Thermal Comfort Analysis of Buildings with Emphasis on Roof Types

A thesis submitted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

by

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THESIS CERTIFICATE

This is to certify that the work contained in the thesis entitled **Thermal Comfort Analysis of Buildings with Emphasis on Roof Types** by **Gangadhara Kiran Kumar L**, a student of the Department of Mechanical Engineering, Indian Institute of Technology Guwahati, for the award of the degree of **Doctor of Philosophy** has been carried out under my supervision and that this work has not been submitted elsewhere for any degree.

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ABSTRACT

Energy consumption in Indian buildings is expected to increase substantially due to economic growth, rapid growth in the construction sector and improvement in the living standard of the people. The demand for energy to operate the appliances such as televisions, air-conditioning and heating units, refrigerators, fans, etc. will increase substantially as the living standard rise in India. Also the growth in commercial sector and the shift from rural to urban living will continue to take place. This will also result in a substantial increase in energy demand from the buildings sector alone. Therefore, concerted efforts need to be taken for bring down the energy consumption by buildings through various measures.

Reducing operating energy significantly through use of passive and active technologies even if it leads to a slight increase in embodied energy can reduce life cycle energy demand for building. However, an excessive use of passive and active features in a building may be counterproductive. To implement the energy efficient technologies in existing buildings, one has to know about its thermal comfort conditions. It shows the need for thermal comfort studies to understand the comfort levels in existing buildings. Judicial use of passive techniques for providing thermal comfort to residents demands the need of thermal comfort standards. Thermal comfort standards in naturally ventilated buildings depend on several factors like, psychological, physiological and adaptive nature of residents. Further, it also depends on the climatic zone in which building is located.

Kozhikode district of Kerala, in warm-humid climatic zone, was considered for conducting detailed thermal comfort analysis of existing buildings. Three types of buildings were selected namely Asbestos cement roofed (ACR) house, Reinforced cement concrete (RCC) roofed house and Traditional mud tile (TMT) roofed house for quantitative analysis. Dwellings considered for the study were hostel rooms in National Institute of Technology (NIT) Calicut. To understand the effect of roofing on thermal performance of dwellings, study was carried out on rooms, which are similar in all construction features except roofing. Detailed thermal performance analysis of ACR dwelling was carried out during the end of summer season and onset of rainy season for the period of 15 days. Out of 15 days, analysis of first 3 days was during summer with near zero ventilation, next 2 days was during summer with night ventilation, next 4 days was during summer with ventilation, next 3 days was during rainy season with ventilation and last 4 days was during rainy season with near zero ventilation. Later similar studies were carried out on both RCC roofed dwelling and TMT roofed dwelling during summer with near zero ventilation conditions. Results obtained from the quantitative analysis shows that most of the time, inside temperatures of the RCC building are above the ambient and reached to a maximum of 40°C which is 4°C more than ambient. At the same time TMT roofing maintained the inside temperatures well below the ambient at peak time and reached a maximum of 33.6°C which is 2.4°C less than ambient. In case of quantitative analysis, the difference observed in inside temperatures of RCC roofed residential buildings when compared to TMT and ACR houses are huge and reached to a maximum of 7.5°C and 4°C respectively. This study highlighted the role of roof in providing thermal comfort in dwellings. Quantitative analysis showed that under non-ventilated conditions, TMT roofed room performed better than that of other types where as the performance of RCC roofed room and ACR room were comparable.

Reduced scale models of a prototype of typical living room of a residential building with dimensions 3 m x 3 m x 3 m have been designed. Five identical reduced scale models were fabricated with different roofing materials, which are commonly used in southern India viz., Reinforced Cement Concrete (RCC) block, Mud tile, Corrugated asbestos cement sheet, Metal deck and Flat asbestos cement sheet. Models were fabricated in such a way that only roof was exposed to sunlight. All the joints of models were sealed to maintain zero ventilation conditions. Experiments were carried out over fifteen days under sunlight to predict the thermal performance of each roof. Comparative analysis indicated that RCC roof was better than other roofs. Later, similar experiments were conducted with the help of an artificial heating arrangement and identified the input parameters for each type of roofing to replicate the experiments under sunlight. By utilizing the identified input parameters, a comparative study has been performed between RCC roof model and ventilated flat asbestos cement roof model. Results showed that optimum air gap between main roof and false roof for roof ventilated model is 6 cm. Comparative analysis between RCC roofed model and ventilated roof model showed that better indoor condition than that of RCC roofed model is possible by providing suitable roof ventilation technique. Reduced scale model study upheld the results obtained from quantitative analysis.

Residential buildings were considered for subjective analysis in Kozhikode district, Kerala, India. Rooms with Traditional Mud Tile (TMT) roofing, Reinforced Cement Concrete (RCC) roofing and Asbestos cement roofing (ACR) were considered for subjective analysis. A total of 936 subjects were participated in survey, in which 402 subjects from TMT roofed residential buildings, 406 subjects from modern RCC roofed residential buildings and remaining 128 subjects were from ACR buildings. Thermal Sensation Vote (TSV) based on ASHRAE seven-point scale was collected for identifying the perception of occupants on thermal comfort of their dwellings. Subjective analysis was carried out in all three seasons namely, summer, monsoon and winter. Majority of subjects felt comfortable in both winter and monsoon irrespective of whether the roof was traditional or modern. In this study, rooms were selected in such a way that they were almost similar in all aspects except roofing. Based on subjective analysis, it has been found that residential buildings with TMT roofing were faring better in providing thermal comfort than that of ACR and RCC roofed buildings during summer. The percentage of satisfied residents were 41% and 34% in case of RCC roofed dwelling and ACR dwelling, at the same time mud tile roofed dwelling able to provide satisfaction to more than 52% subjects. Performance of RCC roofed dwellings was slightly better than ACR dwellings. Results obtained from subjective analysis indicated that, for the climatic conditions of Kerala, ventilation was playing major role in providing thermal comfort. At the same time the effect of roof on thermal comfort is negated by the effect of ventilation and adaptive nature of subjects. Subjective analysis upholds the adaptive thermal comfort theory, which suggests that thermal comfort not only depends on temperature, humidity etc. but also on factors like physiological, psychological and behavioral adaptations.

Thermal comfort study was carried out in differently roofed hostels in National Institute of Technology Calicut, Kerala, which is located in warm humid climatic zone of India. Measurements of ambient temperature, globe temperature, relative humidity and air velocity were carried out in eight hostels, and in parallel a paper based survey was conducted among students to know about their Thermal Preference Vote (TPV) and Thermal Sensation Vote (TSV) based on ASHRAE seven point scale. Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) have been evaluated based on Fanger's theory of thermal comfort by utilizing the field measurements. Preferred operative temperature, neutral effective temperature and neutral humid operative temperature were obtained based on the Predicted Mean Vote (PMV). Similarly the preferred operative temperature neutral effective temperature and neutral humid operative temperature were identified for both Thermal Sensation Vote (TSV) and Thermal Preference Vote (TPV). Thermal comfort conditions for 80% satisfaction were also determined in each case. A correlation between the Predicted Mean Vote (PMV) and the Thermal Sensation Vote (TSV), as well as between the Predicted Mean Vote (PMV) and the Thermal Preference Vote (TPV) were obtained. Results indicated that PMV is over predicting the thermal comfort conditions in naturally ventilated buildings and the predicted neutral temperature is 2 to 3°C more when compared to that of TSV and TPV. A linear relationship, PMV = 0.746* TSV + 1.454 and PMV = 0.852* TPV + 1.239 were developed based on the results for obtaining Thermal Sensation Vote (TSV) and Thermal Preference Vote (TPV) respectively in terms of Predicted Mean Vote (PMV). Based on this study, thermal comfort standards for the region of Kozhikode were proposed in this thesis.

NOMENCLATURE

CLO	Clothing Insulation Level, clo (1clo = 0.155 m^2 K/W)
d	Diameter, mm
ET*	Effective Temperature, °C
L	Length, m
MET	Metabolic Rate, (1 met = 58.1 W/m^2)
P	Power, kW
RH	Relative Humidity, %
T_a	Ambient Temperature, °C
T_c	Comfort Temperature, °C
T_g	Globe Temperature, °C
T_o	Outdoor Temperature, °C
T_{oh}	Humid Operative Temperature, °C
T_{op}	Operative temperature, °C
V	Voltage, V
V_a	Air Velocity, m/s
X	Characteristic Dimension, m
ρ	Resistivity, Ω mm^2/ m

Abbreviations

ACR	Asbestos Cement Roof
ACR_F	Building F with Asbestos cement roof with ceiling
ACRNC_F	Building F with Asbestos cement roof with no ceiling
ACS	Adaptive Comfort Standard
AMV	Adaptive Mean Vote
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
AST	Attic Space Temperature
AT	Ambient Temperature
AT3	Air Temperature at 0.9 m from Roof

AT6	Air Temperature at 1.8 m from Roof
ATNR	Air Temperature Near Roof
BEE	Bureau of Energy Efficiency
CAS	Corrugated Asbestos Cement
CEN	European Committee for Standardization
CIBSE	The Chartered Institution of Building Services Engineers
ECBC	Energy Conservation Building Code
FAS	Flat Asbestos Sheet
FRT	False Roof Temperature
GIS	Galvanized Iron Sheet
LST	Living Space Temperature
MDR_G	Building G with Metal deck roof with ceiling
NBC	National Building Code
NIT	National Institute of Technology
PMV	Predicted Mean Vote
PPD	Predicted Percentage Dissatisfied
PRC_C	Building C with Pitched reinforced cement concrete roof with paved mud tiles
PRC_D	Building D with Pitched reinforced cement concrete roof with paved mud tiles
RCC	Reinforced Cement Concrete
RCC_B	Building B with Reinforced cement concrete roof
RCCC_E	Building E with Reinforced cement concrete roof covered with asbestos cement shingles
RRT	RCC Roof Temperature
SET*	Standard Effective Temperature
TMT	Traditional Mud Tile
TMT_A	Building A with Traditional mud tile roof with ceiling
TPV	Thermal Preference Vote

CONTENTS

List of Figures

List of Tables

Chapter 1

INTRODUCTION

Energy is one of the essential requirements to lead the human life comfortably. It is very difficult to survive in the present world without electricity. Basic sources for electricity generation are power plants based on hydropower, nuclear power and fossil fuels such as coal, oil and natural gas. Power produced from the renewable energy sources such as wind, biomass, solar, etc. are very small in comparison with the primary energy sources. With increase in population and living standard of the people, the demand for energy is increasing every year. Total world energy consumption has increased from 11296 Mtoe (million-ton of oil equivalent) in 2007 to 12730 Mtoe in 2013. The reserves of the fossil fuel are depleting fast and at the same time, the demand for energy has increased by nearly 1450 Mtoe within six years. Details of world energy consumption and its energy sources are provided in Table 1.1.

Moreover, the use of fossil fuels for power production causing lot of damage to environment due to the generation of harmful gases during combustion process. These harmful gases causing air pollution that resulted into several unwanted situations like global warming, ozone layer depletion, extinction of living spices etc. Drawbacks with nuclear power plants are the management of nuclear waste and the chances of release of radioactivity into atmosphere etc. Submergence of land in case of hydroelectric plants is the serious concern, which results into loss of valuable plants, living spices and environmental changes due to diversion of natural flow of water bodies. In view of the above stated problems with the use of conventional energy resources, now the focus is shifted towards the clean energy, energy conservation and energy efficient technologies.

Table 1.1: Year wise world energy consumption in million ton of oil equivalent (MPNG, 2014)

Energy source	2007	2008	2009	2010	2011	2012	2013
Oil	4018	4000	3925	4040	4085	4139	4185
Natural Gas	2647	2717	2666	2864	2914	2986	3020
Coal	3200	3256	3239	3464	3629	3724	3827
Hydro-Energy	701	728	738	782	795	834	856
Nuclear Energy	622	619	614	626	600	560	563
Renewables	108	123	142	169	206	241	280
Total	11296	11444	11313	11945	12229	12483	12730

1.1 Global Energy Scenario (MPNG, 2014)

Coal

Out of total global coal reserve, nearly 50% of global reserves are with USA, Russia and China. The percentage share of global coal reserves owned by USA, Russia and China are 25.4%, 15.9% and 11.6% respectively. It was estimated that nearly 9,84,453 million tones of proven coal reserves are available in the world. India has the reserve of nearly 8.6% of world coal reserve. It was also estimated that world coal reserves last for200 years as per current reserve to production ratio.

Oil

Nearly 23% of global oil reserves are located in Saudi Arabia. It was estimated that nearly 1147 billion barrels of proven oil reserves are available in the world. It was also estimated that world oil reserves last only for 45 years as per current reserve to production ratio.

Gas

Nearly 27% of global gas reserves are with Russia. It was estimated that nearly 176 trillion cubic meters of proven oil reserves are available in the world. It was also estimated that world gas reserves last only for 65 years as per current reserve to production ratio.

1.2 Energy Distribution Between Developed and Developing Countries

The growth in energy consumption is illustrated in Fig. 1.1, which gives the detailed picture of growth in energy consumption in developed nations and the emerging economies. Developed countries accounts for nearly 40% of the total world's energy consumption even though their population is mere 20% of world's population.

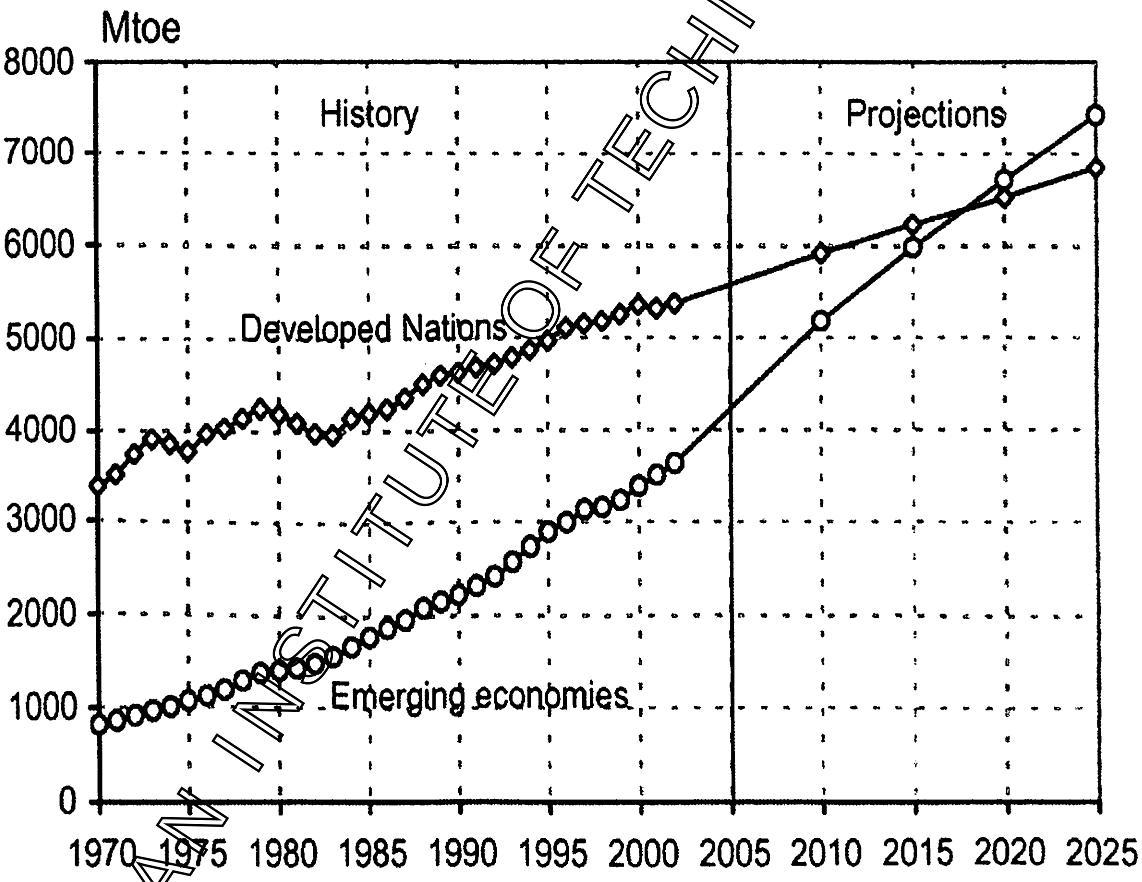

Fig. 1.1: Growth in energy consumption (Luis et al, 2008)

It means that nearly 80% of world population is consuming only 60% of available energy all over the world. It was estimated that developing countries share of energy consumption will reach to that of developed countries by 2020. High per capita energy consumption in developed countries is due to their living standards that directly depend on financial status. Low per capita energy consumption in developing economies is not only due to financial status but also due to high population density resulting into large gap between demand and supply. People in developing countries are utilizing only 0.4 to 0.5 times that of world average energy consumption per person and this value falls further and varies between 0.1 to 0.2 times when compared to that of the energy consumption per person in developed countries. Indians consumes nearly 32 times less commercial energy than that of Americans.

1.3 Energy Scenario in India (MPNG, 2014)

Coal

Coal is the major source of energy in India and it provides nearly 55% of total primary energy consumption. About 8.6% of world coal reserves are in India and estimated that these reserves may support the energy needs of India for almost 230 years at current reserve to production ratio. Production of coal is increased to 633 million tonne by 2013 from 407 million tonne in 2006. Even though India is placed at fourth position in terms of production of coal, but it failed to cater the energy needs of the country due to its huge population. Coalmines in India are located mainly in Bihar, Jharkhand, Madhya Pradesh, Maharashtra, Orissa, Telangana, Uttar Pradesh, and West Bengal.

Oil

Oil is the major source of energy in India after coal and it provides nearly 36% of total primary energy consumption. India has proven oil reserves of nearly 763 million tonne by the year 2013. Production of oil is increased by mere 4 million tonne in a span of 6 years from 34 million tonne in 2007 to 38 million tonne in 2013. At the same time, Consumption of oil is increased by 60 million tonne in a span of 6 years from 156 million tonne in 2007 to 222 million tonne in 2013. During the same period oil imports were increased from 121 to 189 million tonne. India is one of the major oil-importing nations in world and is the fourth largest oil consumer in Asia after China, Japan and Korea. Almost 70% of oil imports are from gulf countries. The major oil reserves in India are located in the Assam, Bombay High, Cambay and Godavari-Krishna basin.

Natural Gas

India has proven gas reserves of nearly 1427 billion cubic meter by the year 2013. Production of LPG from natural gas is increased by mere 0.08 million tonne in a span of 6 years from 2.09 million tonne in 2006 to 2.17 million tonne in 2011. At the same time, Production of natural gas is increased by 20 billion cubic meter in a span of 6 years from 32 billion cubic meter in 2006 to 52 billion cubic meter in 2011. Production was comedown to 35 billion cubic meter in 2013. Nearly 15% of total primary energy needs are catered by natural gas.

1.4 Energy Security

By looking into energy scenario in India, it is clear that India in not secure in terms of energy. As per the present statistics, oil production companies in India meet only 25% of crude oil requirement and remaining 75% requirement is met by imports, whereas coal production in India meet nearly 80% of the current requirement. Similar the case with natural gas where 80% of the net gas requirement is met by imports. India remains as a developing economy as long as the dependency on imported energy continues. There is a need to look for other alternatives, since the fossil fuel resources are limited in India.

Following strategies may be employed to reduce the dependency gradually:

- Reserve stock has to be increased to control price fluctuations.
- Importing oil from multiple sources to avoid dependency on single nation.
- Fuel switching technology provides opportunity to reduce single fuel dependency.
- Controlling demand by reducing subsidies on fuel.
- Developing energy efficient techniques through research and development.
- Harvesting energy through renewable energy sources.

