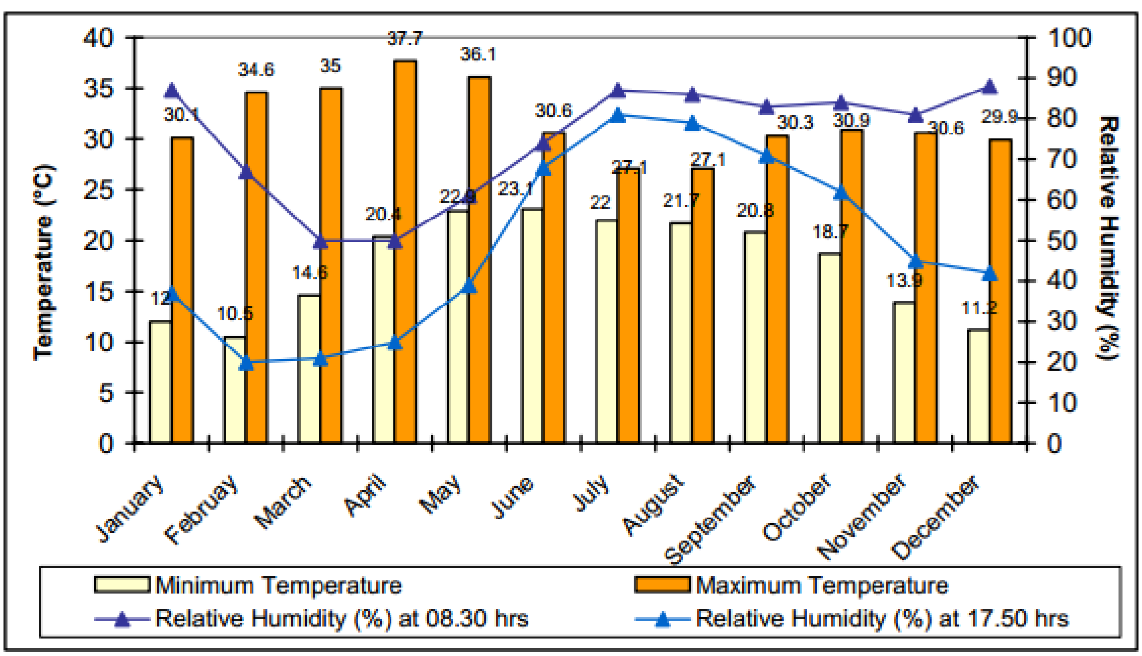


Figure 20: Annual Variations in Temperature and Humidity at Pune (2001)(Source: Dy.Director-General, Regional Metrological Department, Pune (2001))

5.4 Current Scenario in Pune

According to a report, which compared the addition of the office space in various metros, placed Bangalore and Hyderabad below Pune’s market. The reason for the good performance for Pune was the delayed completion of a number of commercial and Special Economic Zone (SEZ) projects in the last quarter of 2013. Given its performance last year, of being the second highest office space growth market after Mumbai, “*Pune's total office space absorption in 2013 stood around 2 million sq ft.”* (Indian Express, February 6, 2014).

The amount of energy accounted for buildings has been increasing in the past few years and the hike has been attributed to the following reasons of;

1. A significant growth in the IT (Information Technology) sector and an increase in the use of air conditioning equipments to enhance comfort in recent years.
2. Secondly, there has been apparent advancement in the aggregate number of new buildings erected, especially more intense in the offices sector in recent years resulting to longer occupancy hours.

CHAPTER 6 – ONLINE QUESTIONAIRE SURVEY

6.1 Methodology

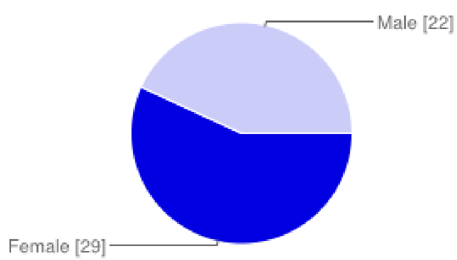
A subjective questionnaire / online survey was undertaken during November2013--January 2014, in the moderate climatic zone of India-Bangalore and Pune offices and these work places were mechanically ventilated. The internal temperature of the offices ranged from 20-23℃, while the outdoor temperature ranged from 19℃-26℃. the purpose of the survey was to find out the occupants take on the current office environments.

The purview and configuration of the questionnaire is establised on the Indoor Environmental Quality (IEQ) survey questionnaire from the Centre of the Built Environment (CBE) at the University of California, Berkeley. A few supplementary questions that were imperative for the analysis and research were affixed to the sample survey. The survey questions are providede in annexure A.

6.2 Results of all the cases:

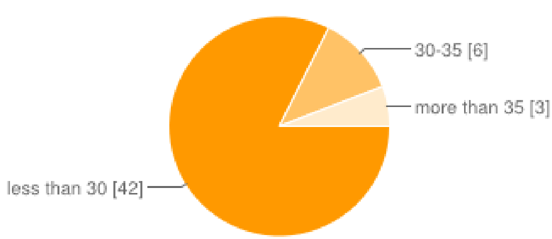
The observations received from the employees responding to the questionaire are :

- ***Gender***



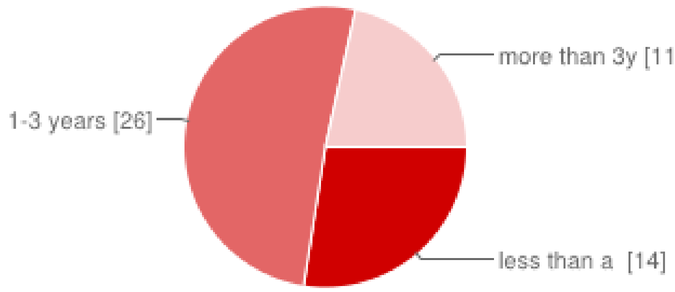
Female	57%
Male	43%

- ***Age***



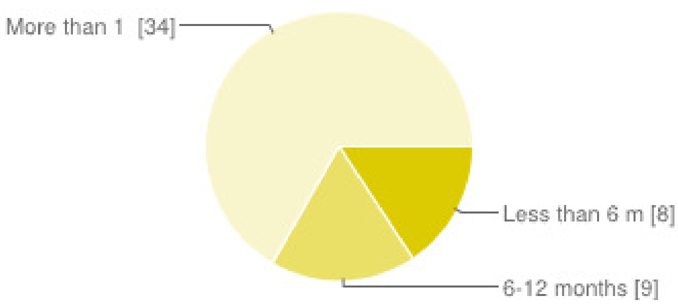
less than 3	82%
30-35	12%
more than	6%

6.2.a) Number of years employed in this building?



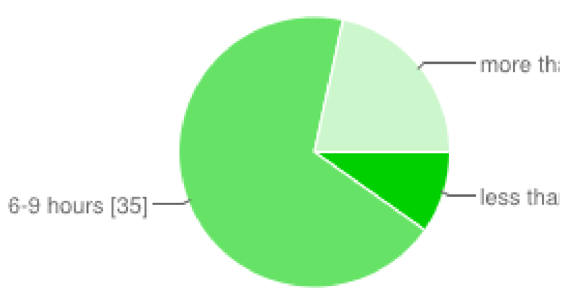
less than a year	27%
1-3 years	51%
more than 3years	22%

6.2.b) Duration of working at the present workspace / office cabin?



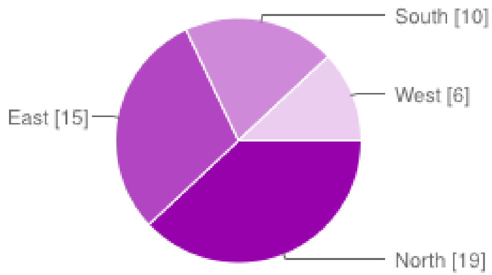
Less than 6 months	16%
6-12 months	18%
More than 1 year	67%

6.2.c) On an regular working day,what is the duration of time you spend in the workspace?



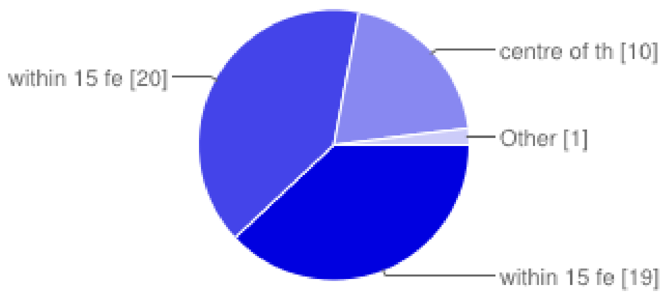
less than 6 hours	10%
6-9 hours	69%
more than 9 hours	22%

6.2.d) Towards which direction is the workspace ?



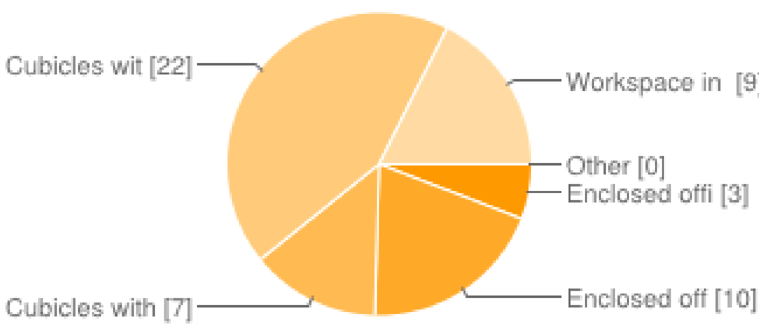
North	38%
East	30%
South	20%
West	12%

6.2.e) Where exactly is the workplace located?



within 15ft of an exterior wall	38%
within 15 ft of a window	40%
centre of the room	20%
Other	2%

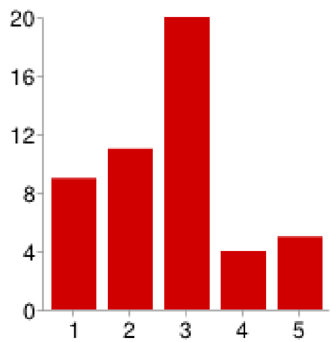
6.2.f) Which describes your workspace precisely?



Enclosed office, private	6%
Enclosed office, shared with other people	20%
Cubicles with high partitions (about five or more feet hi	14%
Cubicles with low partitions (lower than five feet high)	43%
Workspace in open office with no partitions (just desks)	18%
Other	(

6.2.g) Rate the following: visual privacy

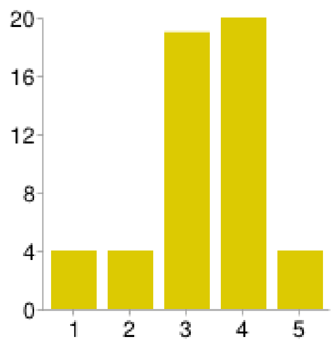
1-very dissatisfied
5- very satisfied



Very satisfied	18%
Somewhat satified	22%
neutral	41%
Somewhat dissatified	8%
Very dissatisfied	10%

6.2.h) Rate the following : Amount of space available

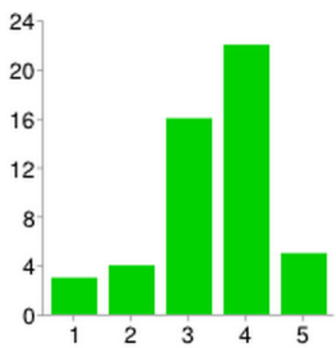
1-very dissatisfied
5- very satisfied



Very satisfied	8%
Somewhat satified	8%
neutral	37%
Somewhat dissatified	39%
Very dissatisfied	8%

6.2.i) Rate the following : temperature / thermal comfort

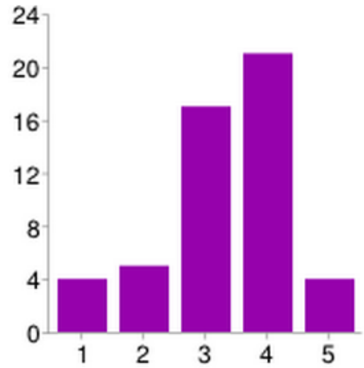
1-very dissatisfied
5- very satisfied



Very satisfied	6%
Somewhat satified	8%
neutral	32%
Somewhat dissatified	44%
Very dissatisfied	10%

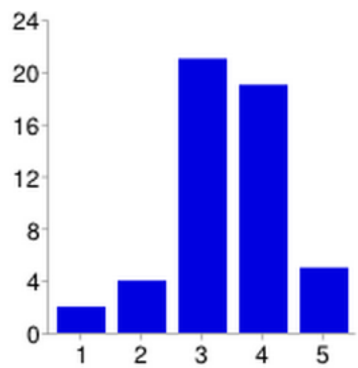
6.2.j) Rate the following : Complacency with the comfort of office furnishings provided (chair, desk, computer, equipment, etc.)?