- Sustainable development.

Even though the points mentioned above are feasible to implement, it takes some time for implementation. Renewable energy sources like solar energy, wind energy etc., are only the solution before India for sustainable development. Implementation of energy production through renewable energy sources demands huge investment and it may take decades to put into operation. Increasing fuel stock, fuel imports from different nations and fuel-switching technology only help in control the immediate impact of demand fluctuations on world market. For sustainable development, for coming two decades, there is a need to adopt energy efficiency measures to keep control on ever rising imports.

1.5 Energy Consumption in Buildings

Energy consumption pattern of the residential buildings in the developing countries like, India, and China shows that the overall energy consumption in the residential building sector of the developing countries would be much higher than that of developed countries by 2020 (Luis et al, 2008). This increase in demand is not only due to raise in living standards but also due to the population share of these countries in the world. Life cycle energy analyses of the 73 buildings across 13 countries predicted that energy use in operating phase and embodied phase of building's life cycle are 80–90% and 10–20% respectively. Energy consumption in buildings for developed countries and world are shown in Table 1.2. Sector wise energy consumption in developed countries is shown in Table 1.3.

Table1.2: Energy consumption based on building type (Luis et al, 2008)

Energy consumption (%)	Business sector	Residential sector	Total
USA	18	22	40
UK	11	28	39
EU	11	26	37
Spain	8	15	23
World	7	16	24

Table 1.3: Energy consumption based on sector (Luis et al, 2008)

Sector wise energy consumption (%)	1973	2004	Ratio
Industry	39	30	0.76
Transport	25	28	1.14
Other sectors	36	42	1.16

Lifetime energy demand varies in between 150 – 400 kWh/m^2/per year for conventional residential buildings in India (Ramesh et al, 2010). Reducing the energy consumption of the buildings through the use of either passive or active techniques, even though it results into slight increase in embodied energy, can reduce building's life cycle energy demand significantly.

1.6 Energy Efficient Buildings

The purpose of building is not only for protecting the residents from extreme environmental conditions but also to provide thermal comfort to residents. Thermal comfort may be provided in buildings either by active or by passive means. In active means, energy is utilized to drive the mechanical equipment's like air-conditioner, fan etc., for maintaining the comfort levels within the building, which increases energy consumption of buildings. In case of passive techniques, the methodology is to reduce incoming heat or cold by providing suitable insulations and to eliminate the accumulation of heat by using suitable ventilation techniques. The best results can be obtained by incorporating the passive techniques during the construction stage itself, which reduces the need of active means and thereby the reduction of energy consumption can be obtained.

1.6.1 Building Technology

India had a rich tradition in using passive techniques for maintaining thermal comfort in buildings. Before globalization, India has its own technology in building sector, evolved over a period of time based on passive techniques, to face the climatic situations of particular area. Each climatic zone in India has its unique vernacular technology in maintaining thermal comfort in buildings. Due to the influence of industrialization and market driven globalization, traditional techniques lost the race to imported technologies. Implementing the imported technologies without suitable modifications is the cause of increase in energy consumption in building sector. The best example to such an imported technology is the RCC roofing.

Most part of the India is in tropical zone, where the intensity of solar radiation is high. The roof is the part of the building, which is exposed to solar radiation during the entire day. RCC roof, which is having high thermal energy storage capacity, stores energy during daytime and releases the same during nighttime. This roof suits for cold countries, where they need heating effect during the nighttime. In contrast, India is hot country where cooling effect is needed. The result of RCC roofing is allowing heat to come in and then using active cooling techniques to maintain the thermal comfort in buildings at cost of valuable energy resources.

Already, RCC roofed buildings are most common in the cities of India and the trend of concrete buildings are still continuing and spreading towards the rural parts of India. Now people of rural India are also started constructing concrete roof dwellings. Most of the residential buildings in rural area are of single storied buildings. The maximum share of heat entering into such single storied buildings is mainly through the roof. There are several techniques like providing facades, shading devices, overhangs etc., to cut down the heat flow through walls. There is no economical technique available till now, which can cut down the heat gain through roof. It shows the need to rectify the drawbacks in RCC roofed modern buildings by incorporating suitable passive techniques, which are well established in traditional vernacular buildings.

It is possible to meet the demands of residents with minimum use of conventional energy resources by integrating the following techniques during the design stage of building itself.

- Use of passive techniques during the construction stage of buildings, which reduces the unwanted heat gain by buildings.
- Utilization of day light for illuminating living space of buildings.
- Utilization of solar energy for power generation through photovoltaics, water heating through concentrators and for other auxiliary needs of buildings.

- Use of locally available low energy materials wherever possible, which reduces the transportation cost significantly.

1.6.2 Government Initiatives

Seventy percent of India's total population resides in rural India. Before 20th century, majority of houses in rural India were of thatched houses due to socio-economical conditions. Due to several drawbacks of thatched houses like regular replacement of thatched roof, chances of fire accidents etc., Government of India discouraged thatched houses and promoted other low cost houses with several housing schemes like Indira Awas Yojna, Golden Jubilee Rural Housing Finance Scheme, Pradhan Mantri Adarsh Gram Yojana and Productive Housing in Rural Area and Rural Housing Fund. These schemes provided an opportunity to the rural population to replace the thatched roof with an affordable other roofing alternatives like Asbestos Cement Sheets, Corrugated Galvanized Iron Sheets, Color Coated Metal Sheets, Aluminum Corrugated Sheets, Asphaltic Roofing, polyvinyl chloride, RCC and Clay Tiles.

Initiatives taken by Government of India to reduce energy consumption in building sector are provided below:

- Energy conservation act was introduced in 2001
- Bureau of Energy Efficiency (BEE) came into existence on 1st March 2002
- Energy Conservation Building Code (ECBC) was introduced voluntarily in May 2007
- Energy audits on public buildings revealed that retrofitting with energy efficient techniques has the potential to reduce energy consumption by 23% - 46%.
- Nine public buildings were retrofitted with energy efficient techniques in first phase. Details are provided in Table 1.4.
- Seventeen additional Government buildings were considered in second phase.
- A national programme to encourage energy efficient buildings is under formulation.

Table 1.4: Energy savings in public buildings (BEE, 2010)

Building particulars	**Annual Energy Consumption (lakh kWH)**	**Annual Energy savings (lakh kWH)**	**Savings %**	**Annual energy savings (Rs. Lakhs)**	**Investment (Rs. Lakhs)**	**Pay back period (years)**
Rashtrapati Bhawan	34.1	9.8	27	59	51.2	1
PMO	8.3	2.7	32	16.9	50.5	3
Sanchar Bhawan	25.6	11.9	46	76	147.1	1.9
Shram Shakti & Transport Bhawan	20.4	8	39	42.9	157.5	3.7
Airport	713	145	20	586	810	1.5
Rail Bhawan	23.5	6	25	40	163	4.2
AIIMS	369	93.1	29	712	1070	1.5

Salient features of Energy Conservation Building Code (ECBC, 2007) for energy efficient design or retrofit of existing buildings are given below:

- ECBC gives priority to building function and occupant's requirement.
- To minimize life cycle cost of building i.e., both construction and running cost.
- Energy consumption in ECBC compliant building is fixed at 110 kWh/m^2/ year
- National Benchmark for energy consumption in buildings is fixed at 180 kWh/m^2/ year
- ECBC covers the following components
  - ➢ Walls, roofs, windows and openings of building envelope.
  - ➢ Illumination of indoor and outdoor spaces
  - ➢ Thermal comfort systems like air-conditioners, heaters, ventilators etc.
  - ➢ Solar water heaters
  - ➢ Electrical appliances

Energy efficient buildings are the only solution to keep control on ever raising demand of energy from building sector. An energy efficient building demands the incorporation of low energy intensive methodologies, locally available materials, energy harvesting techniques and passive techniques at the time of planning stage itself to gain maximum advantage. Traditional buildings, such as "Naluketu" in Kerala, are the good examples of energy efficient buildings and they succeeded in providing thermal comfort in those days.

Engineers and researchers not only to look for modern materials and techniques but also need to consider good aspects of traditional buildings while designing energy efficient buildings. Buildings designed today are highly energy intensive and basically depends on active means for providing thermal comfort. This has resulted into depletion of conventional energy resources like fossil fuels and causing environmental pollution. Builders need to consider passive technologies even if it leads to slight increase in initial cost, which may results into the reduction of the running cost. One has to look building not only as a shelter but also as energy generator to cater the future needs. Its possible to design a net zero energy building with judicial use of passive techniques, energy efficient techniques, modern materials and energy generators.

1.7 Motivation of the Present Work

India is a country with population of 1210 million, standing second place in terms of population after China. The country's economy is on positive growth since 1991, due to economic reforms. Construction sector supports growth in country's economy by contributing 6.5% GDP on an average. Energy utilization in Indian building sector is on raise due to the growth in economy, construction sector and population. Buildings consumes significant amount of energy during its life cycle. As per the statistics provided by Central Electricity Authority in his 17th Electrical Power Survey (EPS) report, energy consumption in building sector is expected to rise by 8% per annum and projected that the electricity demand will increase by 43.7% by 2016-17 when compared to that of the demand in 2011-12. It is also projected that the demand may increase by another 37.5% by 2021-22 when compared that of the demand in 2016-17 (CEA, 2007). This will result in considerable increase in energy demand from the building sector alone. Therefore, there is a need for constructive mechanisms and corrective measures to control the energy consumption in buildings.

Bureau of Energy Efficiency, India (BEE, 2010) estimated that on an average space conditioning, lighting, refrigeration, television, and other appliances utilizes about 45%, 28%, 13%, 4% and 10% respectively of the total electricity consumption in a typical urban residential building. Most of the residents from rural part of the nation depend mainly on locally available energy sources like fire wood and cow dung. Nearly 56.5% of rural households don't have electricity connection and the households who are having electricity connection are utilizing it only for lighting during nighttime. Residential buildings in India consume nearly 80 kWh/m^2/annum for lighting and air conditioning. As per the present scenario, by considering the 10% growth in building sector, the demand for electricity in both commercial and residential buildings may increase by 5.4 billion kWh per annum. From the above discussion it is clear that, building sector will be one of the major contributors to energy demand. There is a need for research and development in building sector to control the ever-raising energy demand in Indian buildings. Hence, it was decided to work in the area of energy efficient buildings and an attempt was made in the direction of thermal comfort analysis of buildings.

1.8 Structure of the Thesis

The thesis is organized into eight chapters and the details included in each chapter are highlighted below:

Chapter 1 briefed the introduction about the energy scenario, energy demand in buildings and motivation behind the work.

Chapter 2 detailed about the climatic zones and the present building scenario in India.

Chapter 3 presented the state of art on the development of thermal comfort model for naturally ventilated buildings, literature review on various thermal comfort studies carried out in different climatic zones etc. and the objectives for the present work.

Chapter 4 presents the quantitative analysis carried out on three dwellings selected based on type of roof.

Chapter 5 describes the design details of reduced scale model, the experimental setup, the procedure followed for conducting experiments and the results based on experiments conducted on reduced scale models.

Chapter 6 presents the subjective analysis carried out buildings with selected roofs.

Chapter 7 presents the procedure followed for evaluating thermal comfort standards for the selected climatic zone and outlines the thermal comfort standards obtained from the study.

Chapter 8 gives the outcome of the overall work, conclusions obtained based on present work and future scope in this area.

Chapter 2

CLIMATIC CONDITIONS AND TYPES OF RESIDENTIAL BUILDINGS

Energy requirement of building basically depends on its proposed use, comfort requirements, type of design and climatic conditions. To utilize the energy resources judicially, single comfort condition may not be applicable throughout India due to the existence of different climatic zones. Comfort conditions not only vary with climatic zones but also vary seasonally in the same climatic zone. It shows the need for local comfort surveys, which can establish standards for each climatic zone of India. Once the local standards are developed, suitable changes in building code based on climatic zones is possible. It clearly indicates the need for understanding climatic conditions of particular zone before venturing. So, climatic conditions prevailed in India are discussed in the following section.

2.1 Climatic Zones

India is a land of different climatic conditions varying from very hot and dry to very cold and humid. Each climatic zone has its own characteristics and hence, the comfort conditions may not be same for all climatic zones. Six climatic zones have been identified in India based on the various climatic parameters such as temperature, humidity, air velocity and solar radiation.

Following are the six climatic zones exist in India (Nayak and Prajapati, 2006):

- Cold and cloudy
- Cold and sunny
- Composite

- Hot and dry
- Moderate
- Warm and humid

Climatic conditions of each climatic zone are provided in the following table.

Table 2.1: Characteristics of each climatic zone

Climatic Zone	Mean Monthly Temperature	Relative Humidity
Cold and cloudy	Less than 25°C	Greater than 55%
Cold and sunny	Less than 25°C	Less than 55%
Warm and humid	Greater than 30°C	Greater than 55%
Hot and dry	Greater than 30°C	Less than 55%
Moderate	Between 25°C to 30°C	Less than 75%
Composite	Conditions not fall within any of the above criteria for more than six months	

Kozhikode, Kerala is located in warm and humid climatic zone. Here rainy season is severe and lasts over a period of six months in a year, starts with south-west monsoon from June to August and ends with north-east monsoon from September to November. Winter season is comparatively comfortable with slightly cool nights and lasts for two months during December and January. Summer season is moderate and lasts for four months in a year vary from February to May. Even though the temperatures in summer are not much high, the presence of high humidity levels causes severe discomfort during this period.

2.2 Existing Building Scenario in India

Apart from the climatic conditions there is also the influence of building type on comfort conditions. Following sections gives the brief idea about different types of buildings and its key characteristics.

2.2.1 Building Type

- **Commercial type:** This type includes offices, institutions, hotels, IT parks, shopping malls, retail markets, etc. Majority of the buildings in this category are with RCC roof.
- **Residential type:** This type constitutes single and multi-storied buildings with different types of roofs.

- Reinforced cement concrete roofed buildings
- Traditional mud tile roofed buildings
- Asbestos cement roofed buildings
- Metal deck roofed houses
- Thatched roof houses

RCC roofed buildings mainly are of flat roof type and buildings with pitched RCC roof are also exists. TMT, ACR, metal deck and thatched roofs are of pitched roofs with inclinations varying from 30 to 60 degrees.

Traditional houses of Kerala are with mud tile roof and they are named as nalukettu. The basic form of nalukettu is an open courtyard surrounded by four building blocks with pitched TMT roof. Open courtyard creates the driving force for air circulation, which results in enhanced air circulation inside the house. Air in courtyard heated up due to radiation coming from sun that results into upward motion of air which in turn powers the cold outside air into courtyard through the openings of four surrounded blocks. Ceiling/False roof beneath helps in reduction of heat transfer from main roof to living space. Air space enclosed by main roof and ceiling acts as thermal insulation there by reduces the conduction mode of heat transfer into living space. Even today some nalukettu houses are exist, which are more than 100 years old. It has been observed that the majority of TMT houses exist today are not in the form of nalukettu. Due to space constraint, the existing houses are designed either single blockhouses or double blockhouses without courtyard.

Most of the new houses coming up are with RCC roof. People prefers RCC roof mainly because of its structural stability, longevity, and possibility to construct multi-storied buildings. It also provides accessibility to roof area that serves for many auxiliary purposes. Maintenance cost for RCC roof is almost nil where as it is not same with other type of roofs. Rainy season is very severe in Kerala and it last for nearly 6 months in a year and because of this reason metal deck or asbestos sheet covering over the flat concrete roof houses are also seen. Few buildings with pitched RCC roof with mud tiles pasted over the roof also exist. Mainly pasting of mud tiles over pitched concrete roof are for aesthetic purpose, which also serves in reduction of heat transfer into buildings.

Some houses of thatched roofs with palm leaves and few with coconut leaves are also exist in few parts of the Kerala. Since government is discouraging the thatched houses and houses with Reinforced cement concrete (RCC) and Traditional mud tile roofs are not affordable for low-income population, they started preferring the houses with asbestos-cement roof. TMT roofed residential buildings and RCC roofed residential buildings are most commonly seen in southern part of India whereas asbestos cement roof (ACR) dwellings are comparatively less in presence but preferable housing option for low-income people. Low-income people prefer Asbestos cement roof to other roofing options because of its characteristics like weather proof, non-corrosive nature, durability and mainly due to its low cost. Basic form of this roof is pitched roof. Most of the top floors of schools, institutions, hospitals and hostels are using asbestos cement roof. In these type of roofing's false roof is playing important role in reducing heat transfer into the living space of building.

Basic structure of ACR house is almost similar to that of TMT roof house. ACR house also consists of main roof, attic space, false roof and living space similar to that of TMT roof house. Major difference is that in ACR house asbestos cement shingles are used for main roof where as mud tiles are used in case of TMT roof house.

2.2.2 Need of the Present Work

Buildings generally consume huge amount of energy resources starting from construction stage to till the end of the life of building. This excessive use in energy resources causes lot of damage to the environment. Sustainable buildings reduce the dependency on conventional energy resources not only during construction stage but also during the lifetime of building. At the same time the building has to provide the comfort conditions for residents such as lighting, ventilation, air-conditioning and heating. An energy-efficient building has to utilize all possible means mentioned above judicially to reduce the energy requirement. Government of India encourages the public and builders to incorporate these energy efficient techniques during construction stage by providing lot of incentives. Even than general public are not showing interest towards ECBC compliant buildings and reasons behind this are:

- Initial cost of energy efficient buildings
- Lack of indigenous technology in this area
- Lack of availability of materials and technical-man power
- Due to different climatic conditions across the country
- Non-availability of local comfort standards

Judicial implementation of energy efficient techniques in buildings need the knowledge about the thermal performance of different types of existing buildings, climatic conditions of that area and the comfort requirements of the people living in that area. The builders/designers need to know about the comfort requirements of the residents of particular climatic zone before implementing any energy efficient techniques in existing buildings/New buildings. This demands the requirement of thermal comfort standards pertaining to particular area for judicial use of resources. Hence, it was decided to carry out research work on determining the thermal comfort conditions of existing buildings in climatic conditions of Kozhikode, Kerala.

Chapter 3

STATE OF THE ART

Brief review of literature related to the development of adaptive thermal comfort model for naturally ventilated buildings, thermal comfort studies on buildings in India and small-scale model studies to analyze the passive techniques in buildings are presented in the following sections.

3.1 Review on Adaptive Thermal Comfort Theory

Fanger (1970) developed a thermal comfort model popularly known as Fanger's PMV model. He initially investigated the mechanisms behind the human body that controls body temperatures and found that sweat rate and mean skin temperature are the two physiological processes playing major role in regulating human body temperature. He also identified that sweat rate and mean skin temperature depend on metabolic activity and metabolic activity in turn depends on activity level. Linear relationship between sweat rate and activity level and mean skin temperature and activity level were developed by considering the data obtained by conducting experiments on young people in climatic chambers along with the available data in literature. These two equations were incorporated in heat balance equations and the thermal comfort equation was developed. Including the available data, based on his work and also the work from the literature, expanded the developed comfort equation. Later the expanded comfort equation was related with ASHRAE seven-point thermal sensation scale and became popular as PMV index. A related index Predicted Percentage

Dissatisfied (PPD) was developed by utilizing the PMV value. It gives the percentage-dissatisfied people in the subjected environment and this value increases as the PMV value moves away from zero (neutral value). Four physical variables namely, air temperature, air velocity, mean radiant temperature, and relative humidity, along with two personal variables namely, clothing and activity level were considered in his PMV model.