1-very dissatisfied
5- very satisfied



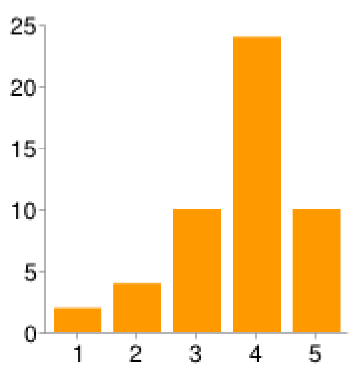
Very satisfied	8%
Somewhat satified	10%
neutral	33%
Somewhat dissatified	41%
Very dissatisfied	8%

6.2.k) Rate the following : the office layout
1-very dissatisfied
5- very satisfied



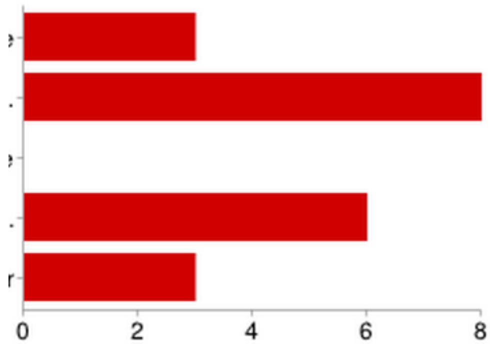
Very satisfied	4%
Somewhat satified	8%
neutral	41%
Somewhat dissatifie(	37%
Very dissatisfied	10%

6.2.l) Rate the following : air quality
1-very dissatisfied
5- very satisfied



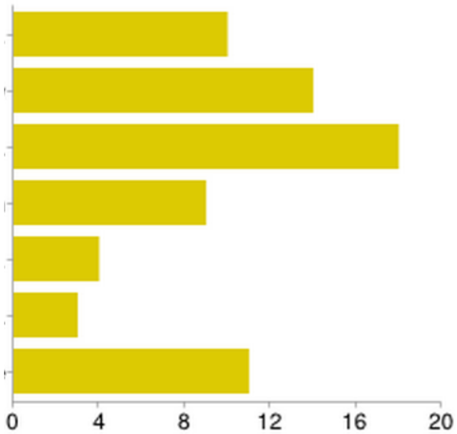
Very satisfied	4%
Somewhat satified	8%
neutral	20%
Somewhat dissatified	48%
Very dissatisfied	20%

6.2.m) If dissatisfied, the air quality in the workspace is unpleasant due to:



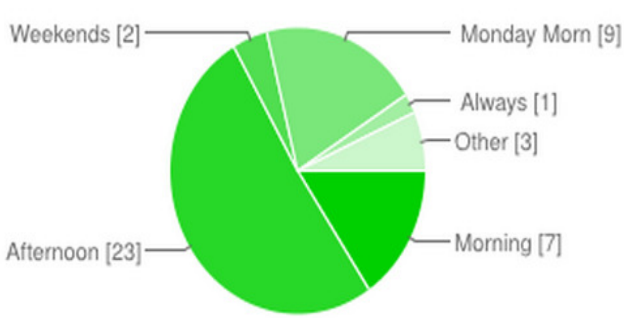
Stuffy / stale	15'
Odourous due to furnishings (carp furniture)	40'
tobacco smoke	0%
photocopiers / printers	30'
Other	15'

6.2.n) Which of the following can be adjusted or controled in the work area?



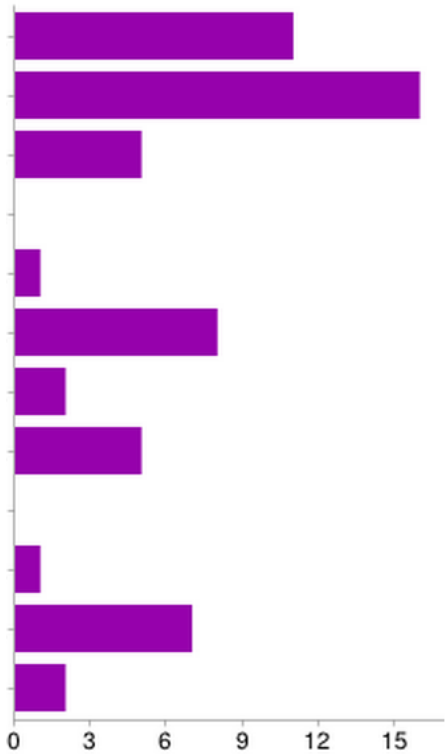
Window blinds or shades	14%
Operable window	20%
Room air-conditioning unit	26%
Ceiling fan	13%
Door to interior space	6%
Door to exterior space	4%
None of the above	16%

6.2.o) If thermal discomfort (temperature and humidity) is encountered, when is the most possibility?



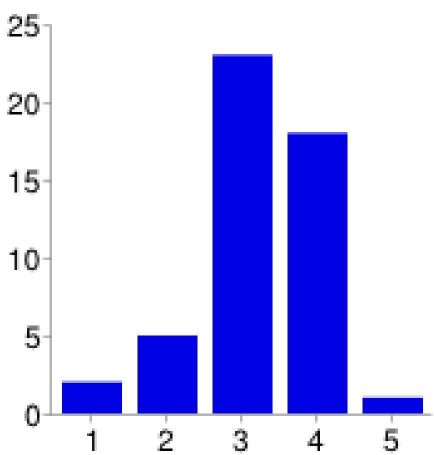
Morning	16%
Afternoon	51%
Weekends	4%
Monday Mornings	20%
Always	2%
Other	7%

6.2.p) If thermal discomfort (temperature and humidity) is experienced, what is the most suitable reason that describes it?



Too much/ too little air movement	19%
Incoming sunlight heats up space	28%
Heat from office equipment	9%
Drafty windows	0%
Vented air is too hot	2%
Vented air is too cold	14%
My workspace is hotter than other areas	3%
My workspace is colder than other areas	9%
Hot floors and walls	0%
Cold floors and walls	2%
Thermostat is inaccessible/ controlled by others	12%
Other	

6.2.q) Level of dissatisfaction with the personal workspace?



Very satisfied	4%
Somewhat satified	10%
neutral	47%
Somewhat dissatisfie	37%
Very dissatisfied	2%

6.3 Conclusions:

The main conclusions from this work are:

- Approximately 44% of the occupants account to being thermally comfortable during the usual working hours in the offices studied. Of the other dissatisfied with the thermal comfort, the main reason was due to incoming sunlight (28%) and was felt at afternoons (51%). The amount of air movement was the other cause of thermal discomfort.
- From an architect's point of view, it is vital to understand the perceived environments of the occupants within the space, and attention given to details of daylight, lighting, furniture, office layout and openings on walls (window / doors). As concluded from the comments received since most of the time spent for the occupants is within their work station, the effect of temperature and air movement amounts of how comfortable the space is. If given an option to personally adjust thermal control inside the workspace, majority of the occupants would like to manage the room air-conditioning unit or the operable windows.
- While most of the employees are fairly satisfied with the quality of air quality provided in their workspaces, 15% of the dissatisfied felt stuffy or stale and 40% felt it was odorous due to furnishings (carpet, furniture). If again, an alternative was given for open able windows, this would be beneficial.
- Another conclusion is that there is an opportunity for improving and developing better indoor environment in Indian offices of the moderate climate, if survey and analysis is done with samples of wider population. The effect of perceived thermal comfort and its relation to the occupants' productivity can also be studied further.

CHAPTER 7 – EXPERIMENTAL STUDY

7.1 Experimental Study

Experimental analysis on thermal comfort (TC) inside a model test room was performed in the laboratory of Hermann Rietschel institute, under the Technical University of Berlin, Germany.

- A **double occupant** office of area 21.80sqm was set up for the experimental study.
- The dimensions of this office room were 5.1m long, 4.275m wide, 3.0m high.
- A total of 6 windows measuring 2.0m x 1.250m were placed on the south and east façade. The north / west all had a glass façade from floor to roof level.

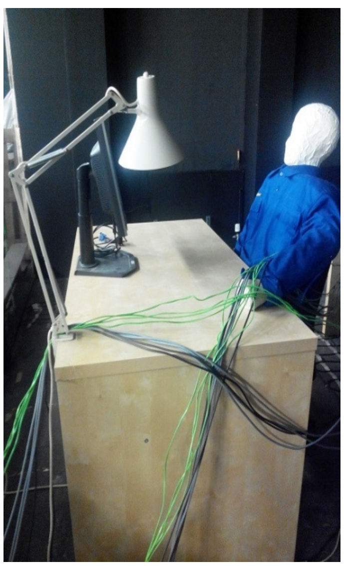


Figure 21: laboratory set up (Source:Author)

Figure22:: laboratory with manikin, computer and office furnishings (Source:Author)

With the aim of a realistic model, a furnished office room was created by installing a computer (for equipment heat calculation) along with a human dummy (for human body heat and clothing insulation calculation) and computer and lighting provided (for heat calculation due to lighting) and most importantly an air conditioning unit providing clean conditioned air was set up to complete the laboratory set up for the experiment to calculate thermal comfort inside a mechanically ventilated office space.

- The indoor air quality is assumed to be within the correct thermal comfort range and in accordance to the standards. The volume of supply air and extracted air are assumed and the value considered is set for the experiment.
- Heated coils are placed on the floor to assume the temperature indoors due to the sun.
- Sensors are placed at the inlet to determine the blowing and suction temperatures of air. Conducive to take the thermal comfort assessment, different values and measures of temperatures, air velocities, solar radiation and appropriate time of the day was considered.
- Physical measurement was carried out using the following instruments / apparatus / sensors:

  1. **Velocity:** Omni Directional Hot-Wire Anemometer (Dantoc)
  2. **Temperature:** Tyke k Thermocouples
  3. Thermal Comfort parameters are measured using the program, **Benchlink Data Logger** and the data is obtained after reading of 180 seconds. The tabulated date received is then used to plot the PMV model to determine the thermal comfort.

Figure 23: office set for experiment in the laboratory(Source: Author)

To achieve the readings for thermal comfort, 2 standing measurement apparatus with various sensors were placed for measurements at locations corresponding to different heights of a human body relevant ,i.e. at floor level, ankle level, head level (while sitting) and head level (standing). In Table 1, the average heights and corresponding body locations are given below..

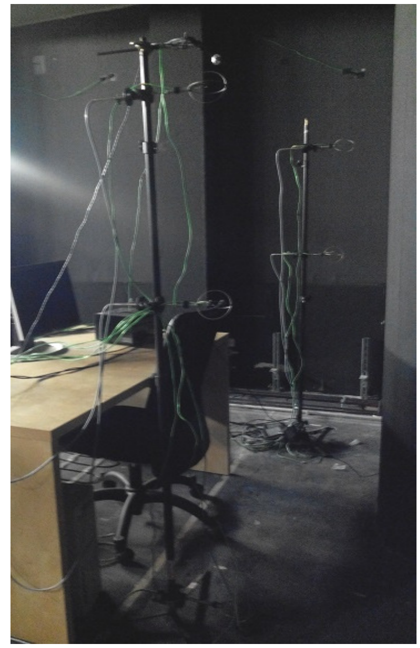


Figure 24: office set for experiment in the laboratory (Source: Author)

Table 8: Average heights of senses

S.no	Sense location	Height
1.	Floor level	0.0 m
2.	Ankle / Foot Level	0.1 m
3.	Head level (seated)	1.1 m
4.	Head Level (standing)	1.7 m

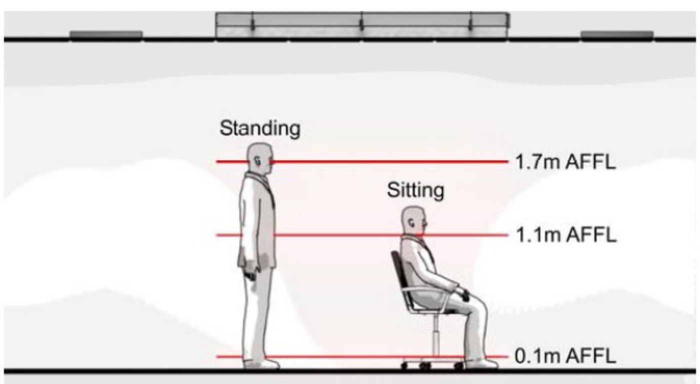


Figure 25: The occupied Zone- standing or sitting (Source: www.feta.co.uk)

From the results, according to the variations in the ventilation characteristics explained above, different temperature distributions were obtained resulting in different thermal comfort conditions.

Figure 26 : office set for experiment in the laboratory(Source: Author)

Two softwares / programs are used to provide the information for the experiment like solar radiation, wall and window temperature, volume of supply air etc and to measure thermal comfort respectively. After feeding the compiled data into the program, another apparatus is used to measure thermal comfort with the help of sensors.

7.2 Methodology

- To allow maximum recordings with most probability and accurate measure of thermal comfort, different cases were studied with changes in time of the day, solar radiation, temperature (indoor, outdoor wall and window), air velocity, humidity factors etc.
- The average working hours is regarded standard as 7 hours, from 9 in the morning to 6 in the evening.
- The seasonal calculations were considered for summer (month of May) and winters (month of December).
- The calculation for outdoor temperature were taken and divided into three categories time of the day - morning (9am), afternoon (1pm) and evening hours (6pm).
- The principle for the thermal environment is based on the thermal comfort factors of PMV-PPD (predicted mean vote & predicted percentage of dissatisfied) along suppositive ideal levels of activity (sedentary work) and clothing factor (winter and summer) for insulation as explained and illustrated in EN ISO 7730.

Table 9: outdoor temperatures at differnt time of the day. (Summer)

Time of the Day(Hour)	Solar Radiation (kW/m²) on Month : May					Ambient Temperature (℃)
	South Surface(per m²)	Solar Radiation for Window (2*1.25)m	East Surface	Solar Radiation for Window (2*1.25)m	Solar Radiation TOTAL (south+east)(kW/m	
9am	0.156	0.39	0.608	1.52	1.91	28.6
13pm	0.215	0.5375	0.215	0.5375	1.075	35.3
18pm	0.054	0.135	0.054	0.135	0.27	32.4

Table 10: : outdoor temperatures at differnt time of the day. (Winter)

Time of the Day(Hour)	Solar Radiation (kW/m²) on Month : December					Ambient Temperature (℃)
	South Surface(per m²)	Solar Radiation for Window (2*1.25)m	East Surface	Solar Radiation for Window (2*1.25)m	Solar Radiation TOTAL (south+east)(kW/m²)	
9am	0.423	1.0575	0.535	1.3375	2.395	19.1
13pm	0.681	1.7025	0.146	0.365	2.0675	28
18pm	0.006	0.015	0.006	0.015	0.03	26.1

- The temperature inside has been assumed as 22℃, 19℃ and 25℃ for the seasons of winter and summer;
- The air humidity percentage was measured for the values of 30%, 50% and 70% and,
- The values of air velocities also changed from 0.05m/s, 0.1 m/s and 0.15m/s.

The thermal comfort readings were then measured under these different conditions and used for calculations.

In furtherance to analyze admissible levels of PMV and PPD, evaluation and survey must be made dependent upon the operation of the zone / area in regard, understanding that an individual's perception and outlook to comfort is dependent upon rate of metabolism (activity level) and the factor of clothing insulation;

Table 11: Metabolic Rates

Activity	**Metabolic rate (met)**
Sedentary Activity (office, dwelling, school , laboratory)	1.2

Table 12: Thermal Insulation of Clothing

Season	**Daily Wear Clothing**	**Insulation of Clothing**
Summer	Panties, Short (short sleeves), Light trousers, socks, Shoes	0.50
Winter	Panties, Shirt, trousers, Jacket, Socks, Shoes	1.00

The PMV is based on the mean value of votes taken from a large group of persons and based on a 7 point thermal sensation scale (Fanger, 1970).

Table 13: PMV thermal scale

+3	Hot
+2	Warm
+1	Slightly Warm
0	Neutral
-1	Slightly Cool
-2	Cool
-3	Cold

For the purpose of study,

Burnt brick wall(210mm) with cement plaster(10mm) was considered.

U-Value calculation for wall:

- Wall thickness = 210mm
- Plaster = 10mm (internal and external)

L1 = 0.01 m; k1 = 0.721 W/m-K (*Thermal Conductivity of cement plaster)*

L2 = 0.19 m; k2 = 0.811 W/m-K (*Thermal Conductivity of burnt brick)*

L3 = 0.01 m; k3 = 0.721 W/m-K

Values of Surface Heat Transfer Coefficient (W/m2-K) taken from MHRE booklet (Source: chapter 4-Thermal Performance of Buildings)

- Still air: hi = 8.3 W/m2-K
- Moving air: ho = 22.7 W/m2-K

RT = 1/8.3 + 0.01/0.721 + 0.21/0.811 + 0.01/0.721 + 1/22.7 = 0.45095

U = 1/RT = 1/0.45095 = 2.2175 W/m2-K

The u-value of wall = 2.22 W/m2-K.

U-Value calculation for window:

- Specification: Saint Gobain Glass
- Single Glazed Unit Clear Glass - U value = 5.8 W/m2K (Source: Saint Gobain Glass)

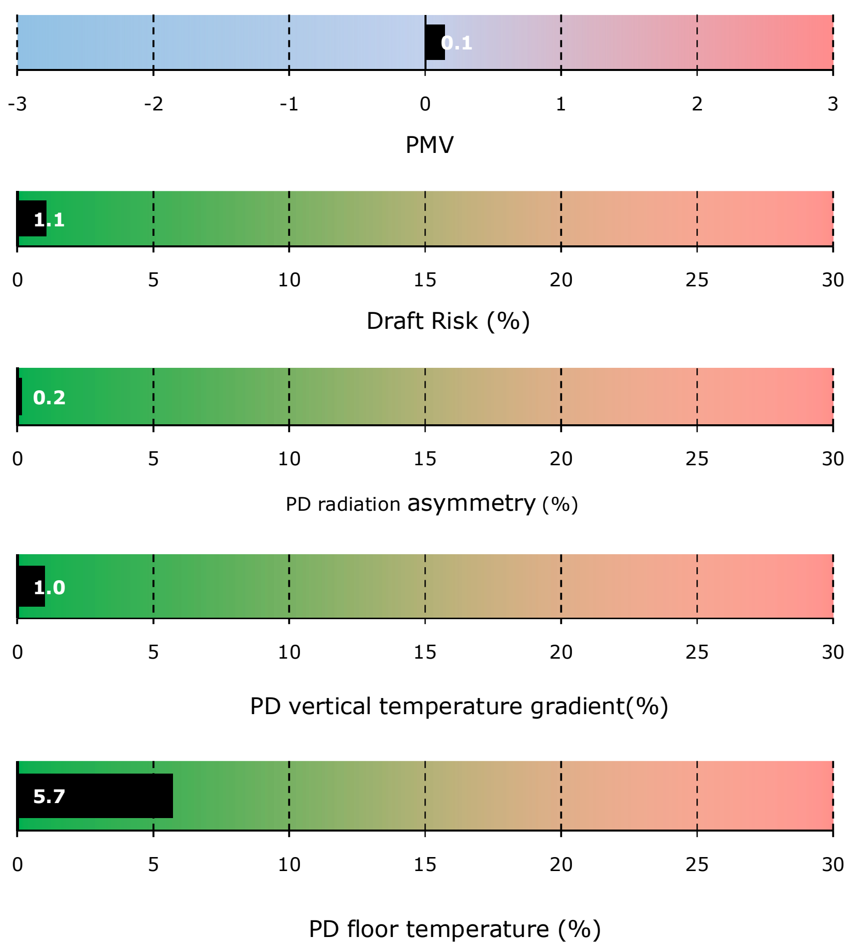
The indoor temperature ranged from 21℃ – 25-5℃ as per the survey done online for mechanically ventilated office buildings and these values were used to calculate the indoor environment conditions. The global solar radiation and ambient temperature data was assumed from the MHRE booklet (chapter 4-Thermal Performance of Buildings) for moderate climate.

7.3 CASE 1: Season- Summer Time: 9am

- Solar radiation: 1.91kW/m^{2}[3]
- Air Humidity = 50%
- Outdoor Temperature: 28.6℃
- Indoor Temperature = 22℃
- U-Value of wall = 2.22 W/m^2-K
- U-Value of window = 5.8 W/m^2-K
- Volume of supply air = 182 m
- Wall Temperature = u/α(T1 – T2)+ T2 = 2.22/8.3 (28.6 – 22) + 22 = 23.76℃
- Window Temperature = u/α(T1 – T2)+ T2 = 5.8/8.3 (28.6 – 22) + 22 = 26.61 ℃

Where, u= U-Value, α = 8.3 (constant), T1 = outdoor temperature, T2 = indoor temperature

Thermal comfort readings:

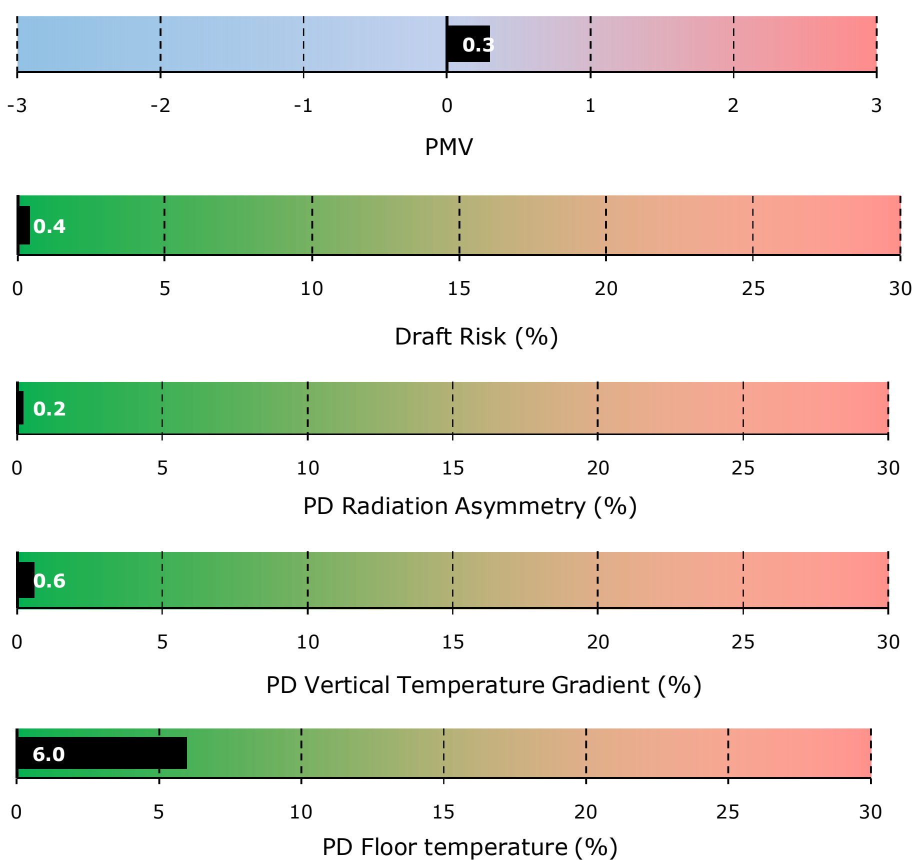


7.4 CASE 2: Season- Summer Time: 13hours

- Solar radiation: 1.075 kW/m^2
- Air Humidity = 50%
- Outdoor Temperature: 35.3℃
- Indoor Temperature = 22℃
- U-Value of wall = 2.22 W/m^2-K
- U-Value of window = 5.8 W/m^2-K
- Volume of supply air = 182 m
- Wall Temperature = $u/\alpha(T1 - T2) + T2$ = $2.22/8.3\ (35.3 - 22) + 22$ = 25.55℃
- Window Temperature = $u/\alpha(T1 - T2) + T2$ = $5.8/8.3\ (35.3 - 22) + 22$ = 31.30 ℃

Where, u= U-Value, α = 8.3 (constant), T1 = outdoor temperature, T2 = indoor temperature

<u>Thermal comfort readings:</u>



7.5 CASE 3: Season - Summer   Time: 18hours

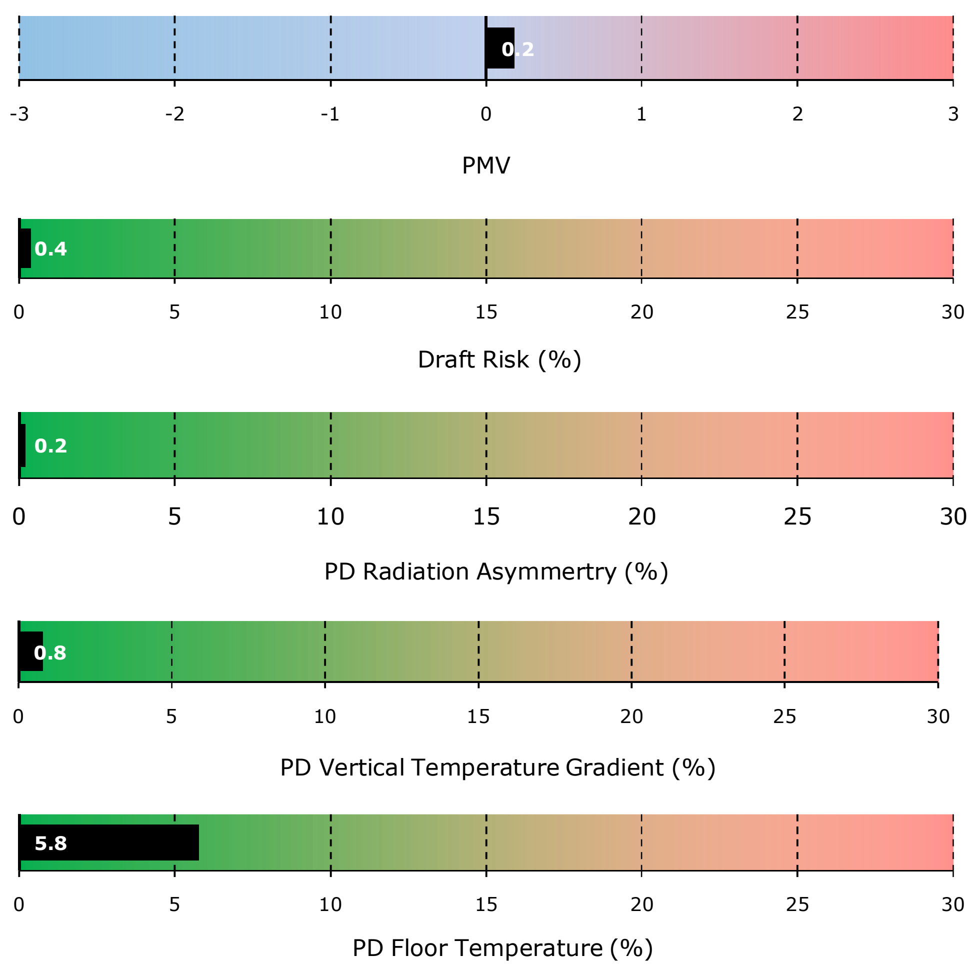
- Solar radiation: 1.075 kW/m²
- Outdoor Temperature: 32.4℃
- U-Value of wall = 2.22 W/m²-K
- Volume of supply air = 182 m³
- Air Humidity = 50%
- Indoor Temperature = 22℃
- U-Value of window = 5.8 W/m²-K