Brager and Dear (1998) reviewed about various protocols adapted in field studies and were mentioned in his paper. Thermal comfort field studies precisely fall into any one of three classes based on the mechanisms adapted while taking physical measurements and subjective questionnaires. The details of three broad classes are discussed below:

- Class I: Field experiments which are 100% compliance with the procedures and measurements prescribed in ASHRAE Standard 55 and ISO 7730 fall in this class. The important aspects of this class are that the measurements of all comfort parameters will be measured at three different heights (0.1,0.6 and 1.2 m) from the floor level.
- Class II: All the procedures are similar to Class I protocol, but the measurements of all comfort measurements will be measured at one height from the floor level.
- Class III: Field studies based on simple measurements of indoor temperature and humidity at one level fall under this class.

Dear and Brager (2002) discussed about the incorporation of adaptive comfort standard in ASHRAE standard 55. The data considered for this study was taken from various locations from four continents, Bangkok, Indonesia, Singapore, Karachi, Quettar, Multan, Peshawa, and Saidu from Asia; Athens, England, and Wales from Europe; Michigan and California from North America; Darwin, Townsville, Brisbane, Sydney, Melbourne, Kalgoorlie from Australia. Analysis of the data was carried out separately for naturally ventilated buildings and air-conditioned buildings. The outcome of this analysis clearly indicated that PMV index predicted the thermal comfort in conditioned buildings accurately, but the predictions in case of naturally ventilated buildings were not accurate. Failure of PMV index in prediction of thermal comfort in naturally ventilated buildings resulted in the inclusion of adaptive comfort standard as an optional method. They also discussed about the scope and limitations of adaptive comfort standard in this paper.

Nicol and Humphreys (2002), detailed about how to utilize field data in developing thermal comfort standards. Major conclusions of their study were (i) it is very difficult to use rational indices in real conditions since they are weak in predicting thermal comfort conditions, (ii) it is necessary to test the standards developed in laboratories in the field before making them as standards, (iii) adaptive comfort standards are the best standards especially for naturally ventilated buildings, (iv) overall effect of available adaptive controls on subjects is the major reason for the failure of rational indices in naturally ventilated buildings, (v) range of comfortable temperature increases due to accessibility of adaptive controls in naturally ventilated buildings, (vi)level of discomfort increases if the adaptive controls are not provided, (vii) change in comfort temperature is in relation with the mean outdoor temperatures and (viii) low energy options has to be preferred where ever possible for sustainability.

Fanger and Toftum (2002) discussed the drawbacks in Fanger's PMV-PPD model and suggested an expectancy factor to overcome the drawbacks of the comfort model. They stated that Fanger's PMV-PPD model is not a static model and it has the ability to predict the neutral temperature in the range of 10 to 35°C based on the values of other five variables. They agreed that Fanger's PMV-PPD model was applicable to steady state conditions but its application was recommended for conditions with small fluctuations, which is true in case of indoor conditions. They also agreed with the studies from various parts of the world and found the Fanger's PMV-PPD model predicting warmer sensation than the actual in case of naturally ventilated buildings. Even though adaptive comfort model works well with naturally ventilated buildings, they mentioned this model as a weak model since it is independent of all the important variables mentioned in Fanger's PMV-PPD model and depends only on mean outdoor temperature. They stated that the difference between the calculated PMV and the actual thermal sensation is due to the failure in estimation of variation in activity level with thermal conditions and they suggested 6.7% reduction in reported metabolic rate with every unit of PMV scale above neutral point for better results. They also proposed an expectancy factor for predicting thermal comfort in naturally ventilated buildings to take care of variation in expectations of residents. They calculated the new PMV value by rectifying the above stated defects and found that the extended PMV model is in good agreement with field studies in naturally ventilated buildings located in warm climatic zones.

Nicol (2004) analyzed the field data from various tropical countries and identified the standards based on Fanger's PMV-PPD model which failed in prediction of thermal comfort standards in tropics. Fanger's PMV-PPD model failed in tropics even though as per the theory it has to predict comfort temperature irrespective of local conditions. Failure of Fanger's model in tropics highlighted the limitations on its applicability.. The author suggested to use the equation $T_c = 0.534T_o + 12.9$, proposed by Humphrey based on field studies, as initial standard and recommended to improve that by conducting local field surveys which reflect local climate and culture. Further, the author was also explained the determination of optimum comfort temperatures and suggested to consider ± 2 to 3°C of the optimum comfort temperature as the comfort zone, and to add another 2°C to the comfort zone if fans are in operation during hot conditions.

Yao *et al* (2009) stated that the advantage in Fanger's PMV-PPD model was that it includes several indoor parameters along with clothing and activity levels in predicting thermal comfort. They explained that people tend to adapt to the conditions mainly by three ways, namely physiological adaptations, psychological adaptations and behavioral adaptations. Physiological adaptations are genetic adaptations, transferred from generation to generation, and acclimatization, limited to single generation. Psychological adaptations mainly depend on past thermal environmental experiences and expectations on present thermal environment. Moreover, quantification of psychological adaptation through measurements is not an easy task. Behavioral adjustments are personal like clothing etc., technological like switching on the fan etc., and cultural like taking rest during hot conditions etc. They developed a theoretical adaptive model of thermal comfort by including all possible factors such as physiological, psychological and behavioral adaptations. They utilized the "Black Box" concept for the development of the theoretical adaptive model called as adaptive predicted mean vote (aPMV) model. Physiological adaptations were considered with the inclusion of Fanger's PMV-PPD model and both psychological and behavioral adaptations were included based on feed back mechanism. They proposed the mathematical relation between Fanger's PMV-PPD model and adaptive predicted mean vote (aPMV) model with the use of an adaptive coefficient, which accounts for both psychological and behavioral adaptations. They evaluated the adaptive coefficient for Chongqing area, located in hot summer and cold winter climate zone in China, with the help of field survey.

Nicol and Humphreys (2010) utilized the data collected by SCATs (Smart controls and thermal comfort) survey based on European Union project. SCATs data, based on 26 European offices located in France, Greece, Portugal, Sweden and UK, collected for a span of one year includes responses of subjects and measurements of air temperature, globe temperature, relative humidity and air velocity etc. In the their study, they discussed about the adaptive comfort model, in European standard EN15251, while the buildings were in free running conditions (especially during summer time). In this paper, they highlighted the drawbacks in estimating neutral temperature based on ASHRAE standards and discussed the new methodology in estimating neutral temperatures that is based on Griffiths constant. They highlighted the use of exponentially weighted running mean outdoor temperature instead of monthly mean temperatures in EN15251. They discussed the effect of Griffith's constant used in derivation of neutral temperature and the effect of weights chosen in determining mean outdoor temperature on comfort conditions. They also discussed the effect of air velocity and humidity on neutral temperatures. They suggested the use of EN15251 for European countries by underlining its advantages over ASHRAE Standards.

Rajib *et al* (2010) studied the use of humidex as an indoor thermal comfort predictor. Humidex used by them is a unit less number derived by using air temperature and humidity. In this study, they utilized the database of ASHRAE RP-884 and compared the performance of humidex over the other comfort factors. They selected air temperature, relative humidity, air velocity and mean radiant temperature of indoor and air temperature, climate and relative humidity of outdoor as the important factors in predicting thermal comfort. By utilizing the Sequential forward selection (SFS) algorithm, they selected outdoor air temperature and air temperature, relative humidity and air velocity of indoor as global factors and also predicted influential local factors for each climatic zone. They compared the performance of humidex with both local and global factors and suggested the use of humidex for predicting indoor thermal comfort in humid areas based on the comparative study. They supported their suggestion by conducting field experiments in 14 offices during winter and summer. Jose and Armando (2011) used a new approach in determining comfort conditions and compared this with PMV and adaptive models. They considered the buildings in Spain, which were similar in all features in construction but only differed in internal coverings with permeable, semi-permeable and impermeable coverings. They collected the data needed for determining PMV index and adaptive models. They performed the 3D curve fit of PMV index with temperature and partial vapor pressure and proposed the new PMV index based on temperature and humidity. They calculated the neutral temperatures based on new PMV index as 21.8°C, 21.2°C and 21°C respectively for buildings with permeable, semi permeable and impermeable internal coverings. They compared these values with the values obtained using PMV index and adaptive models and found that new PMV index was better in predicting thermal comfort than PMV index but not so good in prediction like adaptive models. The authors stated that this model combines PMV index with adaptive models while evaluating thermal comfort.

Liu *et al* (2012) conducted a study to weigh factors effecting thermal comfort in office buildings. They considered analytic hierarchy process (AHP) to quantify the factors effecting thermal comfort. Three factors namely physiological, behavioral and psychological factors were considered as first level factors and the sub category of above three factors like physiological parameters/health status, the indoor environment, the outdoor environment, personal physical factors, environmental control and thermal expectation were considered as second level factors. They carried out the questionnaire survey using 19-point scale to determine the weight of each factor by comparing one to one factor at each level. They conducted the survey in

China and UK among the educated people in office buildings. In case of first level factors, weights for physiological adaptation, psychological adaptation and behavioral adaptation were found to be 0.5, 0.26, and 0.24 respectively in the case study of UK and 0.42, 0.29, and 0.29 respectively in the case of China. In case of second level factors, weights for physiological parameters/health status, the indoor environment, the outdoor environment, personal physical factors, environmental control and thermal expectation were found to be 0.18, 0.27, 0.08, 0.18,0.15 and 0.14 respectively in UK and 0.3, 0.22, 0.12, 0.12, 0.13 and 0.11 respectively in China.

Nguyen *et al* (2012) performed the Meta analysis on the available data and proposed an adaptive comfort model for hot humid Southeast Asia. They considered a total of 5176 data sets from 11 comfort surveys in Southeast Asia. They performed the Meta analysis of this large database by systematically removing the unreliable data and developed the adaptive thermal comfort model by considering monthly mean outdoor temperature. A total of 402 data sets were removed because of unreliability of the survey data. Adaptive thermal comfort model developed by them is much close to the model based on EN 15251 and slightly differs from the model based on ASHRAE standard 55-2004. They carried out the sensitive analysis and found strong dependency of adaptive thermal comfort model on Griffith's constant. They recommended not to use PMV-PPD analysis for prediction of thermal comfort in naturally ventilated buildings even with expectancy factor. They suggested for improvement of the proposed adaptive comfort model by including the comfort studies with thermal conditions falling under 26°C and above 34°C.

Toe and Kubota (2013) utilized the database of ASHRAE RP-884 and segregated the data based on three climatic zones namely, hot humid, hot dry and moderate. They refined the original database with 10065 observations to 7662 observations by neglecting inconsistent data. They developed the adaptive thermal comfort models for each climatic zone by using linear regression model and proposed the acceptable comfort levels by using probit regression model. They related comfort temperature with daily mean outdoor temperature in their adaptive comfort models. Later they developed the adaptive comfort equations by relating the comfort temperature with outdoor temperatures based on daily mean, monthly mean, running mean and prevailing mean for all climatic zones considered in this study. They found that adaptive comfort equation based on daily mean outdoor temperature provided good correlation in hot-humid climatic zone where as all mean outdoor temperatures showed similar correlation in case of hot-dry and moderate climatic zones. They also analyzed the effect of indoor air velocity and humidity on adaptive comfort models.

Wong *et al* (2014) proposed the Bayesian approach that utilizes the concept of probability as explained in Bayes theorem. Authors detailed that there is no scientific approach to decide upon which model to be used to predict the thermal environment condition among the existing models and surveys. They proposed this approach to eliminate the incapability on decision-making based on available information. This approach helps in decision making even with small sample size. In this paper, they applied the Bayes theorem in predicting subjects preference to thermal environment by the use of existing comfort models and subjects surveyed. They suggested that this approach helps in choosing thermal comfort criteria for future building designs.

Yu *et al* (2015) conducted the experiments in Chongqing, located in hot-humid region of China, during summer time for a span of three years, 2008 to 2010, in a climatic chamber that can control air temperature, relative humidity and air velocity. They selected 20 subjects for the study and conducted the experiments for 22 thermal conditions. They took the subject responses through questionnaire survey, measurements of skin temperature at 13 locations for each subject, and measurements of thermal comfort for every 10 minutes during experiments. Subjects acclimatized with the environmental conditions of Chongqing area were only considered during experimentation to study the adaptive comfort model in climatic controlled chamber. They calculated the predicted mean vote (PMV), ASHRAE standard effective temperature (SET*) and used the Bland-Altman analysis to compare PMV and actual mean vote (AMV). Based on the analysis they concluded that PMV is overestimating the thermal sensation in warm conditions, agreement between PMV and AMV is limited to -0.889 to 0.296, and psychological adaptation is the major factor for disagreement between PMV and AMV. They proposed the revised PMV index and suggested to increase the upper limit of ASHRAE SET* point to 26.84°C from 25.24°C, i.e., an increase of 1.6°C for the Chongqing area of China.

Based on the review on adaptive comfort theory, it is observed that Fanger (1970) has developed a thermal comfort model based on laboratory experiments. Four physical variables namely, air temperature, air velocity, mean radiant temperature, and relative humidity, along with two personal variables namely, clothing, and activity level were considered. This model was named as Fanger's PMV model. Consequent works by Dear and Brager (2002), Nicol and Humphreys (2002), Fanger and Jorn (2002) and Nicol (2004) suggested the importance of adaptive thermal comfort model over PMV model as later failed in exact prediction of actual thermal sensation in naturally ventilated buildings.

Recent studies from last five years, Yao *et al* (2009), Nicol and Humphreys (2010), Rajib *et al* (2010), Jose and Armando (2011), Liu *et al* (2012), Nguyen *et al* (2012), Toe and Kubota (2013), Wong *et al* (2014) and Yu *et al* (2015), proposed different approaches for standardizing the adaptive comfort models and few researchers extended the PMV model for naturally ventilated buildings by proposing different corrective measures. The final outcome of these studies is that adaptive comfort model is the best suited for predicting the thermal comfort in naturally ventilated buildings since adaptive comfort model takes care of physiological, psychological and behavioral adaptations. It indicates the need of local comfort surveys to compliment the international standards in developing the region specific adaptive comfort standards. Local comfort surveys are very much essential in tropical countries like India where the standards based on adaptive comfort model are not yet established.

3.2 Review on Thermal Comfort Studies in India

In this section, important thermal comfort studies carried out in various parts of India is discussed.

Sharma and Ali (1986) conducted a study of thermal comfort among Indian subjects. In this study, they collected the observations from 18 subjects. Subjects chosen were young male adults acclimatized to tropical conditions of India. They collected the subject's perception on thermal comfort by using Bedford scale of warmth and measured the dry bulb temperature, wet bulb temperature, globe temperature, air velocity and Kata cooling time during the survey period. Survey was conducted in Central Building Research Institute, Roorkee during the months of May, June and July for three consecutive years. Based on this study they proposed a tropical summer index and showed that the mean correlation coefficient with thermal sensation is high for their index than that of already existing indexes namely, heat stress index, index of thermal stress, wet bulb globe temperature index, equatorial comfort index and TPV index. They also provided the simplified tropical summer index for quick evaluation of comfort conditions.

Singh *et al* (2007, 2009, 2010a, 2010b, 2011) conducted thermal comfort studies in northeast India and discussed about the role of vernacular architecture of northeast India in providing thermal comfort. They discussed about climatic conditions of northeast India and classified the entire north east India into three zones namely, warm and humid, cool and humid, and cold and cloudy (2007). They developed the bio climatic charts for the three zones by considering the meteorological data of past 30 years. They conducted detailed survey on vernacular architecture by considering 42 houses spread over the entire northeast India. Almost all the residents of these houses felt that traditional houses are good in providing thermal comfort when compared to modern houses.

Later (2009), detailed about the vernacular architecture of all the three climatic zones of northeast India. They found that basically three types of houses exist in India namely, kachacha, pukka, and semi pukka. Kachccha houses are less in cost and are built with locally available materials without any processing like mud, bamboo, palm leaves and wood. Pukka houses are high in cost and are built with treated materials like bricks, tiles, metals, stones and uses surkhi/ mortar as binding material. A semi pukka house utilizes techniques and materials used in both kachacha and pukka houses. They clearly outlined the different solar passive techniques utilized by the people of northeast India and also discussed about the different local materials used in construction in each climatic zone. Each climatic zone has its own vernacular architecture that reflects the requirements according to the prevailed climatic conditions.

Singh *et al* (2010a) selected three cities Tezpur, Imphal and Cherrapunjee, one from each of the three climatic zones of northeast India. They conducted thermal performance evaluation for 25 days separately in pre summer, summer/rainy, pre winter and winter periods by measuring temperature, relative humidity and illumination in all the three cities. A total of 150 vernacular houses are investigated and thermal sensation vote was collected from 300 subjects. They evaluated the comfort temperatures based on international standards, regression analysis and thermal sensation vote. They found that international standards predicted comfort temperatures well in summer but failed to predict the same in other periods. Based on their study they proposed the range of comfort temperatures in each climatic zone in each selected period.

Singh *et al* (2010b) conducted a comparative analysis of two houses selected from two different climatic zones of northeast India. They selected one house from Tezpur located in warm humid climate and the other house from Cherrapunjee located in cold cloudy climate. Comfort parameters temperature, humidity and illumination were measured for 25 days each in summer, winter, pre summer and pre winter periods in both the houses simultaneously. They analyzed the data and developed the mathematical equations for predicting maximum, minimum and average temperatures of indoor. Variables considered for the development of these equations are maximum, minimum, average, periods average, diurnal swing and diurnal drop in outdoor temperatures along with ventilation in case of Tezpur house. Where as outdoor maximum and average temperatures along with outdoor temperature swing and a health factor ill were considered for the development of mathematical model in case of Cherrapunjee house.

Singh *et al* (2011) conducted both subjective analysis and objective analysis simultaneously in three climatic zones, warm humid, cold cloudy and cool humid, of northeast India. In subjective analysis they took perception of subjects on ASHRAE thermal sensation scale and some other data like clothing, activity and adaptive actions, but they didn't allow the usage of fan during the survey. In objective analysis they measured the indoor temperature, humidity and other parameters needed for evaluating PMV. By utilizing the data from both subjective analysis and objective analysis, they calculated adaptive mean vote (AMV) along with predicted mean vote (PMV) and found that PMV is not matching with AMV. They developed a relation between clothing level to outdoor temperature and also derived the values of adaptive coefficient to calculate the corrected PMV. They proposed the adaptive comfort models for the three climatic zones of northeast India separately for all four seasons. Complete study was carried out by measuring comfort parameters and collecting data from 300 subjects from 150 houses, 50 houses from each climatic zone, and also concluded that PMV is not suitable for naturally ventilated houses.

Aravind and Tiwari (2009) performed the thermal performance of passive mud house and compared the energy saving potential of this house with RCC house. Initially, they performed the experimental investigation by measuring the indoor and outdoor temperatures along with outdoor solar radiation during a summer day and a winter day. They found that the indoor temperatures vary between 14°C to 18°C in winter and 24°C to 28°C in summer when the outdoor temperatures are measured as 6°C to 18°C in winter and 26°C to 40°C in summer. They developed a thermal simulation model and validated with the experimental data and found a good agreement between them.. Later, by utilizing the thermal simulation model, they predicted the thermal performance of similar mud house in different cities viz., New Delhi, Bangalore, Jodhpur, Mumbai and Srinagar. From their observation, they predicted the energy saving potential of passive mud house was more in comparison with RCC house for all the locations.

Dili *et al* (2010a, 2010b, 2010c, 2010d, 2011) conducted thermal comfort studies in Kerala traditional building and highlighted the importance of vernacular architecture of Kerala in providing thermal comfort. Some of their studies are discussed below.