- Wall Temperature = u/α(T1 – T2)+ T2 = 2.22/8.3 (32.4 – 22) + 22 = 24.78℃

- Window Temperature = u/α(T1 – T2)+ T2 = 5.8/8.3 (32.4 – 22) + 22 = 29.27 ℃

Where, u= U-Value, α = 8.3 (constant), T1 = outdoor temperature, T2 = indoor temperature

Thermal comfort readings:

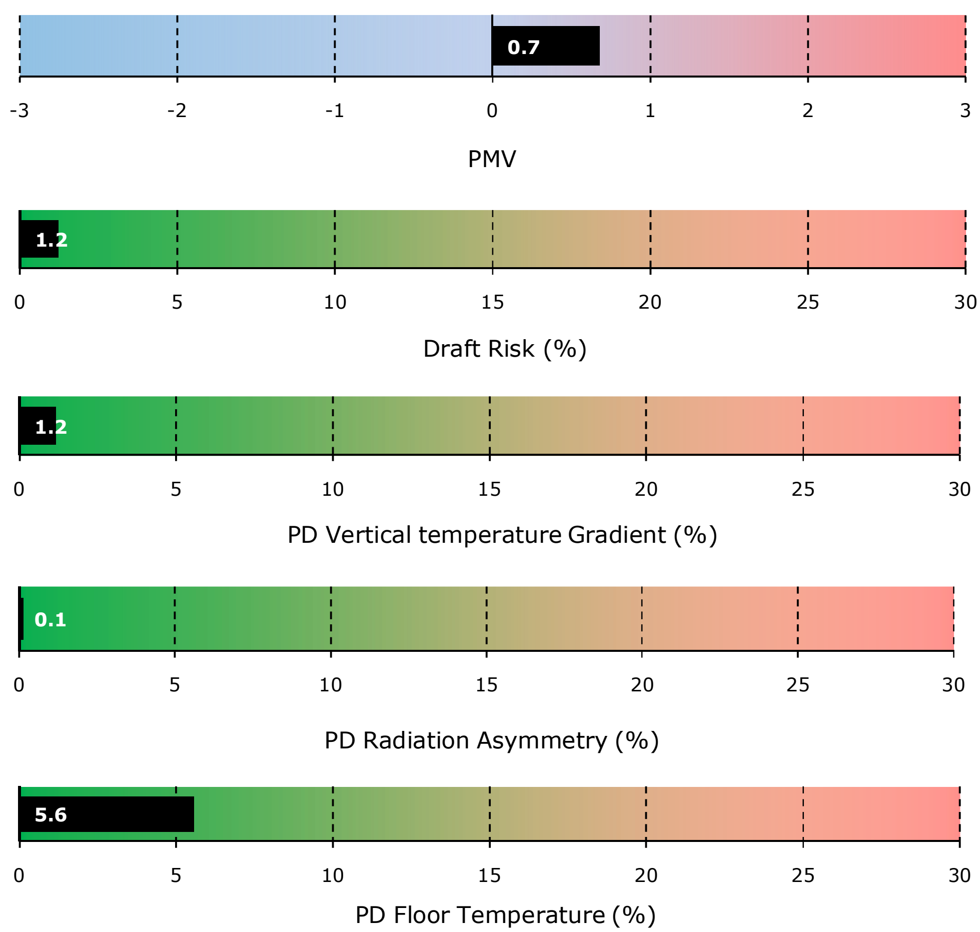


7.6 CASE 4: Season - Winter - Time: 9am

- Solar radiation: 2.395 kW/m^2
- Air Humidity = 50%
- Outdoor Temperature: 19.1℃
- Indoor Temperature = 22℃
- U-Value of wall = 2.22 W/m^2-K
- U-Value of window = 5.8 W/m^2-K
- Volume of supply air = 182 m^3
- Wall Temperature = $u/\alpha(T1 - T2) + T2$ = $2.22/8.3\ (19.1 - 22) + 22$ = 22.77℃
- Window Temperature = $u/\alpha(T1 - T2) + T2$ = $5.8/8.3\ (19.1 - 22) + 22$ = 24.03℃

Where, u= U-Value, α = 8.3 (constant), T1 = outdoor temperature, T2 = indoor temperature

<u>Thermal comfort readings:</u>



7.7 CASE 5: Season - Winter - Time: 13hours

Solar radiation: 2.066 kW/m^2 - Air Humidity = 50%

Outdoor Temperature: 28℃ - Indoor Temperature = 22℃

U-Value of wall = 2.22 W/m^2-K - U-Value of window = 5.8 W/m^2-K

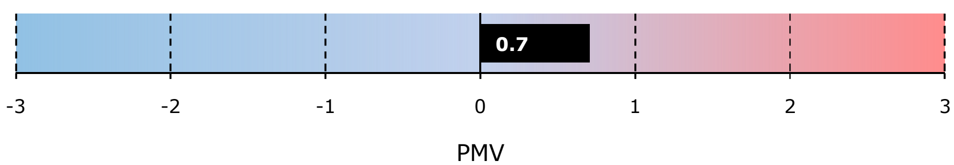
- Volume of supply air = 182 m^3

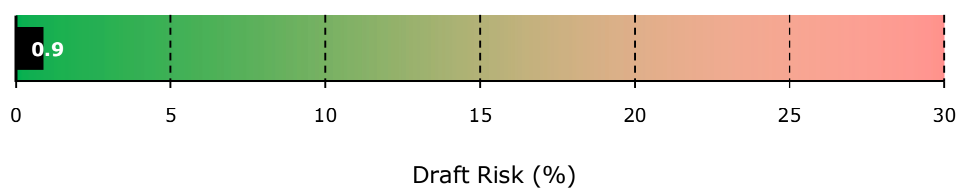
- Wall Temperature = u/α(T1 – T2)+ T2 = 2.22/8.3 (28 – 22) + 22 = 23.60℃

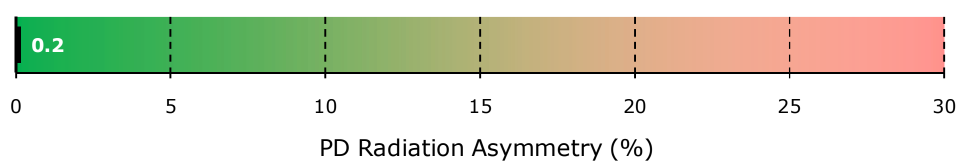
- Window Temperature = u/α(T1 – T2)+ T2 = 5.8/8.3 (28 – 22) + 22 = 26.20℃

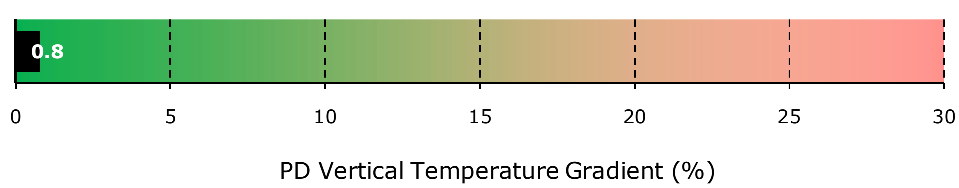
Where, u= U-Value, α = 8.3 (constant), T1 = outdoor temperature, T2 = indoor temperature

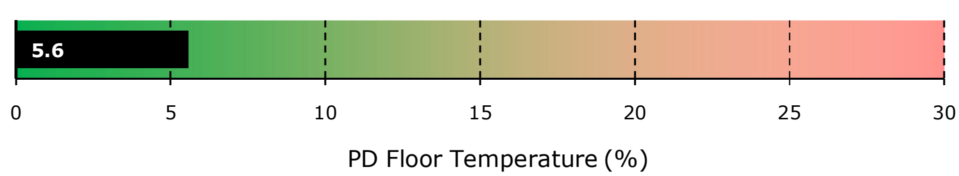
Thermal comfort readings:









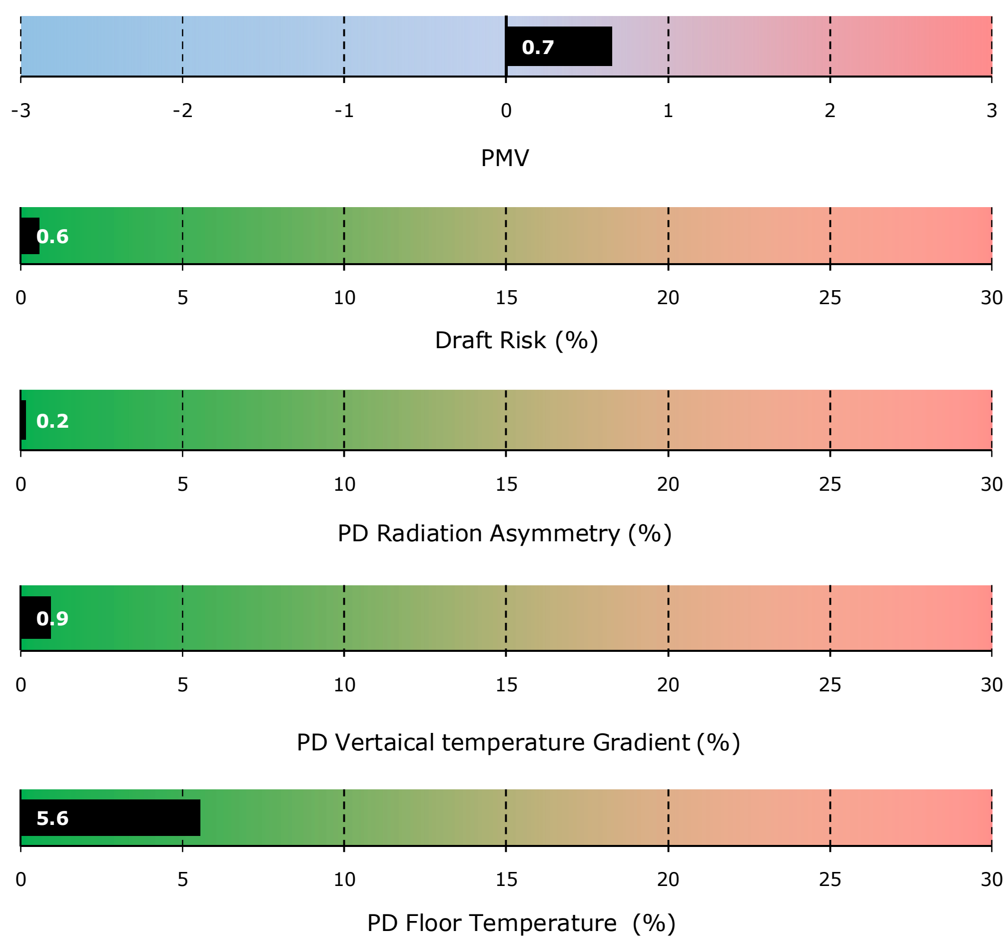


7.8 CASE 6: Season - Winter - Time: 18hours

- Solar radiation: 0.03kW/m² - Air Humidity = 50%
- Outdoor Temperature: 26.1℃ - Indoor Temperature = 22℃
- U-Value of wall = 2.22 W/m²-K - U-Value of window = 5.8 W/m²-K
- Volume of supply air = 182 m³
- Wall Temperature = u/α(T1 – T2)+ T2 = 2.22/8.3 (26.1 – 22) + 22 = 23.05℃
- Window Temperature = u/α(T1 – T2)+ T2 = 5.8/8.3 (26.1 – 22) + 22 = 24.86℃

Where, u= U-Value, α = 8.3 (constant), T1 = outdoor temperature, T2 = indoor temperature

Thermal comfort readings:



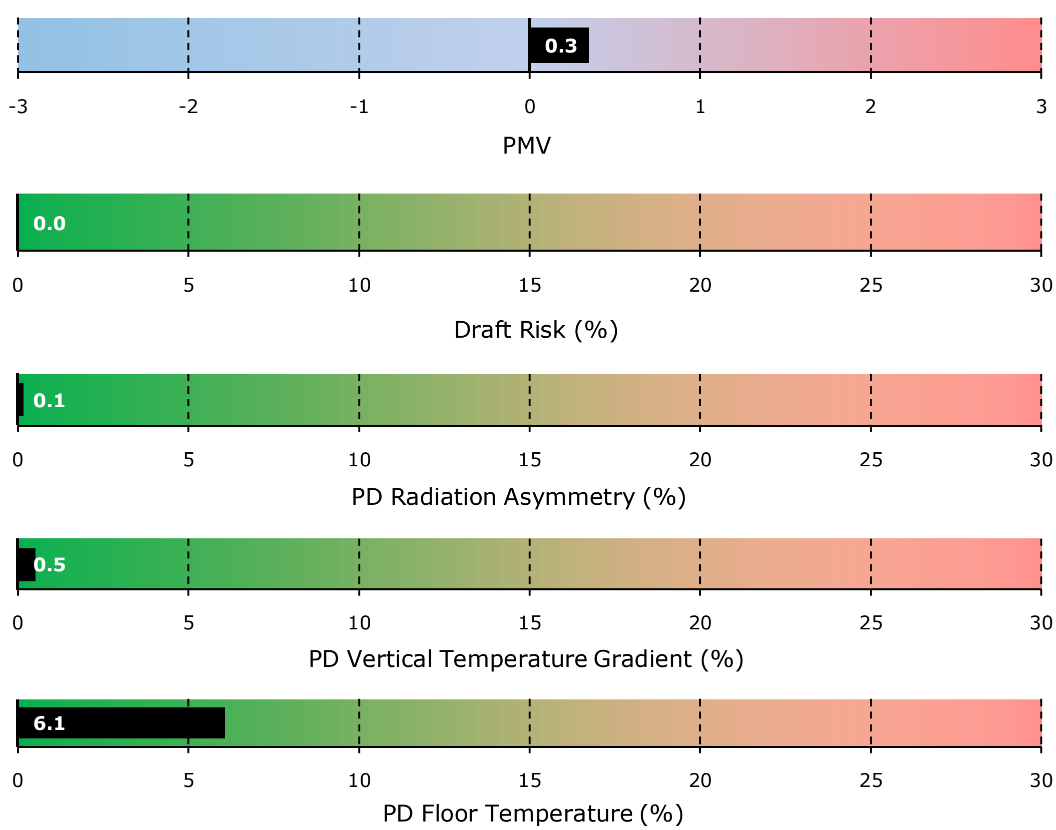
Case 7,8 and 9th are assumption taking the maximum indoor temperature of 25℃ for summer days.