Dili *et al* (2010a) initially carried out a qualitative analysis of traditional building of Kerala and explained the importance of passive features of the selected building. Kerala's traditional houses known as "nalukettu" were able to provide comfortable environment mainly due to its passive features like internal courtyard, building orientation, arrangement of spaces, construction methodology and use of local materials. They supported qualitative analysis by conducting quantitative analysis through field measurements and finally concluded that Kerala's vernacular architecture employed in traditional buildings of Kerala is predominantly successful in providing thermal comfort through out the year irrespective of seasons.

Dili *et al* (2010b) presented a detailed quantitative analysis of Kerala's traditional house carried out during summer and winter seasons. They continuously measured the thermal comfort parameters like, air temperature, globe temperature, air velocity, humidity both in indoor and outdoor. They utilized custom made equipment called as "Architecture evaluation system" for measuring thermal comfort parameters. After analyzing the data quantitatively, they concluded that Kerala's traditional houses were able to maintain comfortable indoor conditions irrespective of outdoor conditions.

Dili *et al* (2010c) presented a comparison between the Kerala's traditional houses and the modern buildings based on subjective analysis. They selected nearly 200 people from each type of house and collected the responses from them through questionnaire survey. They took the responses from subjects on various comfort factors like temperature, humidity, air velocity, and over all thermal comfort. From the subjective analysis they found that, in case of traditional houses nearly 70% of the residents voted for very comfortable, 27% voted for comfortable and 3% voted for slightly uncomfortable and in case of modern buildings nearly 9% of the residents voted for very comfortable, 21% voted for comfortable, 22% voted for slightly uncomfortable, 17% voted for uncomfortable and 31% voted for very uncomfortable. They upheld their quantitative analysis, Dili *et al* (2010b), through this study and reiterated that the results obtained from subjective analysis clearly indicated that Kerala's traditional buildings were best in providing thermal comfort in all seasons. Results based on subjective analysis showed that modern buildings failed in competing with traditional buildings of Kerala in providing thermal comfort.

Dili *et al* (2010d) presented a quantitative analysis of Kerala's traditional building in rainy season. In Kerala rainy season lasts over six months and there is a maximum fluctuation in environmental parameters during this period. Based on the fluctuations in environmental conditions, they divided the entire rainy season into four categories namely beginning of rainy days, normal rainy days, heavy rainy days and non rainy days. They continuously measured the thermal comfort parameters like, air temperature, globe temperature, air velocity, and humidity in both indoor and outdoor by utilizing custom made equipment called as "Architecture evaluation system". They found the variation of temperature between 24°C to 31°C in outdoor and 27°C to 29°C in indoor during beginning of rainy days, 24°C to 28.5°C in outdoor and 26.5°C to 27.5°C in indoor during normal rainy days, 22.5°C to 26°C in outdoor and 25°C to 27°C int indoor during heavy rainy days and 23°C to 35.5°C int outdoor and 27°C to 30.5°C int indoor during non rainy days. They analyzed the extreme conditions of indoor, by using Bio-climatic chart and also by PMV-PPD analysis, and found that the indoor conditions of Kerala's traditional house are falling within the comfort conditions. They also found that the Kerala's traditional house maintained indoor temperatures higher than outdoor temperatures when outdoor temperatures fall below the neutral temperatures and indoor temperatures lower than outdoor temperatures when outdoor temperatures recorded as more than the neutral temperatures.

Dili *et al* (2011) presented a comparison between Kerala's traditional house and modern building based on quantitative analysis conducted during the most discomfort period of summer. Study was carried out in parallel on both traditional and modern houses. Comparative analysis revealed that traditional building was able to maintain the temperatures between 31°C and 35°C where as in modern buildings the temperatures varied between 31°C and 37°C when the outdoor temperatures varied between 28°C and 41°C. They attributed the better performance of traditional building over modern building to air movement and temperature control and they also stated that relative humidity is independent of building envelope. With the help of monitored thermal comfort parameters, they conducted the PMV-PPD analysis along with analysis based on bio climatic chart. In both the analysis indoor conditions of traditional buildings fall with in the comfort conditions where as modern buildings failed in providing comfort conditions.

Indraganti *et al* (2010a, 2010b, 2010c, 2010d, 2010e, 2011, 2013, 2014) conducted several thermal comfort studies on residential apartments and office buildings in Hyderabad and Chennai. The major outcomes of her studies are discussed below.

Indraganti *et al* (2010a) reported the thermal comfort studies conducted in Hyderabad during the months of May, June and July.. They selected five apartments at different locations in Hyderabad and conducted the survey by collecting data from nearly 113 occupants from 45 flats. They used ASHRAE seven-point scale for thermal sensation, Nicol's five-point scale for thermal preference and ASHRAE's thermal acceptance scale to identify thermal comfort of the residents. Further, they also collected data such as age, gender, financial status, ownership, tenure, illumination level, air movement, humidity sensation, noise level and indoor air quality. They took the measurements of air temperature, globe temperature, relative humidity, and air velocity for both indoor and outdoor conditions. Clothing level and activity level were estimated based on ASHRAE standards. Observations made based on their study were less effect of age and gender on thermal sensation, increase in demand for more comfort with financial status, owners voted for high level of acceptance than renter, air movement, humidity sensation and illumination showed dependency on temperature, air quality sensation showed less dependency on thermal comfort, and subjects felt slightly noisy in apartments.

Indraganti (2010b) also determined the comfort conditions of the few apartments located in the city of Hyderabad. She also analyzed the data by dividing into two groups, residents from top floor and residents from other than top floors, and found that the neutral temperature for top floor residents was always more than that of residents from other floors. She proposed the neutral temperature as 29.23°C and the comfort range of temperatures as 26°C to 32.45°C for the residents of naturally ventilated apartments in Hyderabad. She also found that only about 40% residents of apartments felt comfortable during summer. She suggested for providing the adaptive opportunities for the residents in summer and additional provisions for adaptive controls in case of top floor residents. She also suggested the modification of national standards since the comfort standards obtained from her study were far above than the national standards.

Indraganti (2010c) analyzed the data and determined the comfort conditions in the city of Hyderabad and compared these standards with other reported studies. She presented the analysis to determine the effect of different parameters on thermal comfort. More over, she compared these standards with national standards and also with comfort conditions based on PMV-PPD analysis. She questioned the usage of national standards and PMV-PPD analysis for determining thermal comfort standards and highlighted the implication of these standards on energy usage in buildings.

Indraganti (2010d) studied the use of various adaptive options like clothing, activity, windows, curtains, blinds, balcony doors, and external doors and discussed the hindrances for these adaptive controls like attitudes and privacy. She outlined the suggestions for betterment of adaptive controls to maintain thermal comfort. She presented the detailed analysis carried out on vernacular architecture of settlements in Marikal, a small village of Rangareddy district of newly formed Telangana state of India (2010e). She conducted the detailed study for a span of two years from 2006 to 2008 and highlighted the role of each factor of vernacular architecture of the settlements like form planning, site planning, cluster planning, streets, alleys, courtyards, construction details like walls, roofs, openings, colors and texture, typology and behavioral adaptation. She found that the vernacular architecture of this village is in accordance with mahoney's recommendations such as north south orientation, small courtyards, small spacing's, provisional windows, very small openings, heavy walls and roofs, and provision for sleeping at outdoor etc. She also stated that people of Marikal are slowly neglecting vernacular architecture not only due to the changes in social and economic conditions but also due to the availability of electricity.

Indraganti (2011) presented the complete analysis of entire data collected from the her earlier surveys such as details of survey, Indraganti (2010a), comfort conditions of top floor residents and other floor residents, Indraganti (2010b), PMV-PPD analysis and its variation from actual perception, Indraganti (2010c), and role of various adaptive controls, Indraganti (2010d). She discussed in detail about usage of electrical adaptive controls like fans, air coolers and air conditioners along with other adaptive options.

She also discussed about social and cultural preferences along with attitudinal impediments for operating adaptive controls.

Indraganti *et al* (2013) reported the study conducted in office buildings of Chennai and Hyderabad from March to September 2012. They selected 25 office buildings from Chennai and Hyderabad and collected the data from 1658 subjects. They collected all the necessary data from the subjects and measured the comfort parameters needed for thermal comfort analysis for both the cities simultaneously. They analyzed the data separately for naturally ventilated conditions and air conditioned situations and evaluated the thermal comfort conditions of office buildings for the two cities by using Fanger's PMV-PPD analysis, linear regression analysis and Griffith's comfort equation. They also analyzed the data to study the variation of comfort conditions with seasons, adaptive controls in office buildings, role of fans and limitations on adaptive strategies. Based on their study they proposed the thermal comfort conditions for both air-conditioned and naturally ventilated office buildings in both Chennai and Hyderabad. They suggested that PMV is always over estimating the comfort conditions and recommended for the change of comfort conditions in national building code.

Indraganti *et al* (2014) extended their previous study, Indraganti *et al* (2013), by incorporating the data from 28 buildings from both Chennai and Hyderabad, by including the survey data for all seasons of the year, January 2012 to February 2013, with increased the sample size to 2787 subjects. They carried out similar analysis as explained in Indraganti *et al* (2013) and predicted the thermal comfort conditions for the entire year and compared this proposed adaptive comfort model with different standards namely, National building code (NBC), European committee for standardization (CEN), The chartered institution of building services engineers (CIBSE) and ASHRAE adaptive model.

Deb and Ramachandraiah (2010) performed thermal comfort study in Chennai railway station considering three lounges based on the variations in volume, capacity, type of roof, height of ceiling and material. Different comfort parameters, air temperature, globe temperature, humidity, air velocity, floor temperature and ceiling temperature, were measured from 7:30 AM to 8:30 PM on every day during the period from 1st June to 15th June of 2009 with the help of installed sensors at different locations of the three lounges. Questionnaire survey was also conducted during the same period and data was collected from 432 subjects. Air velocities at the location of subjects were also measured along with questionnaire survey. Physiological equivalent temperature (PET) index was used in this study, and was similar to PMV without clothing and activity level parameters. Neutral temperature obtained were 30.52°C and 31.93°C based on Bedford's thermal comfort scale and ASHRAE's thermal sensation scale respectively. They found the neutral temperature of 27.87°C by using Adaptive comfort standard equation proposed in ASHRAE standard 55 for naturally ventilated buildings and concluded that ACS was under estimating the neutral temperature. They also found that increase in air velocity increased the neutral temperature by 2.6°C.

Rajasekar and Ramachandraiah (2011) discussed the influence of construction material on thermal performance of buildings in Chennai. They considered apartments with aerated concrete block walls and solid block walls for the study. Both quantitative analysis and subjective analysis were carried out in parallel by taking measurements of indoor air temperature, radiant temperature, relative humidity, air velocity, outdoor air temperature, clothing and activity level along with subject's perception. A sample size of 50 subjects participated in the questionnaire survey and found the neutral temperature as 29.5°C. By correlating thermal sensation vote with PMV they found the expectancy factor as 0.6 for the apartments. They finally concluded that solid block walls are better in thermal performance than that of aerated concrete block walls. They also studied the influence of building orientation and height of location on indoor thermal parameters.

Chitra and Nagendra (2012) conducted a study to identify the indoor air quality of a primary classroom located beside the traffic road. Site selected for study is a primary classroom of Kendriya vidyalaya, which is located near Central leather research institute, Chennai. They conducted survey in two seasons, winter and summer, for 60 days during January to May 2011. They measured the concentration of particulate matter of different sizes, carbon monoxide and carbon dioxide along with the comfort parameters temperature and relative humidity for both indoor and outdoor. They analyzed the data to identify the effect of outdoor pollution, comfort parameters and micrometeorology on indoor air quality. Based on analysis they observed that concentration of particulate matter was high during occupied periods, concentration of finer particulate matter and carbon monoxide varied with outdoor concentrations and indoor quality varied seasonally having poor indoor quality in winter season when compared to summer season.

Priya *et al* (2012) presented the qualitative and quantitative analysis of vernacular buildings in coastal area of Nagapattinam, Tamilnadu. They first analyzed the passive features like the effect of building orientation, role of internal courtyard, role of openings like wind catchers, windows and ventilators along with the effect of thick walls, thinnai and roof of the vernacular buildings qualitatively. They performed quantitative analysis using mini meteorological unit with 18 sensors by continuously recording comfort parameters during the period from May to December 2010. Sensors were utilized to measure air temperature, humidity and air velocity at different locations of indoor and outdoor conditions. They found that, diurnal variation of temperature and relative humidity at outdoor were 18°C with a range of 24°C to 45°C and 50% with a range of 45% to 95% respectively, where as the same for indoor were 8°C with a range of 24°C to 32°C and 15% with a range of 65% to 80% respectively. Similarly they noted that air velocity in indoors were maintained at 1.5 to 2 m/s. Based on the analysis using bio-climatic chart, they concluded that the vernacular houses of Nagapattinam were able to maintain the indoor comfort conditions with in the acceptable zone.

Dhaka *et al* (2012) considered a hostel room in Hyderabad and developed the building simulation model. They compared the simulation model with experimental values, inner roof surface temperature, outer roof surface temperature and indoor air temperature, obtained from the hostel room and refined the model for exact prediction. Later they modified the model for air-conditioned situation. With the developed simulation model, they performed analysis by incorporating six energy conservation measures independently and all together for three cities, Hyderabad in composite climate, Ahmadabad in hot and dry climate and Chennai in warm and humid climate, of India. They carried out this study for two conditions, one for fixed comfort temperature and the other for adaptive comfort temperature, along with the variation in building size. They concluded that nearly 40% energy saving was possible by implementing all six energy conservation measures and almost 20% energy saving was possible with roof insulation alone. They also suggested for the use of adaptive comfort temperature instead of fixed comfort temperature, which results into nearly 16% energy savings.

Dhaka *et al* (2013) conducted a thermal comfort analysis of six hostels located in MNIT Jaipur, located in composite climatic zone of India, during summer and monsoon seasons. They performed the survey by taking opinions of around 429 students through questionnaire and in parallel they also measured the thermal comfort parameters air temperature, globe temperature, air velocity and relative humidity. They estimated the clothing level and activity level based on questionnaire survey. The adaptive measures used by students for achieving thermal comfort were opening of windows, use of fan, changing speed of fan and opening of main door. They estimated the thermal comfort temperature as 30.15°C based on ASHRAE's seven point thermal sensation scale and thermal preference temperature as 27.4°C based on Nicol's five point thermal preference scale. Predicted mean vote was observed as 0.88 for the comfort temperature. They observed slight variation in thermal comfort temperature based on gender.

Dhaka *et al* (2015) performed a field study in 30 buildings under naturally ventilated conditions that includes hostel buildings, office buildings and institute buildings located in Jaipur city of India. They conducted the study in a similar way as explained in Dhaka *et al* (2013). In this study, they collected nearly 2859 responses from subjects in a span of three years between 2011 and 2013, of which 1811 responses obtained during naturally ventilated conditions were analyzed. They highlighted the drawbacks of PMV index in the present study and proposed the thermal comfort models for each season, summer, winter and moderate seasons, along with overall comfort model based on regression analysis. They also proposed models for ideal humidity and ideal air velocity, and evaluated the thermal comfort models, separately for 90% satisfaction and 80% satisfaction levels, for both upper acceptability limit and lower acceptability limit. They found neutral temperature as 29.4°C, 27°C and 25.6°C respectively for summer season, moderate season and winter season.

Mishra and Ramgopal (2014a) conducted the field study to identify the comfort conditions of students in undergraduate laboratory, IIT Kharagpur, India. They performed the study by collecting students vote on three point air velocity sensation scale, five point humidity sensation scale, three point thermal preference scale, two point acceptability scale, seven point thermal sensation scale and seven point thermal comfort scale. In parallel they took the measurements of air velocity, dry bulb temperature, wet bulb temperature and globe temperature along with the identification of clothing level. They analyzed the data of air velocity sensation and concluded that students preferred high air velocities. In case of humidity sensation, student's preference was in correlation with absolute pressure of water vapor rather than relative humidity in air. They found nearly 78% subjects showed acceptance to the thermal conditions and they also detailed upon the adaptive actions of the students in laboratory. The important contributions of their study are mentioned below:

- Developed an equation that indicates the variation of clothing with operative temperature
- Calculated the Pearson correlation coefficient for each pair of parameters through multivariate analysis
- Developed the comfort equation that relates mean thermal sensation vote with ambient temperature,clothing level and absolute pressure of water vapor in air.
- Developed the thermal preference equations that relates warmer preference and cooler preference with operative temperature and interrelated the thermal preference with mean thermal sensation vote.

Mishra and Ramgopal (2014b) developed the equations for thermal sensation vote, thermal comfort vote and predicted mean vote based on the operative temperature. They also developed the adaptive comfort model to find the comfort temperature by using seven-day mean outdoor temperature. They predicted the neutral temperatures and the comfort zones based on the above stated votes. Predicted comfort temperatures based on thermal sensation vote, thermal comfort vote and predicted mean vote were 26.5°C, 26.6°C and 19.8°C respectively. Predicted comfort zones with 80% satisfaction based on thermal sensation vote, thermal comfort vote and thermal acceptance vote were 22.7 to 28.9°C, 17.9 to 32.8°C and 19.4 to 30.9°C respectively. They proposed to consider 20 to 31°C as a comfort zone for under graduate laboratory based on students overall comfort level.

Mishra and Ramgopal (2015) analyzed the comfort equations proposed for tropical climates to identify the best one among those equations that could predict well for Indian tropical regions. In this study, they considered the adaptive comfort models for naturally ventilated buildings based on ASHRAE Standard 55, EN15251, Nguyen et al, Toe and Kubota and Indraganti et al. They first collected the metrological data of Hyderabad, Chennai and Kolkata from different sources and utilized that to calculate monthly mean temperature. By utilizing the available field data of these three cities, they compared the comfort conditions of these cities with the values predicted from the five adaptive comfort models and found that adaptive comfort models given by EN15251, Nguyen et al, and Indraganti et al did well. They also calculated adaptive comfort cooling days for the three cities, Hyderabad, Chennai and Kolkata, based on five adaptive comfort models. Based on the comparative analysis, they suggested the use of comfort model given by EN15251 for predicting adaptive thermal comfort conditions of the tropical regions of India. They also suggested to use Humphreys comfort model over the comfort model given by Chartered Institution of Building Services Engineers (CIBSE) for mechanically conditioned buildings.

Chandel and Sarkar (2015) presented a study carried out in Forensic Science Laboratory building located in Mandi, Himachal Pradesh, India. They conducted field survey in the building by collecting data from 50 subjects during winter season. They took the indoor measurements for air temperature, globe temperature, relative humidity, lux, air velocity and estimated the clothing level and activity level of all the 50 subjects while collecting data for thermal sensation based on ASHRAE's seven point scale, thermal preference based on ASHRAE's three point scale and thermal acceptance based on ASHRAE's two point scale etc. Based on the survey they found the comfort conditions of the subjects and proposed the thermal comfort equation by relating thermal sensation vote with operating temperature through regression analysis. Comfort operative temperature predicted based on survey was 16.8°C for winter season. Authors suggested few passive techniques to improve the performance of building and evaluated the annual energy savings with the incorporation of proposed passive techniques in existing building by using the energy simulation model "e-Quest".

Based on review on thermal comfort studies in India, it is observed that the comfort studies available in India are very few and mainly concentrated in prediction of thermal comfort conditions in vernacular buildings of North east India [Singh *et al* (2007, 2009, 2010a, 2010b, 2011)], vernacular building in Kerala [Dili *et al* (2010a, 2010b, 2010c, 2010d, 2011)], vernacular building in coastal area of Nagapattinam, Tamilnadu [Priya *et al* (2012)], modern buildings and apartments in Chennai and Hyderabad [Indraganti *et al* (2010a, 2010b, 2010c, 2010d, 2011, 2013, 2014)], hostels and institute/office buildings in Hyderabad and Jaipur [Dhaka *et al* (2012, 2013, 2015)], laboratory buildings [Mishra and Ramgopal (2014a, 2014b), Chandel and Sarkar (2015)] and a few more studies include study at Chennai railway terminal [Deb and Ramachandraiah (2010)], Mud house in Delhi [Aravind and Tiwari (2009)], and primary school in Chennai [Chitra and Nagendra (2012)].

Recently, Mishra and Ramgopal (2015) analyzed the available adaptive comfort models and suggested the use of comfort model given by EN15251 for predicting adaptive thermal comfort conditions of the tropical regions of India. It indicates that, in India there is a dearth of local field studies to establish standards based on adaptive comfort model. So, there is a need for more local field studies to establish the adaptive comfort standards specific to the concerned zone.

3.3 Reduced Scale Model Studies

In the following subsection, thermal comfort studies reported on a reduced scale model are presented.

Nahar *et al* (1999) conducted the experiments to compare the performances of different passive solar cooling techniques for arid regions. They fabricated five identical reduced scale models, with galvanized steel sheets as roof and walls, with dimensions 1.2 × 0.6 × 0.91 m^3. They considered the simple galvanized steel sheet roof along with four different passive techniques incorporated on roofs, white painted roof, roof with thermal insulation, roof with shallow pond covered with thermal insulation, and roof with soaked gunny bags, for comparative study. Based on the study, they concluded that roof with thermal insulation, white painted roof, roof with shallow pond covered with thermal insulation, and roof with soaked gunny bags able to maintain the inner temperatures of model less than simple galvanized roof model by 3°C, 7°C, 8°C and 10°C, respectively.

Nahar *et al* (2003) extended their previous work (1999) by comparing the performance of seven passive cooling techniques incorporated in roof with regular RCC roofed model. They performed the study on eight small-scale models with dimensions 1.28 × 0.61 × 1.1 m^3 fabricated with galvanized steel sheets and 0.1 m thick RCC roof. They considered different passive techniques over RCC roofs like white paint, vermiculite cement thermal insulation, roof pond, evaporative cooling with jute bags, pasting broken white glazed tile pieces, covering with earthen pots and local Sania thermal insulation. They conducted the study in real environmental conditions during summer and winter days, and found that roofs with white paint, vermiculite cement thermal insulation, roof pond, pasted broken white glazed tile pieces, earthen pots and local Sania thermal insulation were able to maintain inner temperatures more by 0.1°C, 1°C, 2.6°C, 0.1°C, 1°C, and 0°C respectively in winter and maintained low temperatures by 5.4°C, 3.5°C, 6.7°C,11°C, 5.8°C, and 3.4°C respectively in summer, when compared to simple RCC roofed model. Roof with evaporative cooling by jute bags was maintained the temperatures less by 3.2°C in summer than that of RCC roof.

Rahul and Rajiv (2005) conducted a small-scale model study to justify the effectiveness of proposed static sunshade over horizontal static sunshade. Initially, they designed the proposed static sunshade by considering sun path for two days, 22nd December in winter and 23rd March in summer, and implemented this sunshade design on small-scale models. They fabricated four models, two with proposed static sunshade and the other two with horizontal sunshade, and conducted the experiments during December 2002 to July 2003. They measured the temperature, sunlit area and shadow area for the models during the experimentation and analyzed the data. From the analysis, they concluded that proposed static sunshade was able to regulate sunlit area as per the seasonal requirement and there by controlled the inner temperature of models. They suggested the use of this proposed static sunshade in full-scale buildings to reduce the cooling and heating requirements.

Halwathura and Jayasinghe (2008) studied the thermal performance of insulated roofs in tropics. Initially they performed the small-scale model study on four similar models with RCC roof and RCC roofs sandwiched with 25 mm, 38 mm and 50 mm cellular polyethylene insulation. They conducted the experiments in real environment and found that soffit temperature reached to maximum of 42°C for RCC roof with out insulation, where as the maximum soffit temperature for insulated roofs varied between 32°C and 33°C. To demonstrate the actual performance of insulation, they conducted experiments on large-scale model and measured the soffit temperature and roof top temperature of the large-scale model before and after incorporation of 25 mm thick cellular polyethylene insulation. The roof top temperature remained constant at 55°C in both cases, where as the soffit temperatures were found to be 35°C and 45°C respectively for roofs with and without insulation. They analyzed the data through comfort chart and found that the insulated roofed house was able to maintain thermal comfort for residents. Based on this study they proposed the RCC roofs as alternative to conventional roofs by highlighting its advantages.

Jorge and Edgard (2008) conducted the thermal performance study on small-scale models to demonstrate the effectiveness of the insulation system designed by them. They fabricated two similar small-scale models and used these models for experimentation under artificial environment provided by 500 W lamps. They conducted experiments as three sets and compared three insulated models with non-insulated model. They compared the standard model with the model having optimally oriented triangular pattern aluminum sheet with 19.5 mm thick polyurethane layer, adversely oriented triangular pattern aluminum sheet with 19.5 mm thick polyurethane layer, and optimally oriented triangular pattern aluminum sheet with 9.5 mm thick polyurethane layer in three set of experiments. Based on the analysis they found the temperature difference of nearly 20°C, 15°C and 17°C at roof bottom surface in first, second and third set of experiments respectively. Finally, they concluded that almost 70% thermal load can be reduced with the incorporation of aluminum polyurethane insulation.

Jorge *et al* (2009) extended their previous work (Jorge and Edgard, 2008), by conducting similar type of study on nearly eight different passive models. They employed polyurethane, polyethylene, polystyrene and air gap as thermal insulation materials and used aluminum 1100 (flat, corrugated and right triangular) and galvanized steel (flat and corrugated) as reflecting materials. They performed the small scale model study on eight passive cooling systems and found the heat flux reduction by 88%, 84%, 79%, 76%, 74%, 71%, 69%, and 65% respectively for flat aluminum polyurethane, corrugated aluminum polyurethane, right triangular aluminum polyurethane, flat galvanized steel polystyrene, corrugated galvanized steel polyurethane, flat galvanized steel polyurethane, flat galvanized steel with air gap, and flat galvanized steel polyethylene. Finally they concluded to use aluminum with polyurethane yielded the best results.

Ong (2011) presented a small-scale model study for predicting the performance of different roof designs under similar conditions. He fabricated a total of six roof designs namely, standard uninsulated tiled roof, standard tile roof with underneath insulation, standard tile roof with insulation above ceiling, bare metal deck roof, insulated metal deck roof and roof solar collector, and conducted experiments in real environmental conditions. He found that roof solar collector performed better when compared to other roof designs. Based on the observations from his study, he suggested the use of insulation underneath the tiles instead of insulation above ceiling for better performance.

Based on the review on reduced scale model studies it is observed that many researchers conducted experiments on small-scale models to compare different passive techniques in buildings. Researchers opted small-scale model study since the comparative analysis of full-scale buildings not only demands high expenditure but also consumes more time. Results obtained from the model study are limited to comparison of the individual features of buildings and they can't be the replacement for full scale building studies. For the design of sustainable energy efficient buildings, it is necessary to do the comparative analysis that involves both quantitative and subjective analysis.

3.4 Closure of Literature Review

The following conclusions are made based on literature review:

- Lot of research works was carried out in the development of thermal insulation materials and many new materials are under development. No material is suitable for all climatic situations, so the judicial selection of material is crucial.
- Passive techniques are well developed over the years and judicial selection of suitable techniques based on climatic conditions is crucial.
- Small-scale model studies are mostly used to compare different passive techniques in buildings.
- There is a lack of quantitative studies to predict the performance of existing buildings in providing thermal comfort.
- Physiological, psychological and behavioral adaptations play their role in establishing thermal comfort standards for naturally ventilated buildings in addition to the climatic conditions.
- Local comfort surveys and thermal comfort studies on existing buildings are needed to establish thermal comfort conditions of a particular climatic zone.
- In India, there is a dearth of local comfort surveys and field studies, which play a crucial role not only in establishment of thermal comfort standards but also in judicial selection of passive techniques and insulation materials.

3.5 Objectives of Present Work

Following objectives are considered for the research work based on the conclusions reached from literature review:

- To perform quantitative analysis on buildings with different roof types for predicting the role of roof on thermal performance of buildings.

- To conduct experiments on reduced scale models for identifying the best roofing technique in terms of thermal performance.
- To carry out subjective analysis among the subjects living in buildings with different roof types for predicting the perception of subjects on thermal comfort levels.
- To conduct local comfort survey on buildings with different roof types for evaluating the thermal comfort standards for naturally ventilated buildings located in Kozhikode.

The ultimate objective of this work is to evaluate the adaptive thermal comfort standards by giving emphasis on roof type of building.

Chapter 4

QUANTITATIVE ANALYSIS

Main objective of the quantitative study is to identify the influence of roof on living space temperature. Each and every part of the building has its own influence on the inside temperatures. Roof is the part of the building envelope, which has direct interaction with solar radiation throughout the day. Especially, the effect of roof on thermal comfort is predominant in case of single storied buildings. In case of multi-storied buildings, the influence of walls is more than that of roof on living space temperature in all floors except top floor. An assessment was carried out on existing building scenario by visiting various residential zones in Kozhikode district of Kerala. Based on the assessment, it was found that more than 90% of the dwellings are with one of the following roof types,

- Traditional mud tile (TMT) roof
- Reinforced cement concrete (RCC) roof

TMT roofed residential buildings and RCC roofed residential buildings are most commonly seen, whereas asbestos cement roof (ACR) dwellings are comparatively less in presence but preferable housing option for low-income people. It is known fact that thermal performance of TMT roofed houses is better than ACR houses. So, first detailed thermal performance analysis was conducted on ACR house and highlighted its drawbacks. Later, Comparative thermal performance analysis was carried out among TMT roofed dwelling and RCC roofed dwelling by conducting experiments in both the dwellings in parallel under similar conditions. The rooms identified for experimentation are located in National Institute of Technology Calicut, Kozhikode, Kerala, India.

4.1 Details of Site

The site considered for study is in Kozhikode district located towards northern part of Kerala lying between foothills of Western Ghats and the Arabian Sea. Location of site is shown in Fig. 4.1.

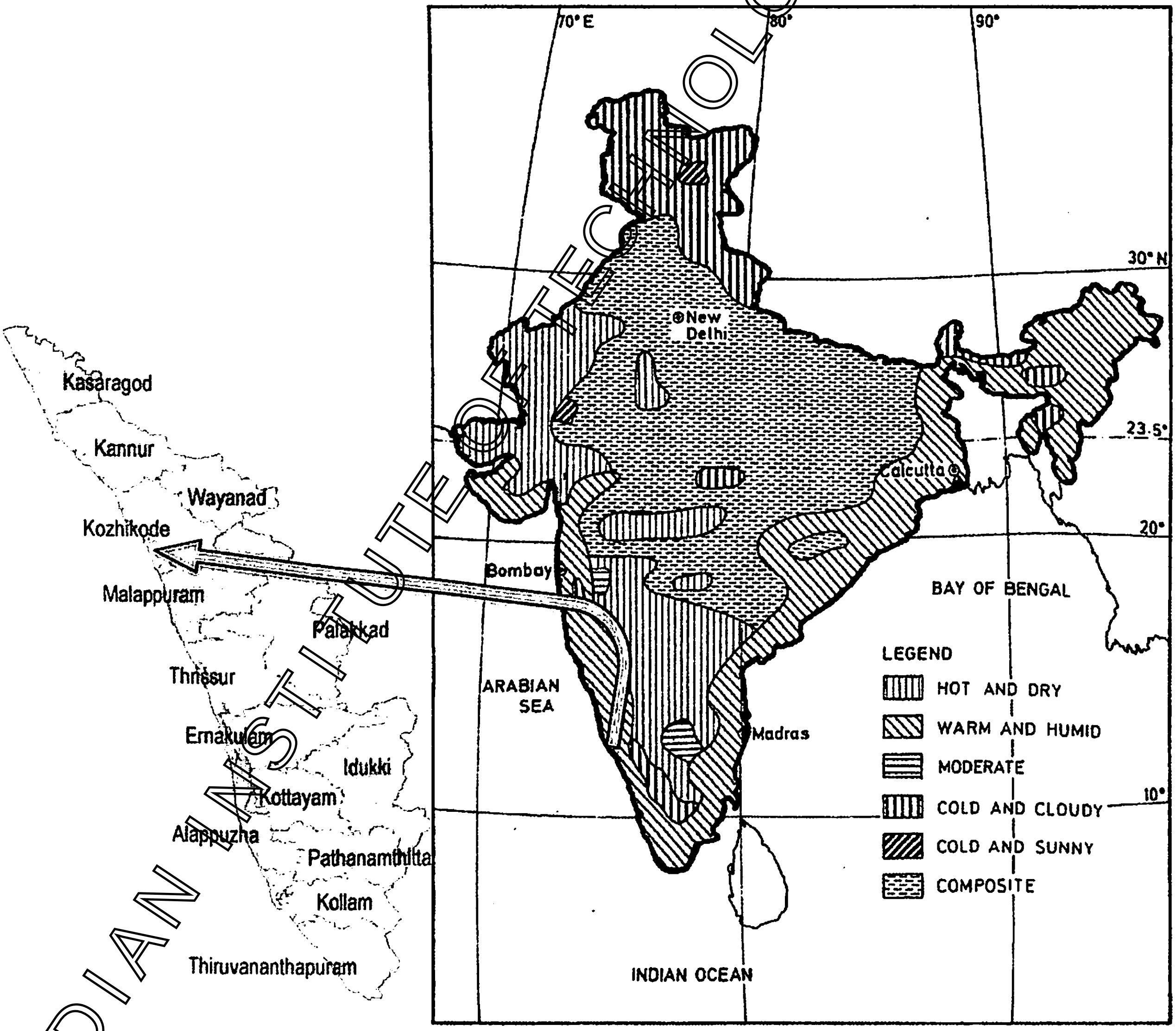

Fig. 4.1: Location of Site

It is falling in warm and humid climatic zone of India and its geographical coordinates are 11° 15' North, 75° 46' East. Kozhikode is the coastal district having Arabian Sea in west, Malappuram district in south, Kannur district in north and Wayanad district in east.

4.2 Thermal Performance Analysis of ACR Dwelling

Detailed thermal performance analysis was conducted during peak periods of both summer and rainy seasons to understand the drawbacks of ACR dwelling. Outcome of this study is presented in this section.

4.2.1 Details of Asbestos Cement Roof (ACR) House

A typical ACR residential living room with dimensions of 3 m length, 3 m breadth and 3 m height is considered for conducting thermal performance analysis. ACR house consists of main roof, attic space, false roof and living space. Main roof is constructed with Asbestos cement shingles and gypsum board is used as false roof. Space enclosed between main roof and false roof is called as attic space and living space is the space between false roof and the floor.

4.2.2 Experimental Investigation

Experimental setup was devised for finding the temperature distribution of different zones of ACR house. The experimental setup consists of Agilent data logger, computer, and temperature sensors. Forty "T" type thermocouples were used for sensing the temperatures at different zones of ACR house. Orthographic projections of a typical ACR house with thermocouples location are shown in Fig. 4.2. Experimental setup has been calibrated before and after experimentation. Experimentation was conducted during the peak periods of summer and rainy season. After completing the installation in ACR house, a trail run was conducted for few weeks. After checking the correctness of the data, experimental investigations have been carried out for the following five conditions:

- Summer day without ventilation
- Summer day with ventilation at night
- Summer day with ventilation
- Rainy day with ventilation
- Rainy day without ventilation

The data obtained is analyzed and an average value of the temperature data at different zones is used for quantitative analysis of ACR house. Fig. 4.2 depicts the locations of thermocouples in ACR house during experimentation.

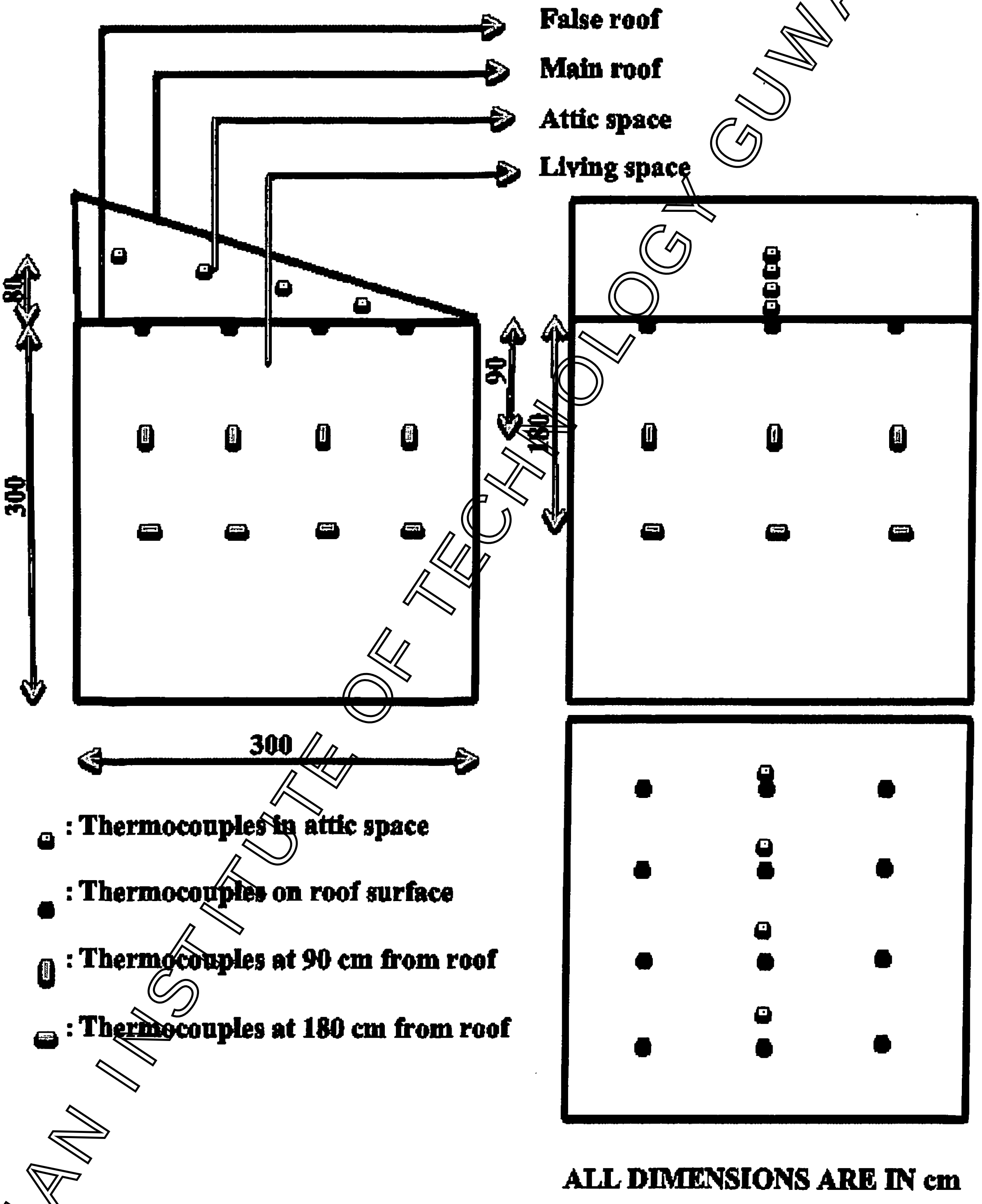

Fig. 4.2: Orthographic views of ACR house.