7.9 CASE 7: Season- Summer - Time: 9am

- Solar radiation: 1.91kW/m²
- Air Humidity = 50%
- Outdoor Temperature: 28.6℃
- Indoor Temperature = 25.5℃
- U-Value of wall = 2.22 W/m²-K
- U-Value of window = 5.8 W/m²-K
- Volume of supply air = 182 m³
- Wall Temperature = u/α(T1 – T2)+ T2 = 2.22/8.3 (28.6 – 25.5) + 25.5 = 26.32℃
- Window Temperature = u/α(T1 – T2)+ T2 = 5.8/8.3 (28.6 – 25.5) + 25.5 = 27.67 ℃

Where, u= U-Value, α = 8.3 (constant) ,T1 = outdoor temperature, T2 = indoor temperature

Thermal comfort readings:

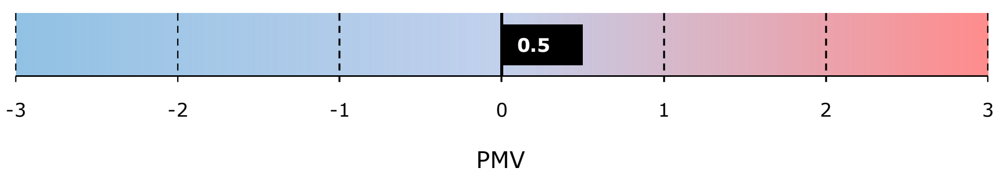


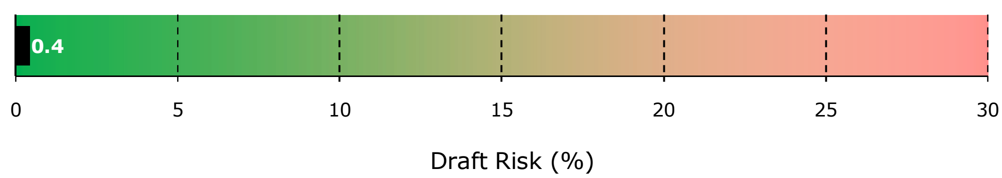
7.10 CASE 8: Season - Summer - Time: 13hours

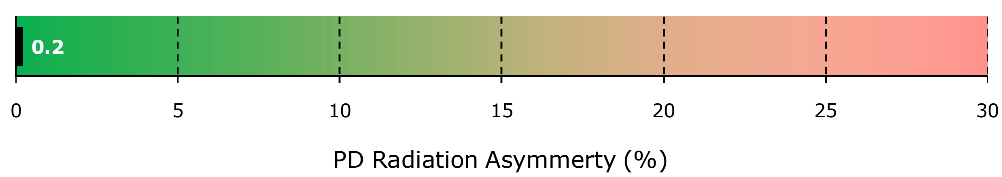
- Solar radiation: 1.075 kW/m²
- Air Humidity = 50%
- Outdoor Temperature: 35.3℃
- Indoor Temperature = 25.5℃
- U-Value of wall = 2.22 W/m²-K
- U-Value of window = 5.8 W/m²-K
- Volume of supply air = 182 m³
- Wall Temperature = u/α(T1 – T2)+ T2 = 2.22/8.3 (35.3 – 25.5) + 25.5 = 28.12℃
- Window Temperature = u/α(T1 – T2)+ T2 = 5.8/8.3 (35.3 – 25.5) + 25.5 = 32.35℃

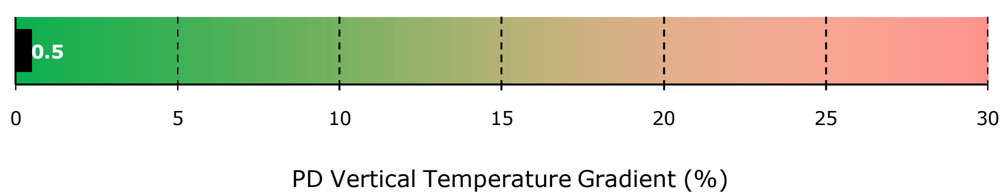
Where, u= U-Value, α = 8.3 (constant), T1 = outdoor temperature, T2 = indoor temperature

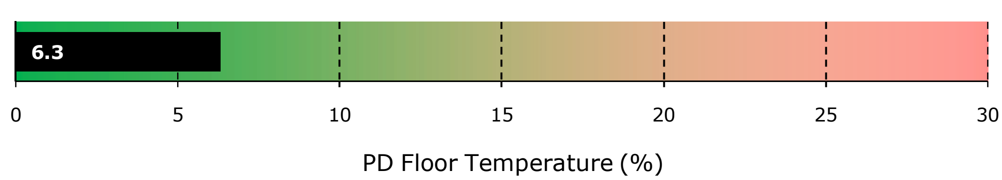
Thermal comfort readings:









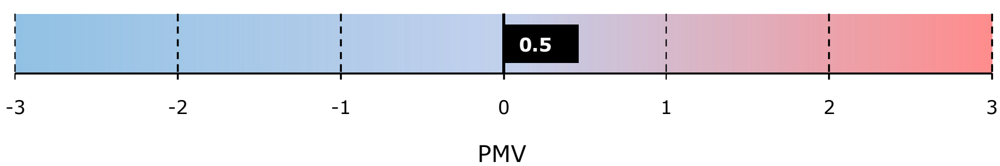


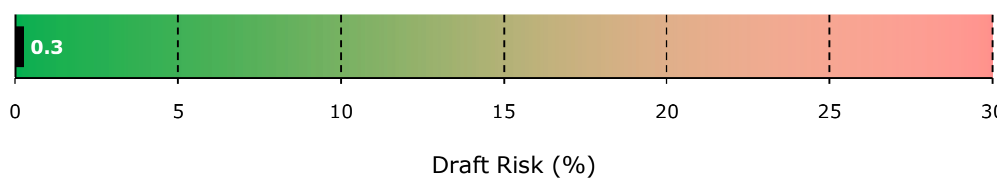
7.11 CASE 9: Season - Summer - Time: 18hours

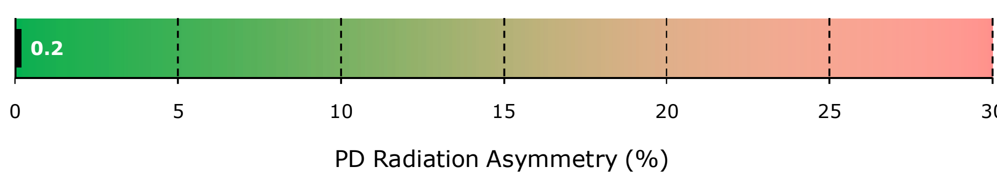
- Solar radiation: 1.075 kW/m^2
- Air Humidity = 50%
- Outdoor Temperature: 32.4°C
- Indoor Temperature = 25.5°C
- U-Value of wall = 2.22 W/m^2-K
- U-Value of window = 5.8 W/m^2-K
- Volume of supply air = 182 m^3
- Wall Temperature = u/α(T1 – T2)+ T2 = 2.22/8.3 (32.4 – 25.5) + 25.5 = 27.24°C
- Window Temperature = u/α(T1 – T2)+ T2 = 5.8/8.3 (32.4 – 25.5) + 25.5 = 30.32 °C

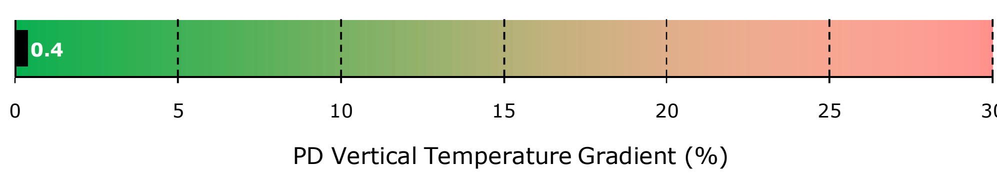
Where, u= U-Value, α = 8.3 (constant), T1 = outdoor temperature , T2 = indoor temperature

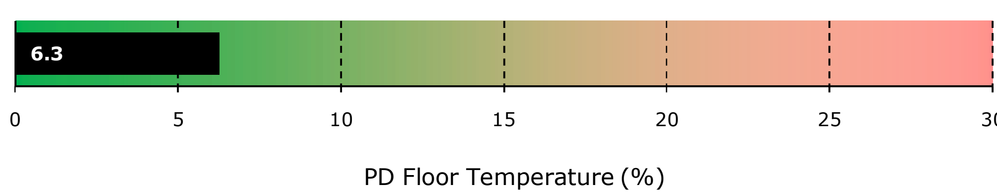
Thermal comfort readings:









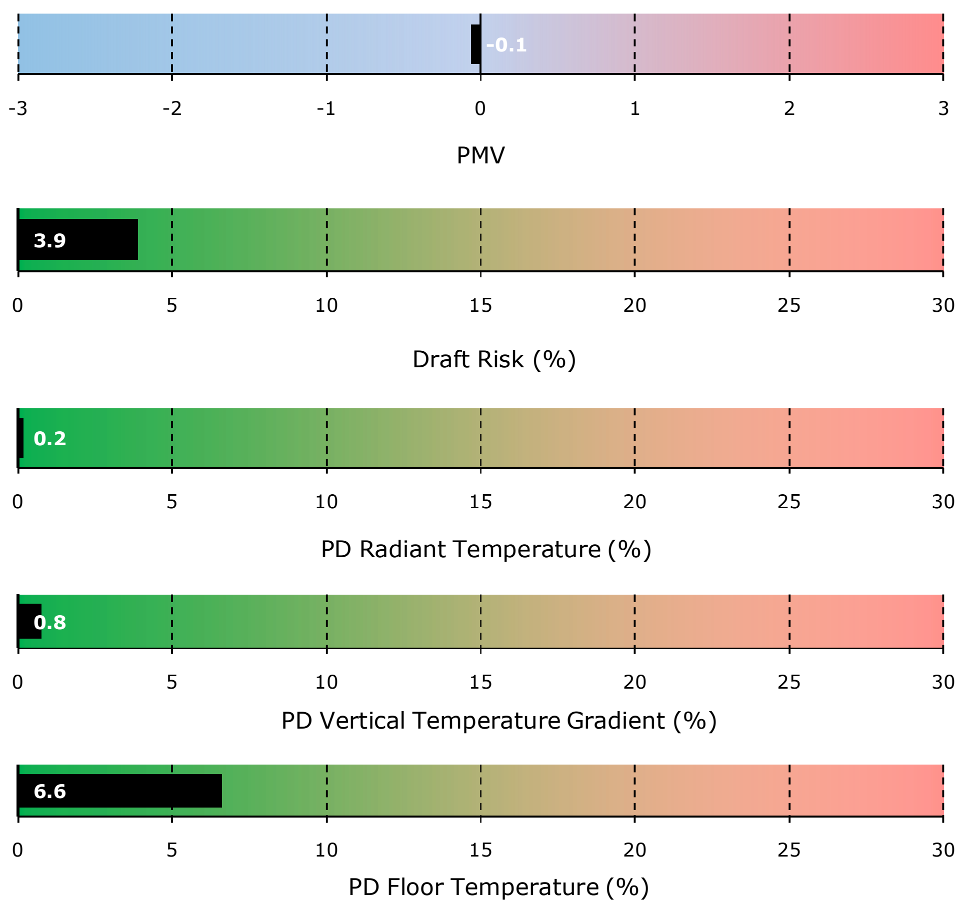


7.12 CASE 10: Season - Winter - Time: 9am

- Solar radiation: 2.395 kW/m²
- Air Humidity = 50%
- Outdoor Temperature: 19.1℃
- Indoor Temperature = 19℃
- U-Value of wall = 2.22 W/m²-K
- U-Value of window = 5.8 W/m²-K
- Volume of supply air = 182 m³
- Wall Temperature = u/α(T1 – T2)+ T2 = 2.22/8.3 (19.1 – 19) + 19 = 19.03℃
- Window Temperature = u/α(T1 – T2)+ T2 = 5.8/8.3 (19.1 – 19) + 19 = 19.07℃

Where, u= U-Value, α = 8.3 (constant), T1 = outdoor temperature, T2 = indoor temperature

Thermal comfort readings:



7.13 CASE 11: Season - Winter - Time: 13hours

- Solar radiation: 2.066 kW/m² - Air Humidity = 50%

- Outdoor Temperature: 28℃ - Indoor Temperature = 19℃

- U-Value of wall = 2.22 W/m²-K - U-Value of window = 5.8 W/m²-K

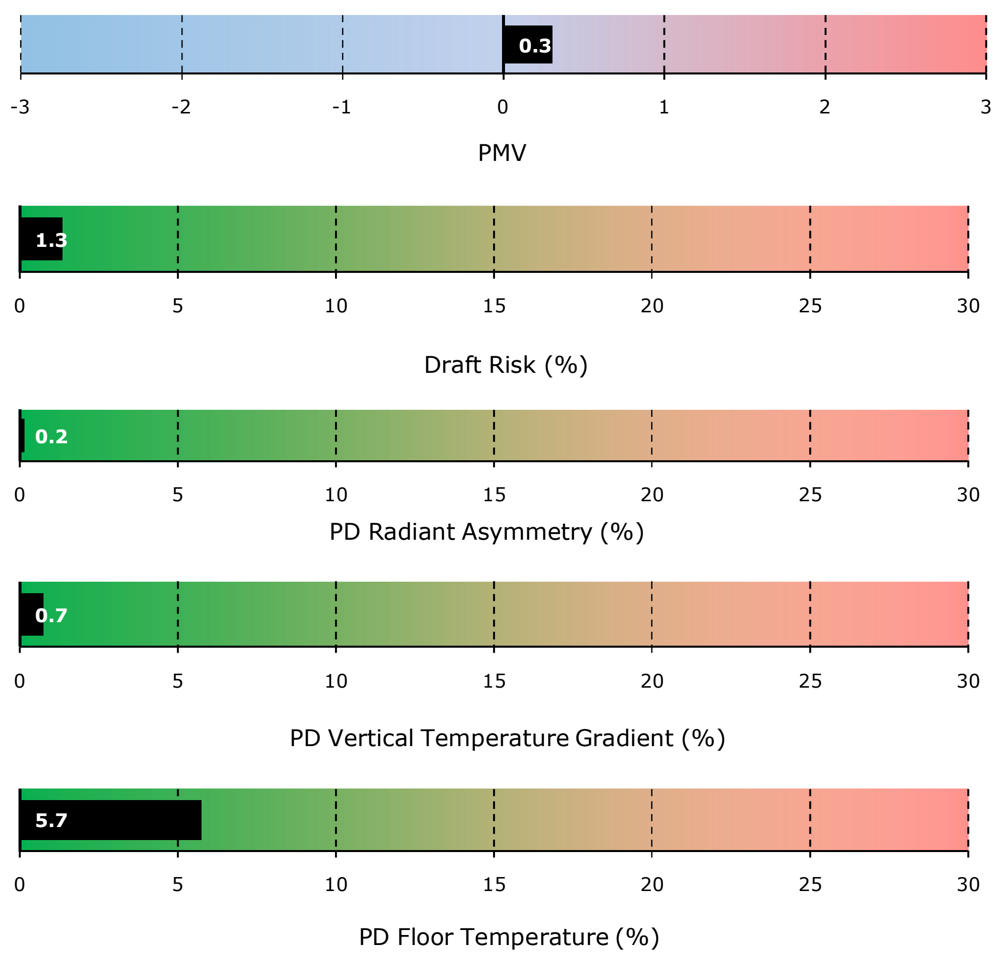
- Volume of supply air = 182 m³

- Wall Temperature = u/α(T1 – T2)+ T2 = 2.22/8.3 (28 – 19) + 19 = 21.40℃

- Window Temperature = u/α(T1 – T2)+ T2 = 5.8/8.3 (28 – 19) + 19 = 25.29℃

Where, u= U-Value, α = 8.3 (constant), T1 = outdoor temperature, T2 = indoor temperature

__Thermal comfort readings:__

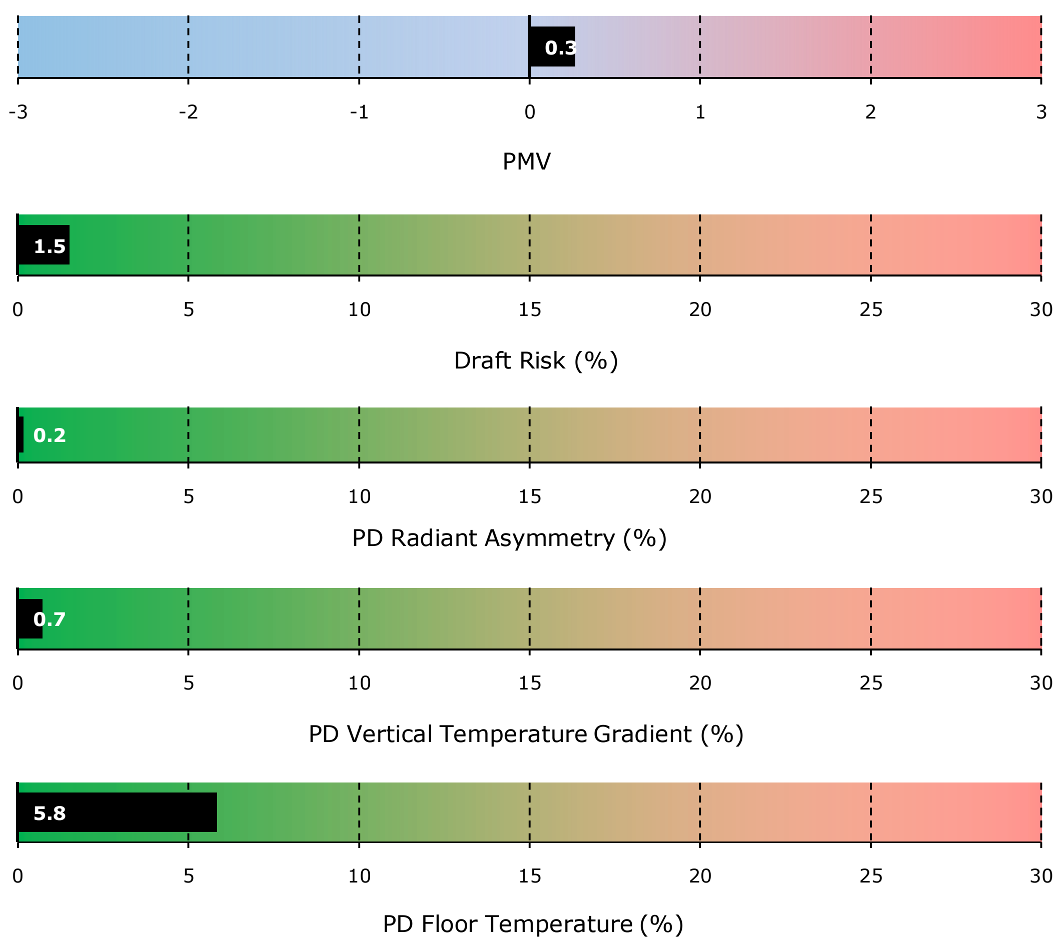


7.14 CASE 12:Season - Winter - Time: 18hours

- Solar radiation: 0.03kW/m²
- Air Humidity = 50%
- Outdoor Temperature: 26.1℃
- Indoor Temperature = 19℃
- U-Value of wall = 2.22 W/m²-K
- U-Value of window = 5.8 W/m²-K
- Volume of supply air = 182 m³
- Wall Temperature = u/α(T1 – T2)+ T2 = 2.22/8.3 (26.1 –19) + 19 = 20.90℃
- Window Temperature = u/α(T1 – T2)+ T2 = 5.8/8.3 (26.1 –19) + 19 = 23.96℃

Where, u= U-Value, α = 8.3 (constant), T1 = outdoor temperature, T2 = indoor temperature

Thermal comfort readings:



CHAPTER 8– EXPERIMANTAL CONCLUSIONS

The thermal comfort analysis was carried out by choosing the temperature as a variable. The humidity was fixed at 50%.

8.1. COMPARISION OF PMVs AND OUTDOOR TEMPERATURE:

When the PMV was compared for different outdoor temperatures at different time of the day with a given indoor temperature, the following readings was observed.
For summer time at 9am, 1pm and 6pm, the PMV measured at 22℃ and 25℃ were as follows:

Table 14: Results of PMV for summer

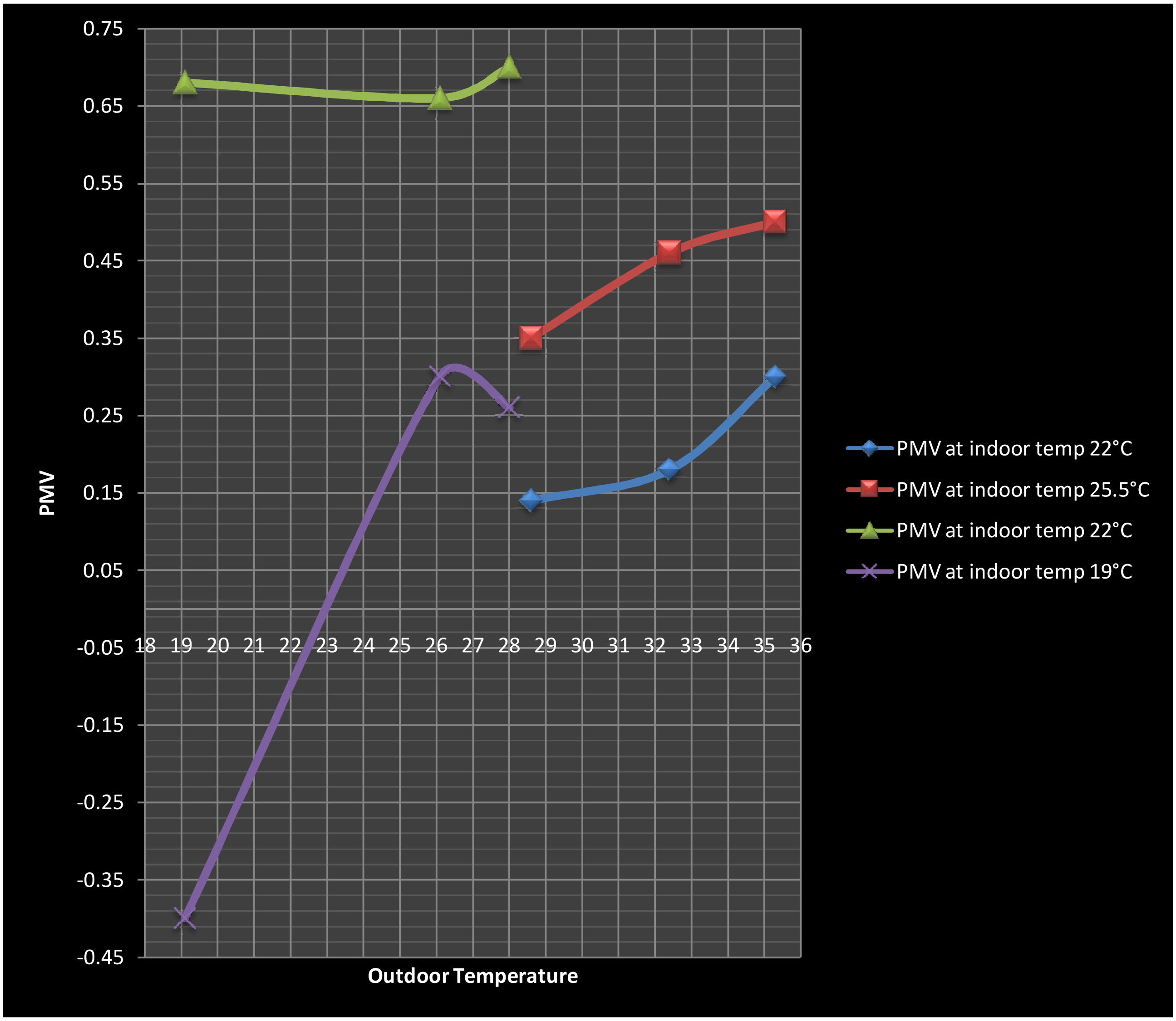
Outdoor Temperature (℃)	PMV at indoor temp 22℃	PMV at indoor temp 25.5℃
28.6	0.14	0.35
32.4	0.18	0.46
35.3	0.3	0.5

For winter time at 9am, 1pm and 6pm, the PMV measured at 22℃ and 19℃ were as follows:

Table 15: Results of PMV for Winter

Outdoor Temperature (℃)	PMV at indoor temp 22℃	PMV at indoor temp 19℃
19.1	0.68	-0.4
26.1	0.66	0.3
28	0.7	0.26

Graph 1: Different PMVs at 19℃ ,22℃ and 25.5℃ indoor temperatures



The PMV for winter season at temperature 19℃ and at 9am was found to be slightly uncomfortably colder. This may be due to the fact that the outdoor temperature being almost the same at 19.1℃. Similarly if the indoor temperature was raised to 22℃, thermal sensation for the occupants would be slightly warmer. This infers that for winter season, except for morning hours, the indoor temperature of 19℃ is found most suited. Raising the temperature above the outdoor temperature may help improve the thermal satisfaction during the morning hours of office.

As a result of the laboratory experiment of thermal analysis, best comfortable settlement was achieved at 22℃ temperature during summers.

8.2 COMPARISION OF HUMIDITY:

If the humidity was changed from 50% to minimum of 30% and maximum of 70%, the following observations were seen.