Forty thermocouples are used for sensing the temperatures at different locations of the room. Twelve of them are installed to measure false roof temperature (FRT). Two sets of twelve thermocouples each are installed, one set at 0.9 m below the false roof and the other set at 1.8 m below the false roof, to sense the living space temperature (LST). Four thermocouples are installed in attic space to measure the attic space temperature (AST).

4.2.3 Results and Discussion

Fig. 4.3 indicates the variation of temperature in different zones namely, false roof temperature (FRT), attic space temperature (AST), and living space temperature (LST) of an ACR house. It shows the variation of the temperature of above stated zones for a period of 15 days starting from 26th May to 10th June. It is also observed that the temperature of all the zones fall considerably by 5°C during the onset of rainy season. Diurnal variation is more in case of FRT and less in case of LST. Out of 15 days, analyses have been conducted in the following sequence. First 3 days was during summer with near zero ventilation, next 2 days was during summer with night ventilation, next 4 days was during summer with ventilation, next 3 days was during rainy season with ventilation and last 4 days was during rainy season with near zero ventilation.

It is observed that during daytime FRT is greater than AST, where as it is reverse in case of nighttime. During the daytime in summer, the difference is varying from 2 to 5°C and it is limited to 0.5 to 2°C in a rainy day. During the night time, AST is slightly less than FRT in summer season and it is slightly greater in rainy season. In both summer and rainy seasons, FRT is greater than LST during daytime and the trend is same in case of nighttime also. In summer the difference between FRT and LST during the daytime is varying from 4 to 6°C and it is limited to 2 to 3°C on a rainy day. In both the seasons, the variation is 1 to 2°C during the nighttime. The variation of AST and LST are in harmony with each other irrespective of seasons. LST is always less than AST by 1.5 to 2°C.

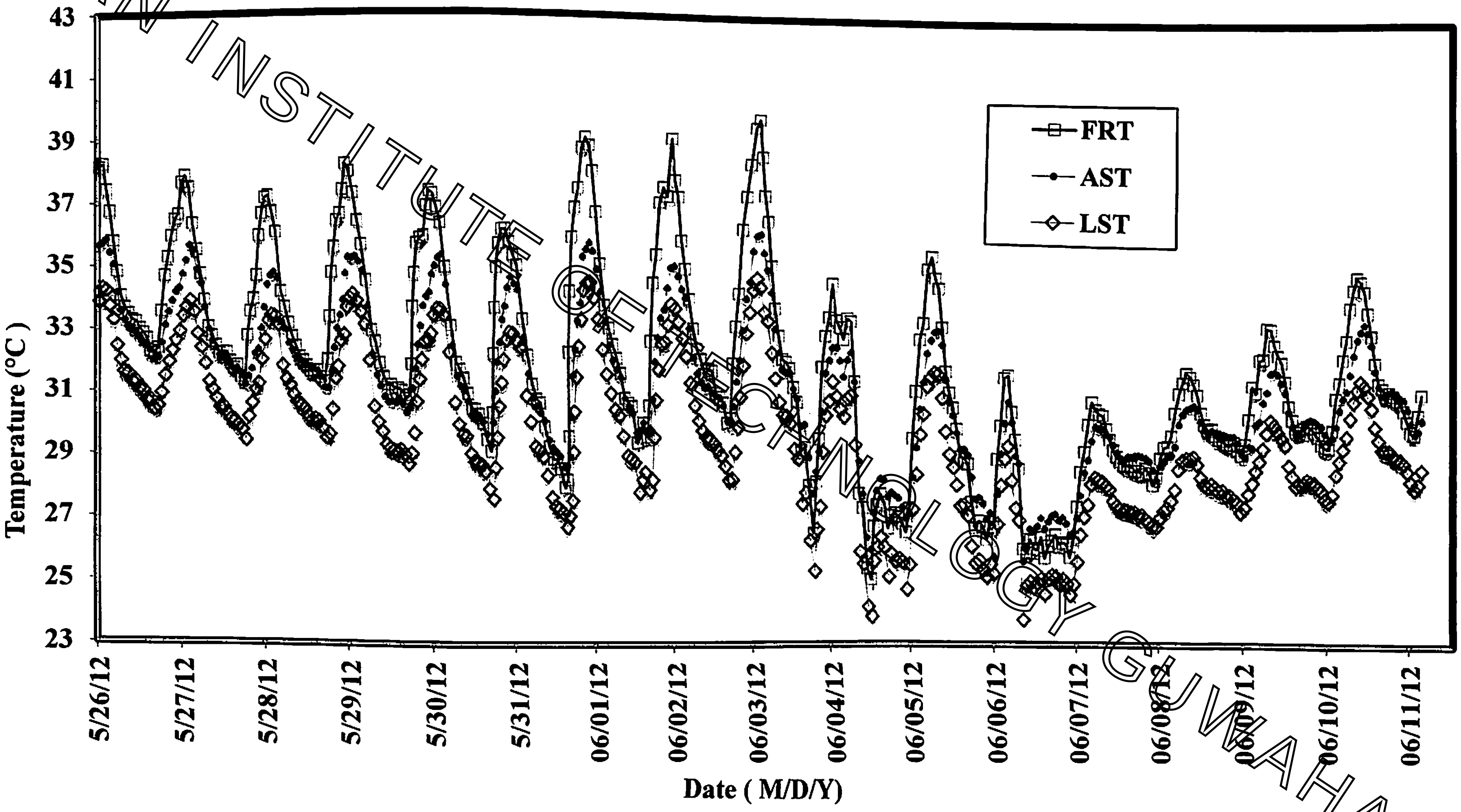

Fig. 4.3: Diurnal temperature variation of different zones for 15 days

4.2.3.1 Summer Day without Ventilation

Fig. 4.4 illustrates the variation of FRT, AST and LST of non-ventilated condition during a summer day dated 28th May 2012. The minimum, maximum and diurnal temperatures variation are 27°C, 34°C and 7°C respectively for ambient temperature; 31.5°C, 37.5°C and 6°C respectively for FRT; 31°C, 35°C and 4°C respectively for AST and 29.5°C, 33.5°C and 4°C respectively for LST. The maximum temperatures observed are at 4 to 5 pm for LST, 4 to 5 pm for AST and 2 to 3 pm for FRT. Minimum temperatures are observed in between 6 to 7 am in case of all zones.

4.2.3.2 Summer Day with Ventilation at Night

Variations of FRT, AST and LST of night-ventilated condition during a summer day dated 30th May 2012 are depicted in Fig. 4.5. The maximum temperatures observed are at 5 to 6 pm for LST, 5 to 6 pm for AST and 2 to 3 pm for FRT. Minimum temperature observed is at 6 to 7 am in case of all zones. The minimum, maximum and diurnal temperatures variation are 28°C, 34°C and 6°C respectively for ambient temperature, 30.5°C, 37.5°C and 7°C respectively for FRT, 30°C, 35.5°C and 5.5°C respectively for AST and 28.5°C, 33.5°C and 5°C respectively for LST.

4.2.3.3 Summer Day with Ventilation

Fig. 4.6 illustrates the variation of FRT, AST and LST of ventilated condition during a summer day dated 3rd June 2012. The minimum temperature, maximum temperature and diurnal temperature variation are 27°C, 34°C and 7°C respectively in case of ambient temperature, 30°C, 40°C and 10°C respectively in case of FRT, 30°C, 36°C and 6°C respectively in case of AST and 28°C, 34.5°C and 6.5°C respectively in case of LST. The maximum temperatures observed in all these zones are at 3 to 4 pm, where as the minimum temperature observed is at 6 to 7 am in case of all zones.

4.2.3.4 Rainy Day with Ventilation

Fig. 4.7 depicts the variation of FRT, AST and LST of ventilated condition during a rainy day dated 5th June 2012. The highest temperature attained by ambient temperature, FRT, AST and LST is 29°C, 35°C, 32.5°C and 31.5°C respectively. Minimum temperature and diurnal temperature variations are 25°C and 4°C respectively for ambient temperature, 27°C and 8°C respectively for FRT, 27°C and 5.5°C respectively for AST and 24.5°C and 7°C respectively for LST. The maximum temperatures are observed at 4 to 5 pm and the minimum temperatures observed are at 7 to 8 am, in case of all zones.

4.2.3.5 Rainy day without ventilation

Variations of FRT, AST and LST of non-ventilated condition during a rainy day dated 10th June 2012 are illustrated in Fig. 4.8. The highest temperature attained by ambient temperature, FRT, AST and LST are 33°C, 35°C, 33.5°C and 31.5°C, respectively. The lowest temperature reached by ambient temperature, FRT, AST and LST are 25°C, 29.5°C, 29.5°C and 27.5°C respectively. The diurnal temperature variation of ambient temperature, FRT, AST and LST are 8°C, 5.5°C, 4°C, and 4°C respectively. The maximum and minimum temperatures observed are at 4 to 5 pm and 7 to 8 am respectively for LST, 4 to 5 pm and 7 to 8 am respectively for AST, 3 to 4 pm and 7 to 8 am respectively for FRT.

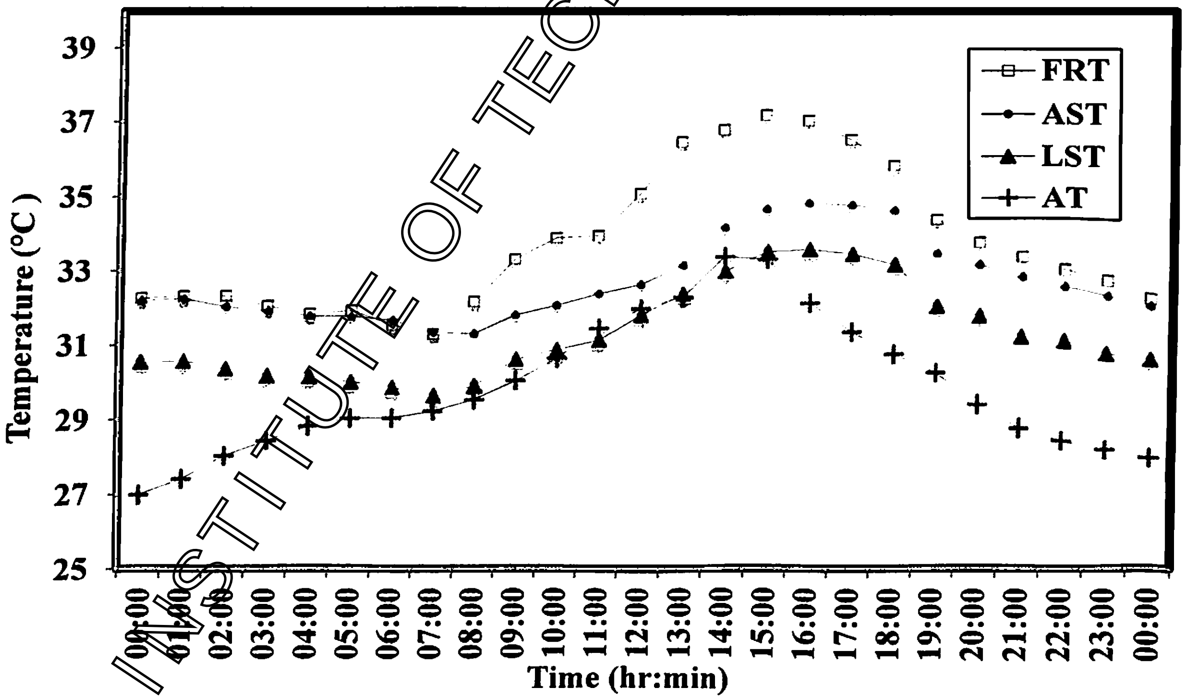

Fig. 4.4:Temperature variation during a summer day dated 28th May 2012 (Non-ventilated condition)

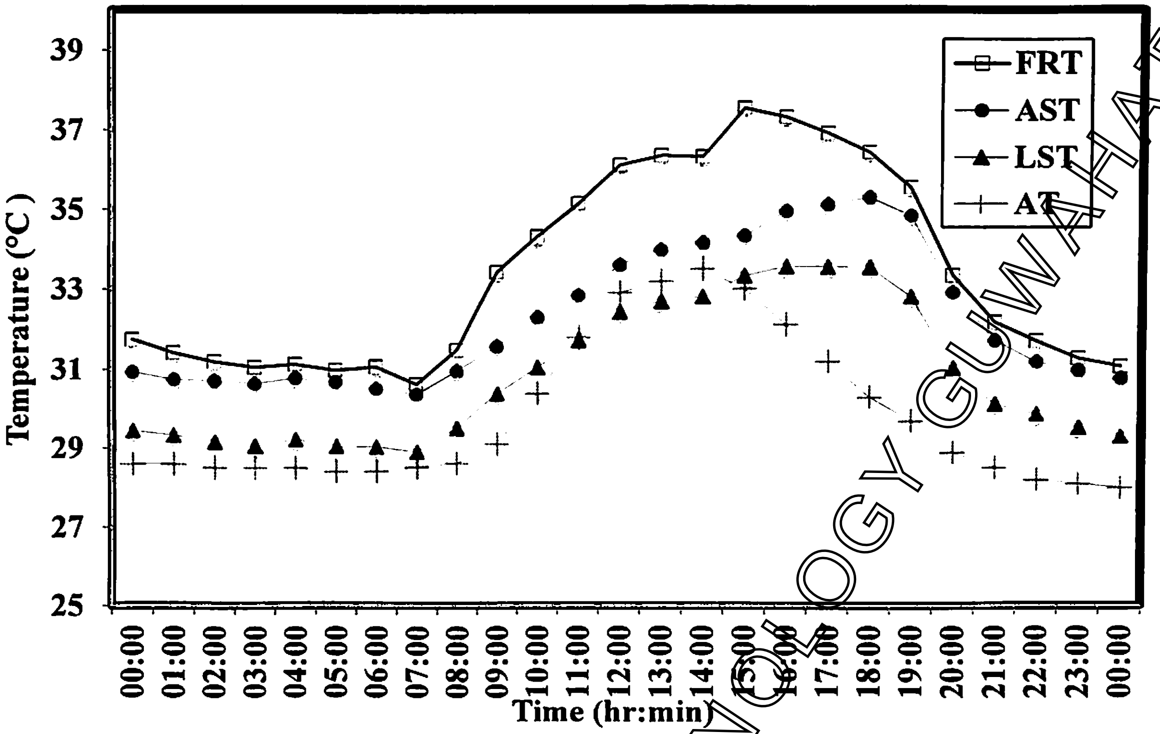

Fig. 4.5: Temperature variation during a summer day dated 30th May 2012

(Night ventilated condition)

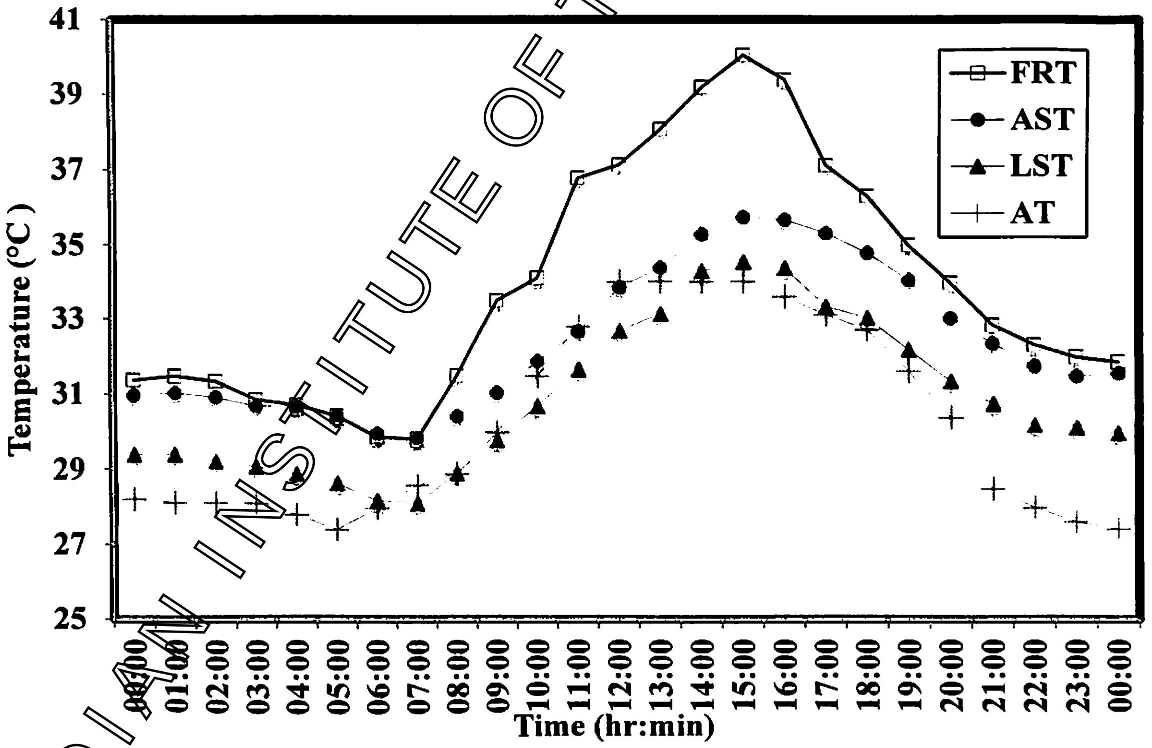

Fig. 4.6: Temperature variation during a summer day dated 3rd June 2012

(Ventilated condition)

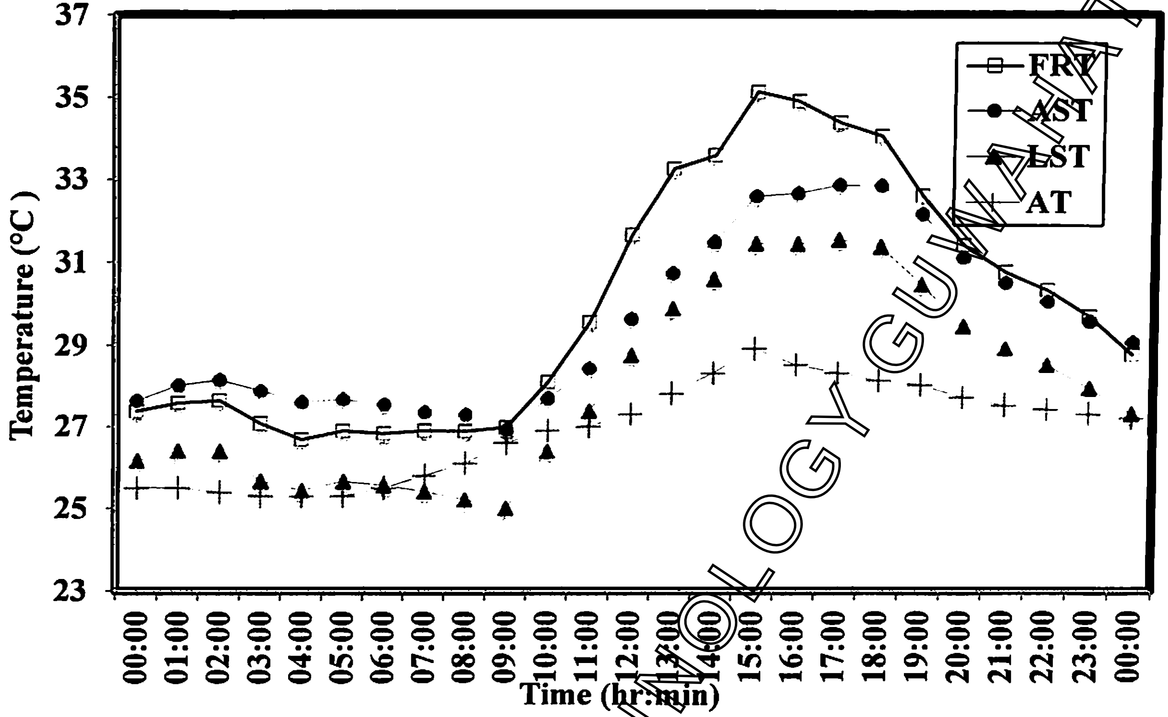

Fig. 4.7: Temperature variation during a rainy day dated 5th June 2012

(Ventilated condition)

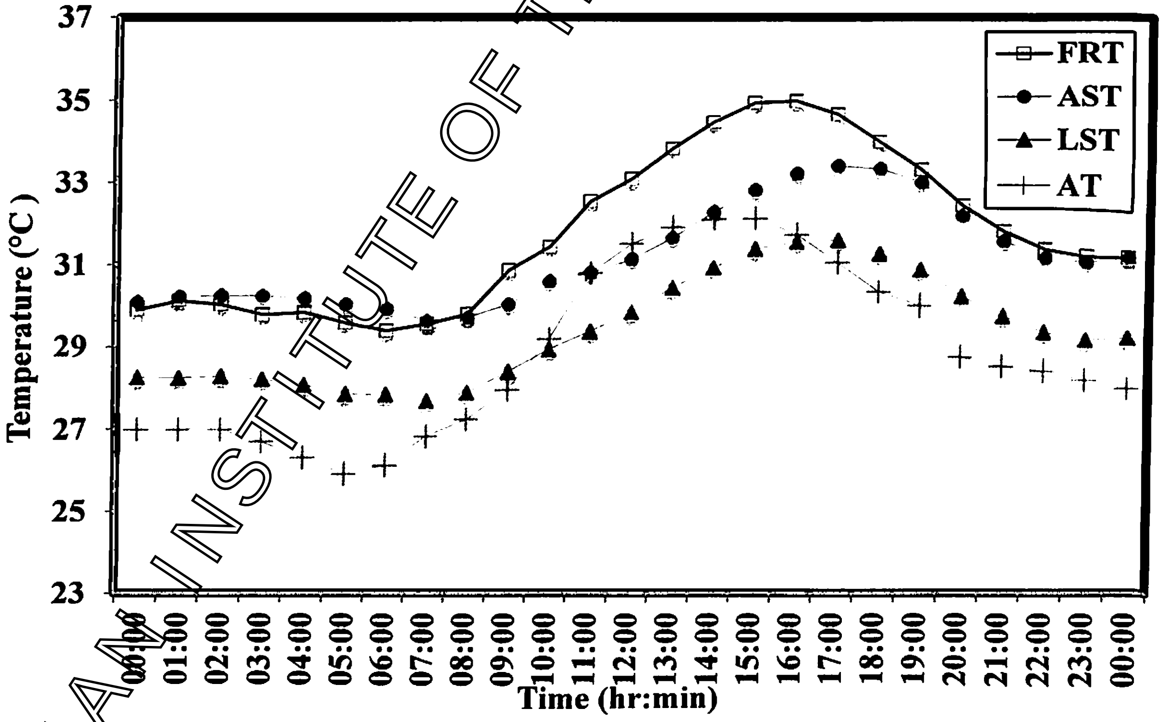

Fig. 4.8: Temperature variation during a rainy day dated 10th June 2012

(Non-ventilated condition)

4.2.3.6 Observations and Summary

The following are major observation from the experimental investigations

a) Non-ventilated conditions during summer

- Accumulation of heat inside the house took place from 7 am to 5 pm.
- Dissipation of heat from the house took prolonged time, which in turn caused discomfort conditions.
- Discomfort conditions prevailed in living space during most of the period.
- The minimum temperature of the living space was 2°C more than minimum ambient temperature and was same as ambient temperature in case of maximum.
- Time lag of 3 to 4 hr was observed in case of attaining maximum temperature inside the living space when compared to false roof.

b) Night ventilated conditions during summer

- Accumulation of heat inside the house took place from 7 am to 5 pm.
- When ventilation was provided in night 75%, heat was dissipated within three hr, but it took prolonged time in dissipating remaining amount of heat.
- Discomfort conditions prevailed in living space as it was failed to maintain the temperature of living space less than atmospheric temperature.
- The minimum and maximum temperatures of the living space were in tune with ambient temperature.
- Time lag of 3 to 4 hr was observed in case of attaining maximum temperature inside the living space when compared to false roof.

c) Full day ventilated conditions during summer

- Accumulation of heat inside the house took place from 7 am to 3 pm.
- The slope of heat dissipation curve was more or less similar to heat accumulation curve.
- Discomfort conditions prevailed in living space.

- The minimum and maximum temperatures of the living space were in tune with ambient temperature.
- Negligible time lag was observed in case of attaining maximum temperature inside the living space when compared to false roof.

d) Full day ventilated conditions during rainy season

- Accumulation of heat inside the house took place till the sunset.
- Dissipation of heat from the house took prolonged time than that of summer.
- Period of discomfort was less when compared to summer period.
- The minimum temperature maintained in living space was slightly more than the ambient temperature. Where as, maximum temperature of living space completely depended on the cloud cover.
- Negligible time lag was observed in case of attaining maximum temperature inside the living space when compared to false roof.

e) Non-ventilated conditions during rainy season

- All the conditions prevailed are more or less similar to that of the case of ventilated conditions during rainy season. Only difference observed is one-hour time lag while attaining maximum temperature inside the living space when compared to false roof.

In the warm humid climatic conditions, the thermal performance of an ACR house in rainy season is better than that of summer season. ACR house performed better in maintaining thermal comfort during rainy season in case of both ventilated and non-ventilated conditions. The effect of ventilation on thermal performance is negligible in rainy season. During summer season, significant improvement in thermal performance is achieved by providing full day ventilation. But ACR house failed in maintaining thermal comfort even after providing ventilation to living space. The major drawback of ACR house is its inability in restricting heat flow to living space in summer. Positive aspects, negative aspects of ACR house along with suggestions for betterment are provided below:

Positive points:

- Attic space reduced the LST by 2°C by restricting the conductive heat transfer from main roof to false roof.
- False roof helped in reducing the radiant heat flow to the living space and acted as a barrier for radiation emitted by main roof.
- Attic space restricted the heat loss from the living space during rainy season.

Negative points and suggestions:

- Attic space failed in dissipating heat by convection to the environment and in turn caused the accumulation of heat in attic space during summer. This negative aspect can be minimized by roof ventilation technique, which provides ventilation to attic space.
- Attic space failed in restricting radiant heat flow from main roof to false roof. Due to this reason, the FRT is always more than that of AST during summer and it increased the heat flow into living space. Providing suitable reflective coating, which reduces the radiant heat flow from main roof to false roof, over the false roof can rectify this drawback.

Thermal performance of ACR house in summer season can be improved by incorporating the above stated suggestions.

4.3 Comparative Analysis of RCC and TMT Roof Dwellings

Selection of residential buildings for quantitative analysis is the key aspect for comparative study and proper care was taken in selection of residential buildings. Since the area of concentration is on roof, selection of houses were done by keeping all the remaining features, which influence the temperatures of inner spaces, same as far as possible for the selected houses. Hostel rooms of educational institution were considered for experimentation, which are similar in all aspects except roof. Single bedded hostel rooms were selected for comparative study, one of which is in top floor of hostel with TMT roof, second one is in top floor of hostel with RCC roof. The rooms identified for experimentation are located in National Institute of Technology Calicut.

Various factors were kept same for the selected rooms during experimentation are mentioned below:

- Volume of the living space to area of plan view
- Thickness of the walls
- Area of openings and its positions
- Orientation of building
- Zero shading on roof due to trees etc.

On and above all the factors, all the openings of rooms during experimentation were closed to minimize the effect of outside wind on living space. The rooms considered for quantitative analysis chosen in such a way, to avoid any variations in the environmental factors during experimentation, that they are located within the radius of half kilometer.

4.3.1 Thermal Performance Analysis of TMT Roof House

Orthographic projections of a typical TMT house are same as shown in Fig. 4.2. A typical TMT residential living room with dimensions of 3 m length, 3 m breadth and 3 m height is considered for conducting thermal performance analysis. TMT house consists of main roof, attic space, false roof and living space. Main roof is constructed with traditional mud tiles and gypsum board is used as false roof. Space enclosed between main roof and false roof is called as attic space and living space is the space between false roof and the floor.

4.3.1.1 Experimentation

Experimentation kit containing forty “T” type thermocouples, connecting wires and Agilent data logger were used to log the temperature data from thermocouples. Experimentation was conducted during the peak period of summer (April 2013). After completing the installation, a trail run was conducted for few weeks, after checking the correctness of the data; all the openings including doors, windows, and ventilators of the room were closed and started the experimentation process. Location of thermocouples in TMT roofed room during experimentation is similar as shown in Fig. 4.2. Forty thermocouples were used for sensing the temperatures at different locations of the room. Twelve of them were installed to measure false roof temperature (FRT). Two sets of twelve thermocouples each were installed, one set at

0.9 m below the false roof and the other set at 1.8 m below the false roof, to sense the living space temperature (LST). Four thermocouples were installed in attic space to measure the attic space temperature (AST).

4.3.1.2 Results and Discussion

The data obtained is analyzed and an average value of the data is used for quantitative analysis. Fig. 4.9 illustrates the variation of average temperatures of false roof (FRT), attic space (AST) and living space (LST) along with the ambient temperature (AT). Ninety min. lag is observed while reaching to maximum temperature in all zones, i.e. false roof, attic space and living space, when compared with ambient temperature. Ambient temperature (AT) reached to maximum of 36°C between 13:00 to 14:00 hrs. Where as in case of false roof, attic space and living space, temperature reached to maximum of 39°C, 35°C and 33.6°C respectively between 15:00 to 16:00 hr. Minimum AST and minimum FRT are same, and always found greater than that of minimum AT and minimum LST. At the same time minimum LST is always greater than that of minimum AT.

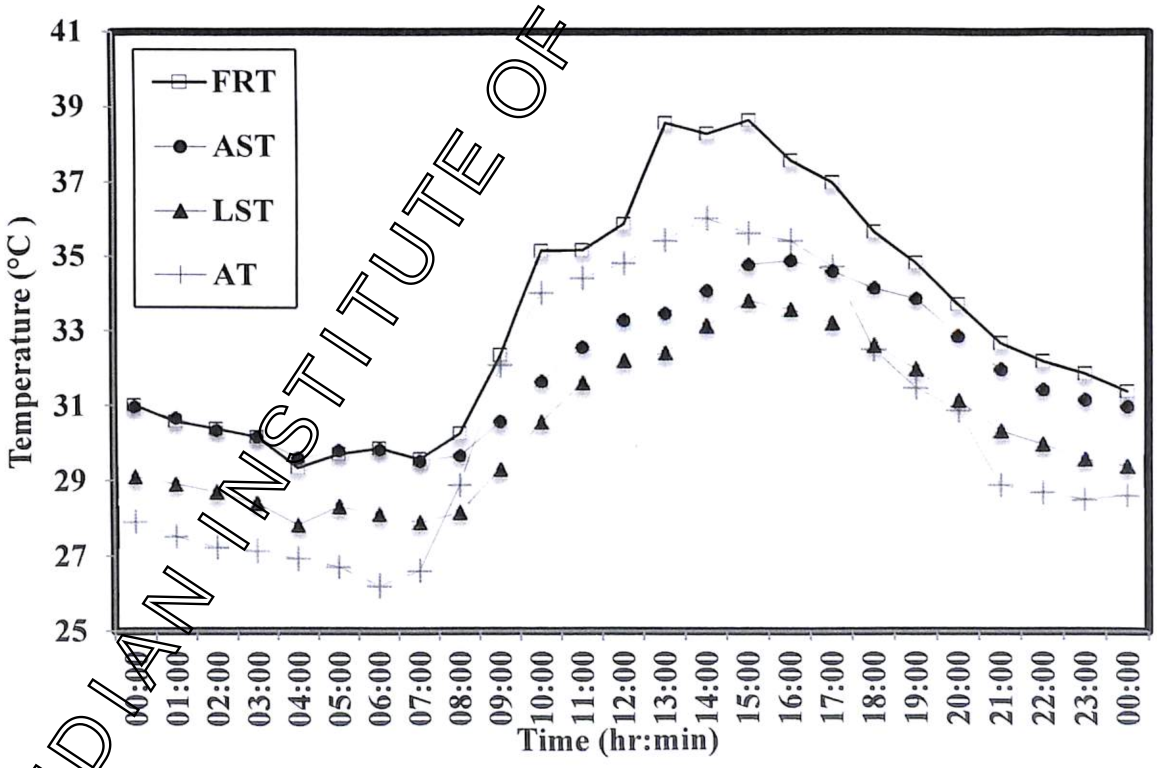

Fig. 4.9: Temperature variation in TMT roofed dwelling

4.3.2 Thermal Performance Analysis of RCC Roof House

A typical RCC residential living room with dimensions of 3 m length, 3 m breadth and 3 m height is considered for conducting thermal performance analysis. RCC house consists of roof and living space with surrounding walls. Roof is constructed with Reinforced cement concrete with 15 cm thickness. Orthographic projections of a typical RCC house are shown in Fig. 4.10.

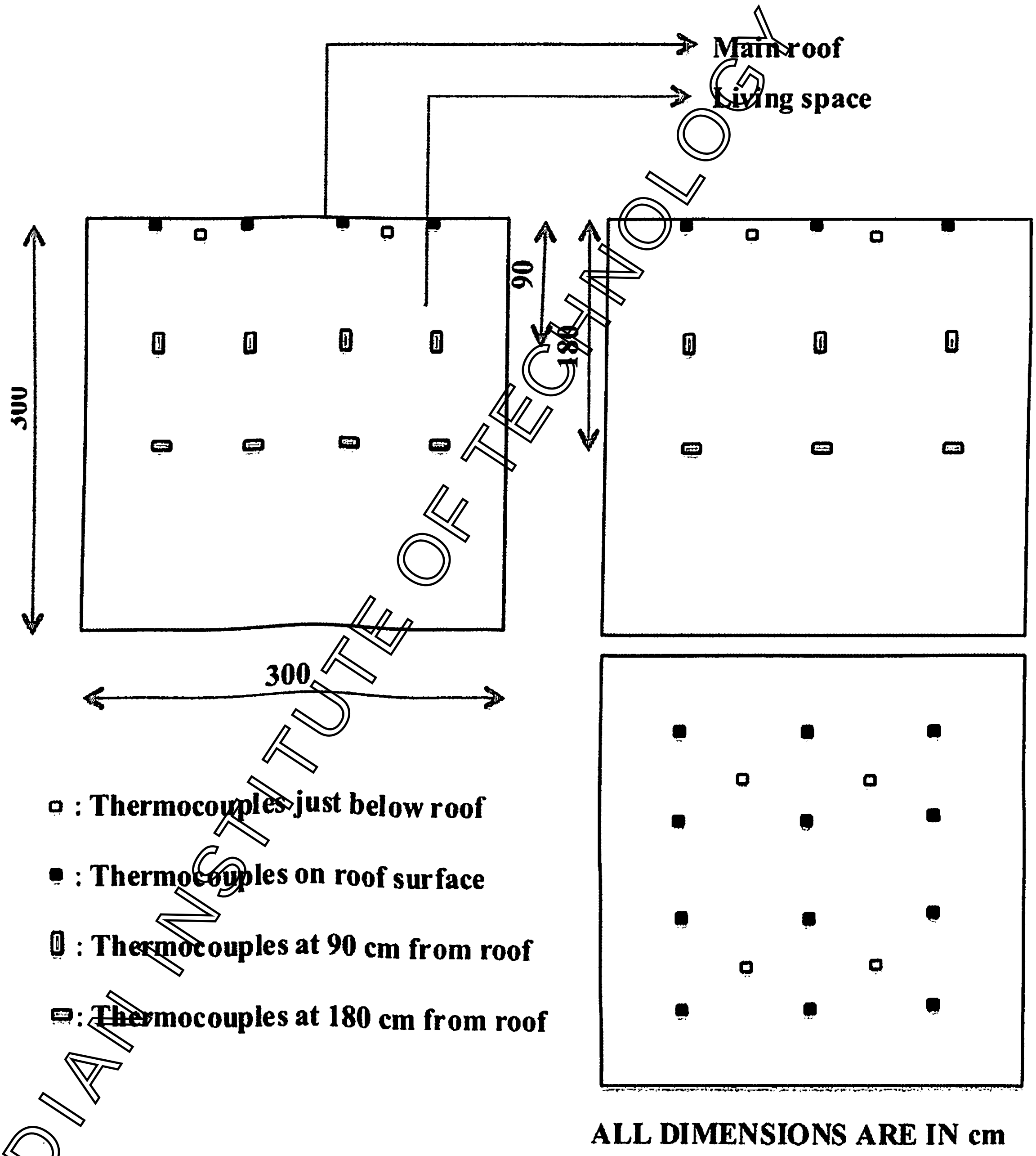

Fig. 4.10: Location of thermocouples in RCC roofed dwelling

4.3.2.1 Experimentation

Experimentation is carried out in similar way, during the same period, as conducted in TMT roof house. Fig. 4.10 shows location of thermocouples in RCC roofed room during experimentation. Forty thermocouples were used for sensing the temperatures at different locations of the room. Four thermocouples were installed just below the roof to sense the air temperature near roof (ATNR). Two sets of twelve thermocouples each were installed, one set at 0.9 m below the roof and the other set at 1.8 m below the roof to sense the air temperature at 0.9 m (AT3) and air temperature at 1.8 m (AT6) respectively. Remaining twelve thermocouples were installed to measure RCC roof temperature (RRT).

4.3.2.2 Results and Discussion

Variation of average temperatures of RCC roof and living space at different levels is shown in Fig. 4.11 along with the ambient temperature. A three-hour lag is observed in case of RCC roof in attaining maximum temperature when compared to the temperature of ambient. Ambient temperature reached to maximum of 36°C between 13:00 to 14:00 hr. RCC roof temperature (RRT) was reached its peak of 45.6°C at 17:00 hr.