Table 16: PMV at varying himidities

Outdoor Temperature (℃)	PMV at indoor temp 22℃ at 50%RH	PMV at indoor temp 22℃ at 30% RH	PMV at indoor temp 22℃ at 70% RH
28.6	0.14	0	0.28
32.4	0.18	0.04	0.32
35.3	0.3	0.16	0.45

Graph 2: Different PMVs at RH of 50%, 30% and 70%

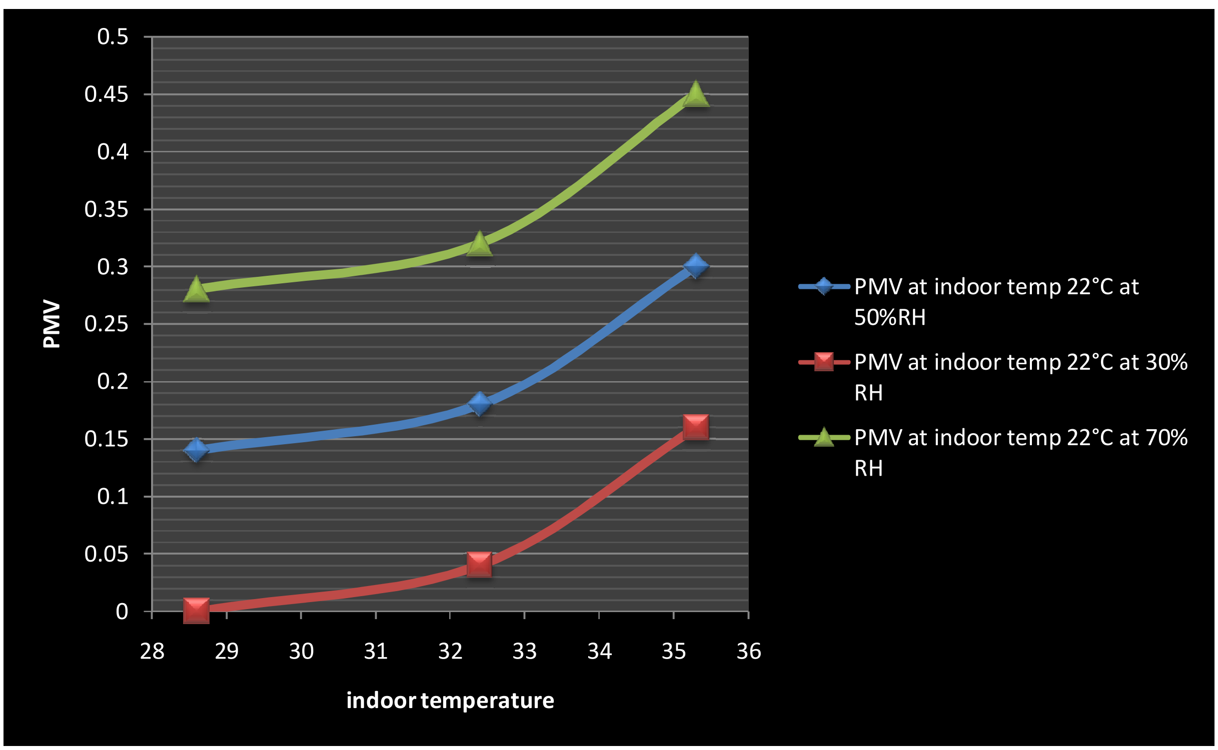


Table 17: PMV at varying himidities

Outdoor Temperature (℃)	PMV at indoor temp 25.5℃ at 50%RH	PMV at indoor temp 25.5℃ at 30% RH	PMV at indoor temp 25.5℃ at 70% RH
28.6	0.35	0.2	0.5
32.4	0.46	0.31	0.61
35.3	0.5	0.35	0.65

Graph 3: Different PMVs at RH of 50%, 30% and 70%

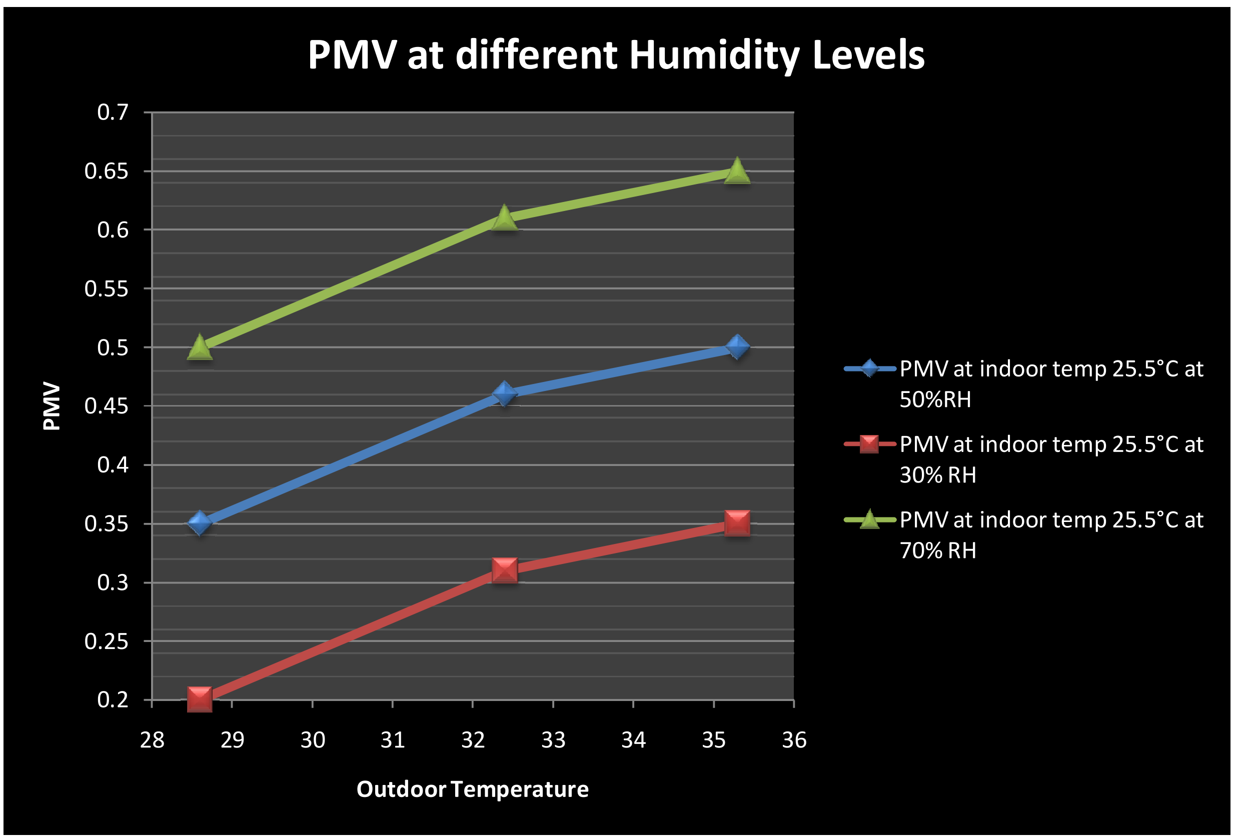


Table 18: PMV at varying himidities

Outdoor Temperature (°C	PMV at indoor ten 22°C at 50%RH	PMV at indoor ten 22°C at 30% RH	PMV at indoor ten 22°C at 70% RH
19.1	0.68	0.54	0.81
26.1	0.66	0.52	0.79
28	0.7	0.57	0.84

Graph 4: Different PMVs at RH of 50%, 30% and 70%

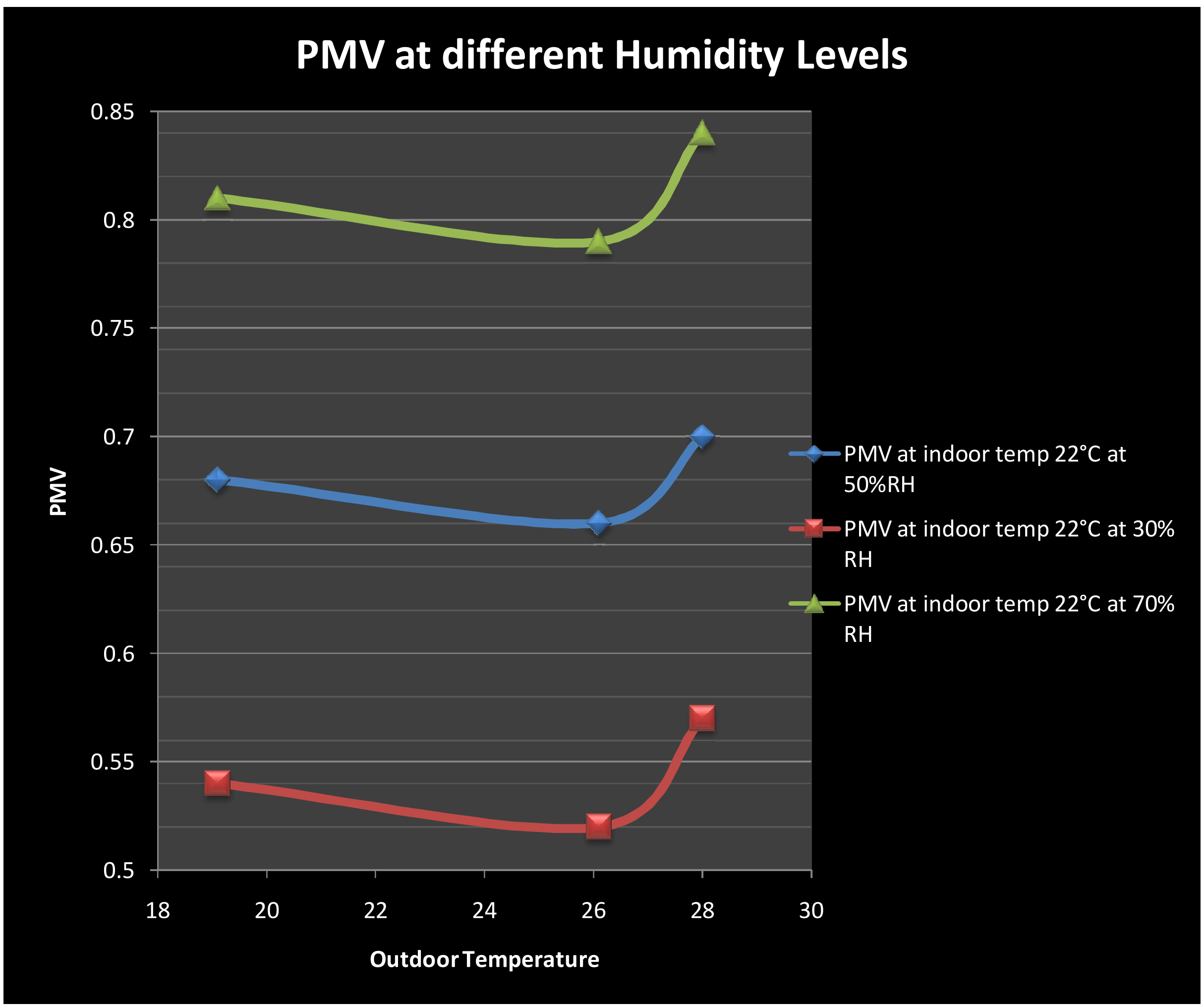
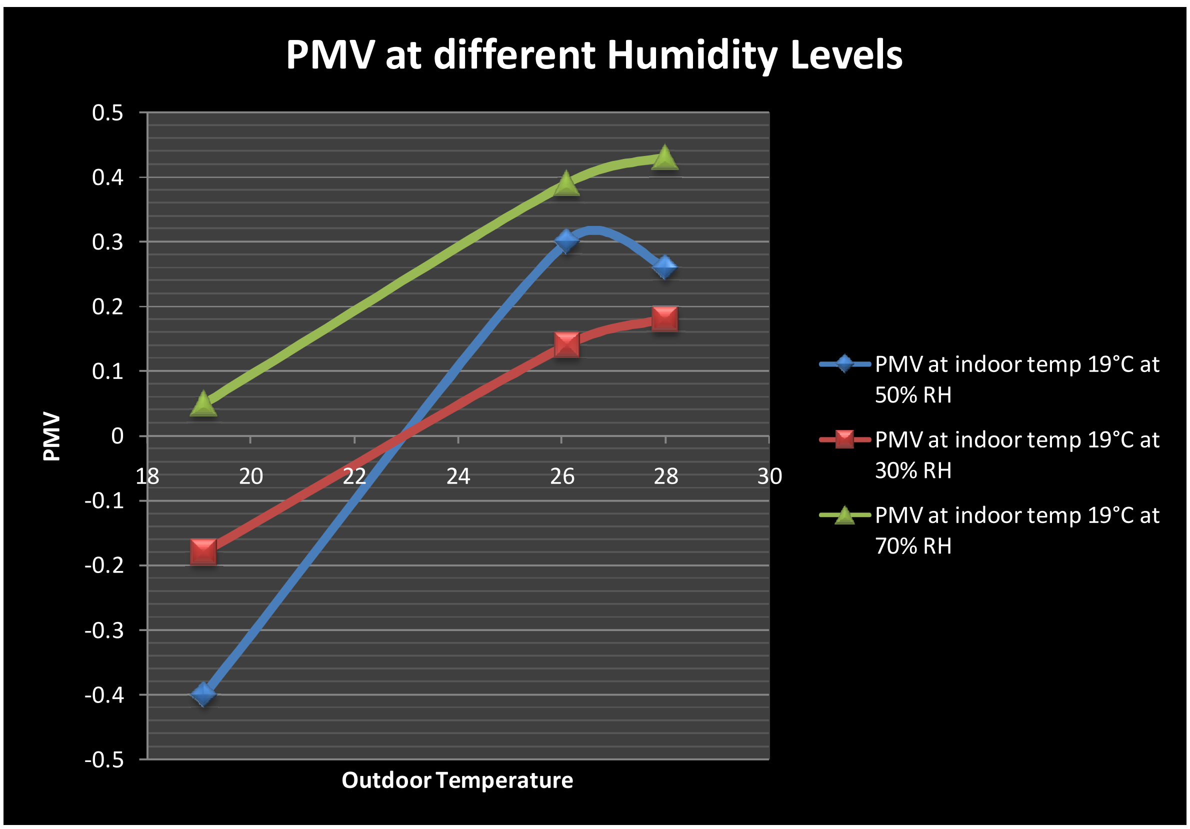


Table 19: PMV at varying himidities

Outdoor Temperature (°C	**PMV at indoor ten 19°C at 50% RH**	**PMV at indoor ten 19°C at 30% RH**	**PMV at indoor ten 19°C at 70% RH**
19.1	**-0.4**	**-0.18**	**0.05**
26.1	**0.3**	**0.14**	**0.39**
28	**0.26**	**0.18**	**0.43**

Graph 5: Different PMVs at RH of 50%, 30% and 70%



Grpah 6

From the above observations, this can be concluded that at a humidity of 30%, the PMV recorded is best; therefore the ideal thermal comfort can be achieved when the humidity is 30% RH.

8.3 COMPARISION OF AIR SPEED:

At fixed temperature of 22℃ and 25℃, and humidity of 50%, if the air velocity was changed from 0.05m/s , 0.10m/s and 0.15m/s; the following observations were of PMV and PPD were studied.

Table:20: Summer (indoor temp at 22°C) and humidi
50%RH

	9am at 28.6°C			6pm at 32.4°C			1pm at 35.3°C		
air velocity m	**PMV**	**PPD**	**DR**	**PMV**	**PPD**	**DR**	**PMV**	**PPD**	**DR**
0.05	0.14	6.0%	1.1%	0.18	6.0%	0.4%	0.30	8.0%	0.4%
0.1	0.10	5.0%	5.4%	0.14	6.0%	5.5%	0.26	7.0%	5.2%
0.15	-0.04	5.0%	9.1%	0	6.0%	9.2%	-0.04	6.0%	9.1%

Table 21: Summer (indoor temp at 25.5°C) and humidi
50%RH

	9am at 28.6°C			6pm at 32.4℃			1pm at 35.3℃		
air velocity m	**PMV**	**PPD**	**DR**	**PMV**	**PPD**	**DR**	**PMV**	**PPD**	**DR**
0.05	0.35	8.0%	0%	0.46+	11.0%	0.3%	0.50	13.0%	0.4%
0.1	0.29	7.0%	5%	0.41	10.0%	4.9%	0.45	11.0%	4.7%
0.15	0.17	6.0%	6%	0.28	7.0%	8.4%	0.32	8.0%	7.8%

8.4 CONCLUSION:

The result concluded was that:

1. Increase in indoor air speed may help the PMV to be better but the draft risk increases significantly.
2. Also, change in humidity to 30% RH and 70% RH did not change the draft risk. It only brought about change in PMV values. Hence, Draft Risk (DR) affected by air velocity and not much in regard to humidity. Controlling air velocity can significantly control thermal discomfort.
3. Individual control of the thermal environment or individual adaptation will increase the level of thermal comfort acceptance.
4. According to the results, best comfortable conditions for offices are achieved by room temperature at approx. 22℃ and at low air velocity of 0.05 m/s. High air temperatures, humidity and air velocities disturb the thermal comfort substantially.

Annexure

The questionnaire establised on the Indoor Environmental Quality (IEQ) survey questionnaire from the Centre of the Built Environment (CBE) at the University of California, Berkeley.

1. Building Name and Location *

2. Gender *
   - ☐ Female
   - ☐ Male

3. Age *
   - ☐ less than 30
   - ☐ 30-35
   - ☐ more than 35

4. How many years have you worked in this building?
   - ☐ less than a year
   - ☐ 1-3 years
   - ☐ more than 3years

5. How long have you been working at your present workspace / office cabin?
   - ☐ Less than 6 months
   - ☐ 6-12 months
   - ☐ More than 1 year

6. On an usual working day,how many hours do you spend in your workspace?
   - ☐ less than 6 hours
   - ☐ 6-9 hours
   - ☐ more than 9 hours

7. On which floor is your workspace located?

   [ ]

8. Which area of the building is your workspace located?
   - ☐ North
   - ☐ East
   - ☐ South
   - ☐ West

9. Exact location of workplace

☐ within 15 feet of an exterior wall
☐ within 15 feet of a window
☐ centre of the room
☐ Other: [ ]

10. Which of the following best describes your personal workspace?
    - ☐ Enclosed office, private
    - ☐ Enclosed office, shared with other people
    - ☐ Cubicles with high partitions (about five or more feet high)
    - ☐ Cubicles with low partitions (lower than five feet high)
    - ☐ Workspace in open office with no partitions (just desks)
    - ☐ Other: [ ]

11. Rate the following: visual privacy

	1	2	3	4	5	
not satisfied	☐	☐	☐	☐	☐	very satisfied

12. Rate the following : Amount of space available

	1	2	3	4	5	
not satisfied	☐	☐	☐	☐	☐	very satisfied

13. Rate the following : temperature / thermal comfort

	1	2	3	4	5	
not satisfied	☐	☐	☐	☐	☐	very satisfied

14. Rate the following : How satisfied are you with the comfort of your office furnishings (chair, desk, computer, equipment, etc.)?

	1	2	3	4	5	
not satisfied	☐	☐	☐	☐	☐	very satisfied

15. Rate the following : the office layout

	1	2	3	4	5	
not satisfied	☐	☐	☐	☐	☐	very satisfied

16. Rate the following : air quality

	1	2	3	4	5	
not satisfied	☐	☐	☐	☐	☐	very satisfied

17. If you are dissatisfied with the air quality in your work area, is it:

- ☐ Stuffy / stale
- ☐ Odourous due to furnishings (carpet, furniture)
- ☐ tobacco smoke
- ☐ photocopiers / printers
- ☐ Other: ______

18. Which of the following do you personally adjust or control in your workspace? (check all that apply)

- ☐ Window blinds or shades
- ☐ Operable window
- ☐ Room air-conditioning unit
- ☐ Ceiling fan
- ☐ Door to interior space
- ☐ Door to exterior space
- ☐ None of the above

19. If you experience thermal discomfort (temperature and humidity), which of the following best describes it?

- ☐ Morning
- ☐ Afternoon
- ☐ Weekends
- ☐ Monday Mornings
- ☐ Always ☐ [ ]

20. If you experience thermal discomfort (temperature and humidity), which of the following best describes it?

- ☐ Too much/ too little air movement
- ☐ Incoming sunlight heats up space
- ☐ Heat from office equipment
- ☐ Drafty windows
- ☐ Vented air is too hot
- ☐ Vented air is too cold
- ☐ My workspace is hotter than other areas
- ☐ My workspace is colder than other areas
- ☐ Hot floors and walls
- ☐ Cold floors and walls
- ☐ Thermostat is inaccessible/ controlled by others
- ☐ Other: [ ]

21. How satisfied are you with your personal workspace?

	1	2	3	4	5	
not satisfied	☐	☐	☐	☐	☐	very satisfied

22. Any additional comments or recommendations about your personal workspace or building overall?

REFERENCES

- **INTERNET SOURCES:**

1. nceub.org.uk
2. dt.fme.vutbr.cz
3. mnes.nic.in
4. www.feta.co.uk
5. www.inive.org
6. www.healthyheating.com
7. ntm.ru
8. en.wikipedia.org
9. www.hse.gov.uk
10. atmos.es.mq.edu.au
11. www.cres.gr
12. ashrae.org
13. shop.iccsafe.org
14. www.cfdc.tu-sofia.bg
15. ecosmart.ca
16. www.designingbuildings.co.uk
17. www.ashrae.org.sg
18. www.asiepi.eu
19. worksafe.act.gov.au
20. www.caerdydd.ac.uk ashraerp.com
21. brentdurken.com
22. www.perfectdrugrx.com
23. www4.nau.edu
24. www.midcindia.org
25. www.esru.strath.ac.uk
26. www.askfinancials.com
27. www.pdhengineer.com
28. www.mymeter.cn
29. www.izes.de
30. gsa.gov

31. hfetag.dtic.mil
32. www.integrateddesign.eu
33. www.cham.co.uk
34. www.thefreelibrary.com
35. www.teknologiateollisuus.fi
36. blogs.healthyheating.com
37. www.ohlearning.com
38. ddr667.tym.cz
39. www.nrel.gov
40. www.labeee.ufsc.br
41. www.energentis.com
42. slb.cf.ac.uk
43. www.punecorporation.org
44. www.eu-ray.com
45. webstore.ansi.org
46. www.pune-info.in
47. www.ashraerp.com
48. sensirion.zynex.ch
49. ceae.colorado.edu
50. ib.cvut.cz
51. leed.gowebdog.com
52. www.bwk.tue.nl
53. www.nascoinc.com
54. www.engg.ksu.edu
55. cache.deltaohmeurope.com

REFERENCES

- **PUBLICATIONS**

1. Wan, J.W.. "A new method of determination of indoor temperature and relative humidity with consideration of human thermal comfort", Building and Environment, 200902
2. Chaiyapinunt, S.. "Performance rating of glass windows and glass windows with films in aspect of thermal comfort and heat transmission", Energy & Buildings, 200507
3. Cooper, I.. "Comfort theory and practice: Barriers to the conservation of energy by building occupants", Applied Energy, 198208
4. Parsons, Ken. "Ergonomics assessment of thermal environments", Evaluation of Human Work 3rd Edition, 2005.
5. Parsons, . "International Standards", Human Thermal Environments, 2014.
6. JuYoun Kwon. "The relationship between environmental temperature and clothing insulation across a year", International Journal of Biometeorology, 09/20/2011
7. Fabbri, Kristian. "Thermal comfort evaluation in kindergarten: PMV and PPD measurement through datalogger and questionnaire", Building and Environment, 2013.
8. Kenneth Parsons. "International heat stress standards: a review", Ergonomics, 1995
9. Noh, K.-C.. "Thermal comfort and indoor air quality in the lecture room with 4-way cassette air-conditioner and mixing ventilation system", Building and Environment, 200702
10. B OLESEN. "Target levels", Industrial Ventilation Design Guidebook, 2001
11. Olesen, B.W.. "Introduction to thermal comfort standards and to the proposed new version of EN ISO 7730", Energy & Buildings, 200207
12. Olesen, B.W.. "International standards and the ergonomics of the thermal environment", Applied Ergonomics, 199508

13. José A. Orosa. "Indoor Air Standards and Models", Green Energy and Technology, 2012
14. Journal of Facilities Management, Volume 6, Issue 1 (2008-03-09)
15. T. Murata. "Fuzzy-timing Petri net model of temperature control for car air conditioning system", IEEE SMC 99 Conference Proceedings 1999 IEEE International Conference on Systems Man and Cybernetics (Cat No 99CH37028) ICSMC-99, 1999
16. Pathak, N.. "Effects of mould filling on evolution of the solid-liquid interface during solidification",Applied Thermal Engineering, 200912
17. Olesen, B.W.. "The philosophy behind EN15251: Indoor environmental criteria for design and calculation of energy performance of buildings", Energy & Buildings, 200707
18. Teli, Despoina, Mark F. Jentsch, and Patrick A.B. James. "Naturally ventilated classrooms: An assessment of existing comfort models for predicting the thermal sensation and preference of primary school children", Energy and Buildings, 2012.
19. Rabadi, N. J.. "Developing a Software to Predict Thermal Comfort of Humans at Work", Jordan Journal of Mechanical & Industrial Engineering, 2011.
20. Herrero Martin, R.. "Thermal comfort analysis of a low temperature waste energy recovery system: SIECHP", Energy & Buildings, 2008
21. Ahmad, Aftab, Shafiqur Rehman, and Luai M. Al-Hadhrami. "Performance evaluation of an indirect evaporative cooler under controlled environmental conditions", Energy and Buildings, 2013.
22. Chow, W.K.. "Overall thermal transfer values for building envelopes in Hong Kong", Applied Energy, 1992
23. Wei Yang. "Air movement preferences observed in naturally ventilated buildings in humid subtropical climate zone in China", International Journal of Biometeorology, 07/19/2009
24. Yau, Y. H., and B. T. Chew. "A review on predicted mean vote and adaptive thermal comfort models", Building Services Engineering Research and Technology, 2012.

25. Parson, . "International Standards", Human Thermal Environments The Effects of Hot Moderate and Cold Environments on Human Health Comfort and Performance Second Edition, 2002.
26. Herrero Martin, R.. "Thermal comfort analysis of a low temperature waste energy recovery system: SIECHP", Energy & Buildings, 2008
27. Teli, Despoina, Mark F. Jentsch, and Patrick A.B. James. "Naturally ventilated classrooms: An assessment of existing comfort models for predicting the thermal sensation and preference of primary school children", Energy and Buildings, 2012.
28. T. Murata. "Fuzzy-timing Petri net model of temperature control for car air conditioning system", IEEE SMC 99 Conference Proceedings 1999 IEEE International Conference on Systems Man and Cybernetics (Cat No 99CH37028) ICSMC-99, 1999