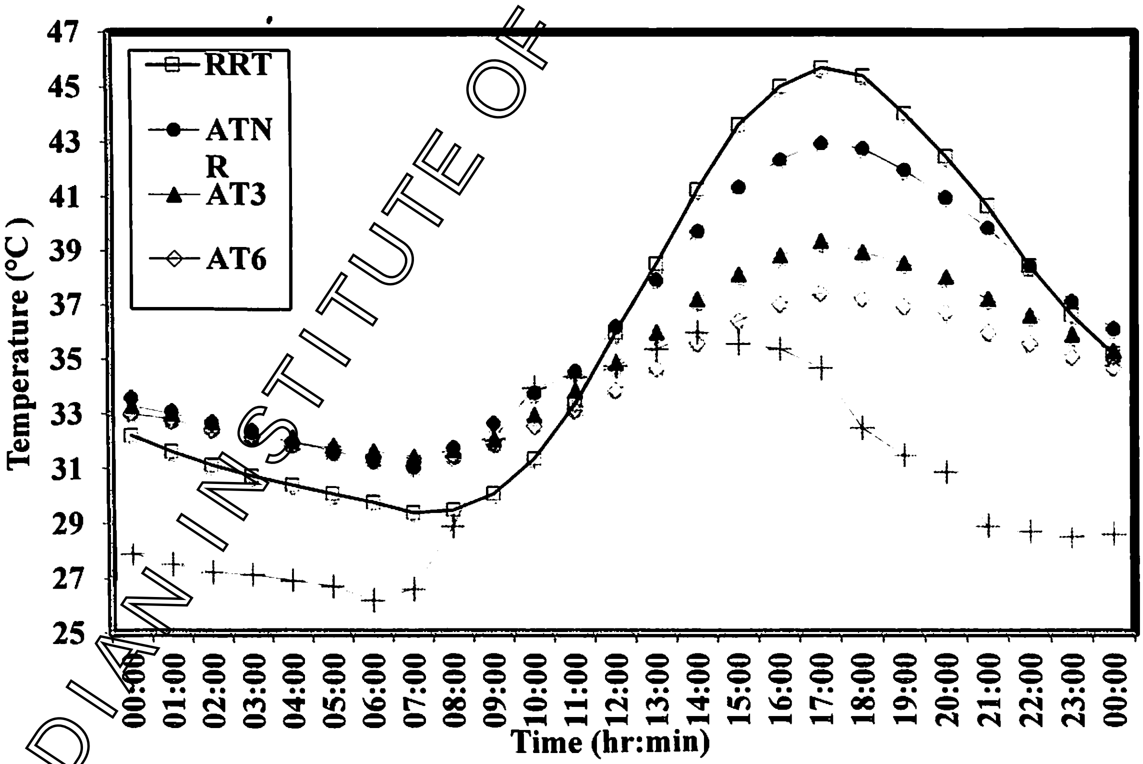

Fig. 4.11: Temperature variation in RCC roofed dwelling

Maximum temperature of air temperature near RCC roof (ATNR), 0.9 m from RCC roof (AT3) and 1.8 m from RCC roof (AT6) were 42.7°C, 39.6°C and 37.3°C respectively at 17:00 hr. Minimum temperature of RCC roof surface and living space were 30.1°C and 32.5°C respectively. These values are greater than the minimum ambient temperature by 2.6°C and 5°C, respectively.

4.3.3 Comparative Thermal Performance Analysis

For comparative analysis, average values of living space temperatures of TMT roofed room (TLST) and RCC roofed room (RLST) is plotted along with ambient temperature (AT) in Fig. 4.12. It provides the insight of how each type of roofing system faring in maintaining the living space temperatures. RCC roofed room maintained the temperature of living space lower than ambient between 8:00 to 12:00 hr. It failed to maintain the temperature below the ambient during the remaining period and the difference reached to maximum of 8.6°C at 21:00 hr. Under similar conditions, mud tile roofed room performed better by maintaining inside temperature below or almost same as the ambient between 7:00 to 20:00 hr. Temperature maintained inside was slightly more than ambient during remaining period and reached to a maximum difference of 1.3°C

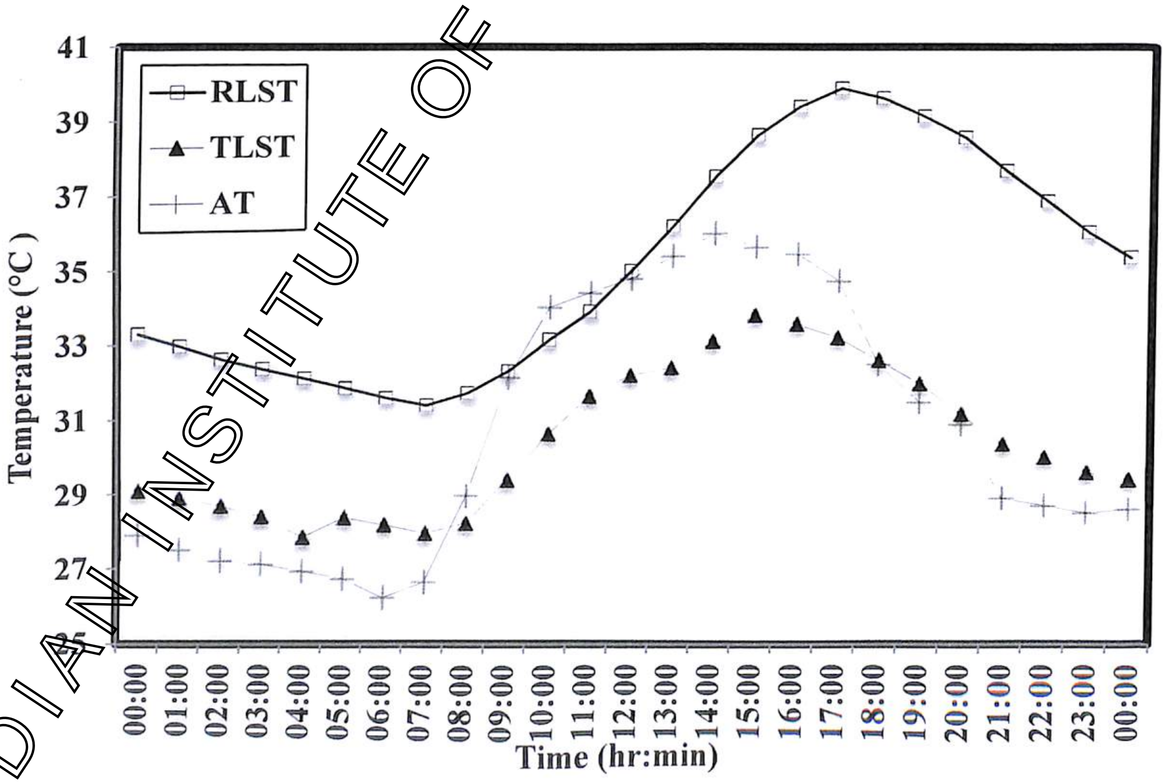

Fig. 4.12: Temperature variation of TMT and RCC roofed house

4.4 Observations and Summary

Quantitative analysis provided the clear picture of the role of roof in maintaining thermal comfort inside buildings. For climatic conditions of Kozhikode, under non-ventilated condition of living space, it is found that RCC roof is not suitable in summer days and failed to maintain the inside temperatures with in the comfortable range. Most of the time, inside temperatures of the RCC building are above the ambient and reached to a maximum of 40°C which is 4°C more than ambient. At the same time TMT roofing maintained the inside temperatures well below the ambient at peak time and reached a maximum of 33.6°C which is 2.4°C less than ambient. It also found that the maximum temperature in living space is slightly more than that of ambient temperature in case of ACR house. So, it is possible to reduce the temperature of living space of ACR house further by providing roof ventilation technique.

Thermal storage capacity of RCC roof is the major reason for elevated temperatures in living space. Thermal energy stored in RCC roof during day time is dissipated into living space during the night time that results into living space temperatures more than ambient during night time. In case of TMT roof, attic space acts as insulator for conductive heat transfer and ceiling acts as a radiation barrier and avoids heat transfer from main roof to false roof. Attic space always in interaction with outside ambient conditions because of unique structure of TMT main roof and it helps in dissipating the heat from attic space to outdoor through the means of convection heat transfer. Due to the above stated reasons TMT roof able to maintain the living space less than ambient conditions during the daytime. To support the outcome of quantitative analysis, reduced scale model study was conducted and details of the study is presented in next Chapter.

Chapter 5

REDUCED SCALE MODEL STUDY

5.1 Design and Details of Reduced Scale Model

The room considered for quantitative analysis is having the dimensions 3 m length, 3 m breadth and 3 m height. Characteristic dimension (X) is defined as the ratio of volume of living space to roof area of living space in plan view and its value for the prototype is 3 m. Dimensions of the reduced scale model was obtained by keeping this characteristic dimension (X) same as that of prototype. Dimensions of reduced scale model, obtained by fixing the shape as the frustum of square pyramid, are 0.45 m square base, 0.15 m square top and height 0.69 m.

Reduced scale models with designed dimensions were fabricated with 12 mm thick plywood sheets with provision for insulation. Entire assembly was made as airtight by sealing all the joints with silica sealant and 2 cm thick thermocol sheets were pasted on both sides of the plywood sheets, i.e., four walls and base, to minimize the heat transfer through the walls and base of the model. Cross sectional view of reduced scale model is shown in Fig. 5.1. Commonly used roofing materials in southern India, Reinforced Cement Concrete (RCC) and Mud tile, along with Corrugated asbestos cement, Galvanised Iron Sheet (GIS) and Flat asbestos sheet were considered for experiments. Properties of each roof material are provided in Table 5.1. Flat asbestos sheet used for experimentation was painted with white cement on top surface. Five identical reduced scale models were fabricated and the selected roofing materials are incorporated on top of each model. Heat transfer through the walls made negligible by providing insulation on both sides of the walls and base.

Table 5.1: Physical properties of roofing material (Norman, 1985)

Roof Material	Thickness (cm)	Density (kg/m^3)	Specific heat (J/kg K)	Thermal conductivity (W/mK)
RCC	12	2300	880	1.58
TMT	1.2	1892	880	0.798
ACR	0.6	1520	840	0.245
GIS	0.05	7520	500	61.06

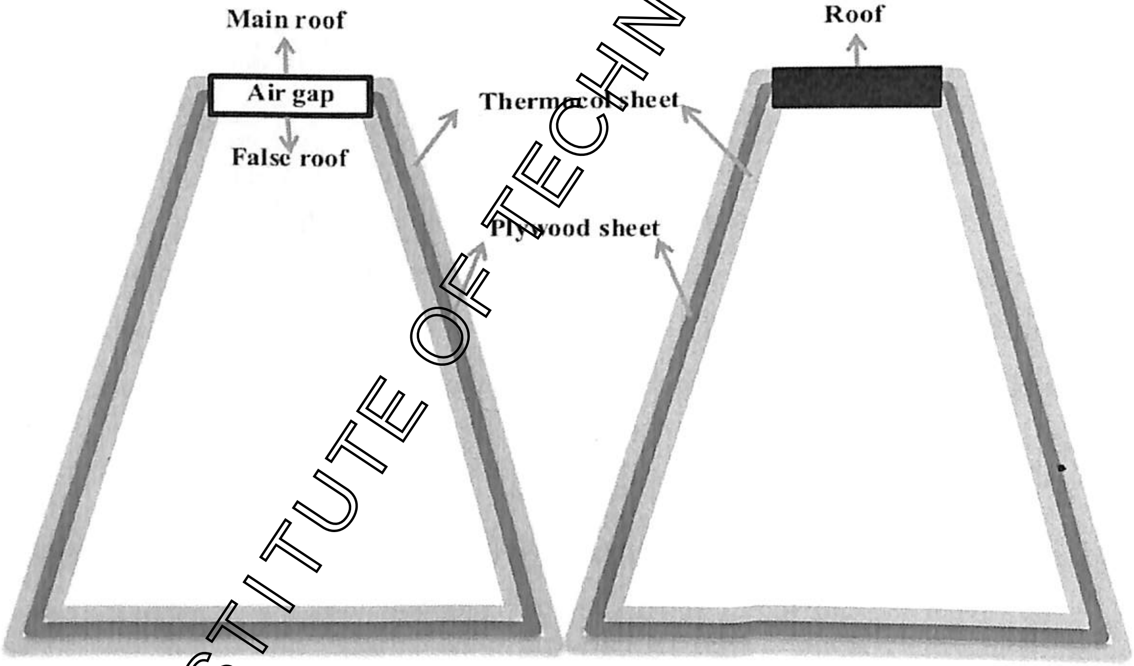

Fig. 5.1: Schematic of reduced scale models with and without roof ventilation

5.2. Experimentation

Each reduced scale model was fixed with four T type thermocouples, one on top surface of the roof, one on bottom surface of the roof and the remaining two were fixed in enclosed space. Total twenty thermocouples were installed in five models and all these thermocouples were connected to a data logger.

All these thermocouples along with data logger were calibrated before and after experimentation. Entire setup was installed in open atmosphere on rooftop of the building and experimentation was carried out over two weeks continuously during summer season (23rd March 2013 to 10th April 2013). Installed setup is depicted in Fig. 5.2. Due to the constraints to conduct the experiments in open atmosphere, similar experiment setup was made to simulate the real conditions inside the laboratory with artificial heating arrangement.

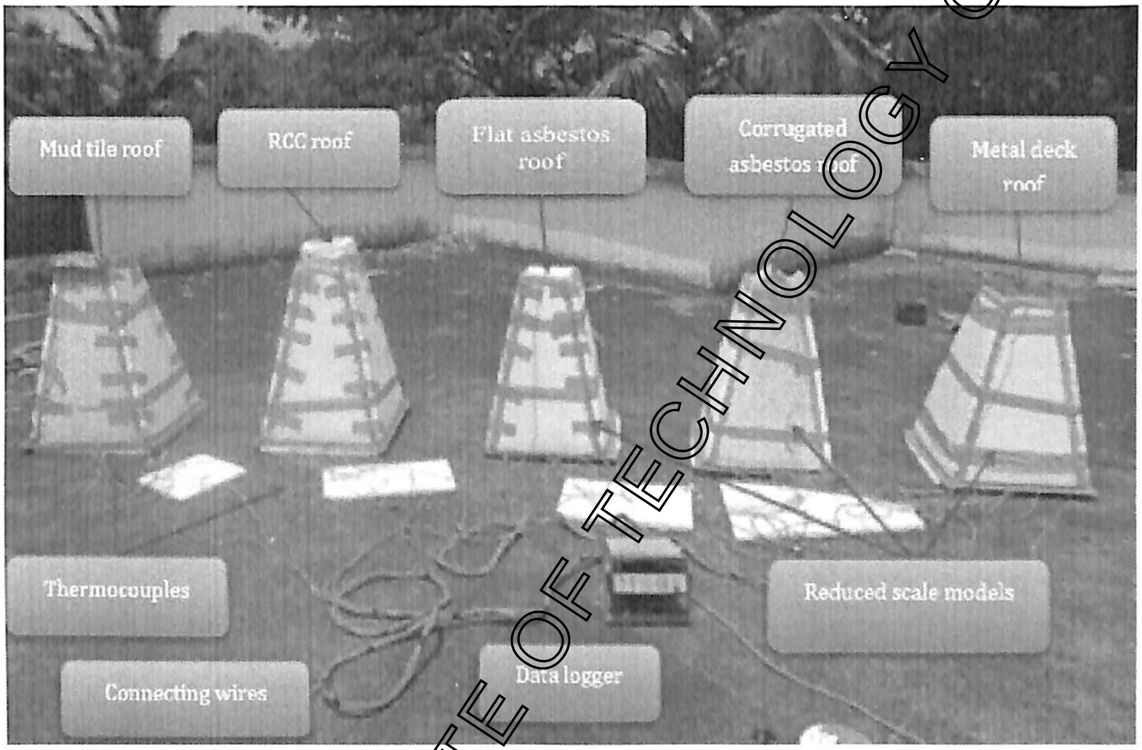

Fig. 5.2: Experimentation with reduced scale models under sun light

The details of experimental components for artificial heating are given below:

Plate heater

Five plate heaters were made using nichrome wire, mica sheet, and aluminium sheet. The nichrome wire is wound around the surface of mica sheet at one side. The dimension of plate heater is (15*15) cm^2, which is equal to surface area of roof.

The length of wire under certain capacity and voltage is given by,

$$L = (U^2 \times \pi \times d^2) / (4 \times \rho \times P \times 10^3)$$

Where, d = Diameter of heating wire, mm

ρ= Resistivity of heating wire, $\Omega\ mm^2/m$ (1.1 to 1.2 $\Omega\ mm^2/m$)

P = Power , Kilowatts

V = Voltage, Volts

L = Length of heating wire, m

Gauge: 30 gauge

$L = (240^2 \times \pi \times 0.2540^2)/(4 \times 1.2 \times .950 \times 10^3)$

$= 3.07$ m

Stand

The stand arrangement is prepared for hanging plate heaters. The stand has the provision for height variation.

Autotransformer (Dimmerstat)

An autotransformer is used to vary the voltage across the heating element (plate heater). The maximum voltage capacity of an autotransformer is 260 V. The calibration of autotransformer carried out by using standard voltmeter and multimeter.

Ammeter

Ammeter is used to measure flow of current through heating element. The range of ammeter is 0 to 10 A. It was calibrated before proceeding to experiments.

An artificial heating arrangement was made for testing the roof ventilation technique on the reduced scale models. The schematic of experimental set up is shown in Fig. 5.3. Five heaters with equal capacity were made and installed on all five models with level adjustable stands. Dimmerstat was used to control the flow of current through heaters by adjusting the voltage. By considering the bottom surface temperature as reference, entire experimentation conducted in open atmosphere was simulated inside the lab by controlling the dimmerstat and operating parameters needed for simulating the experiments were identified for each roofed model. These operating parameters, current and voltage, helps us in maintaining required conditions for each roof material while conducting experiments with artificial heating arrangement.

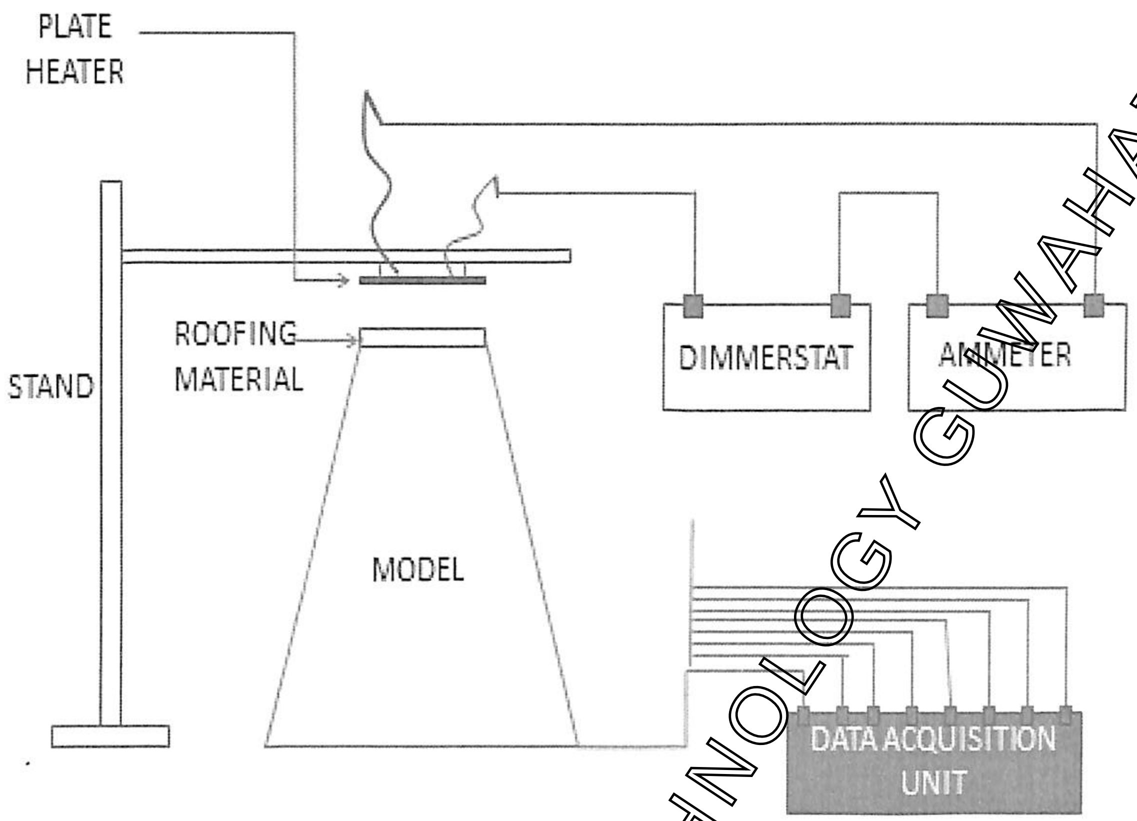

Fig. 5.3: Schematic of experimental setup for artificial heating

To identify an optimum air gap for roof ventilation under free flow condition, five similar ventilated roofs with variable air gap between main roof and false roof were fabricated and incorporated in reduced scale models. Flat asbestos cement sheet was used as main roof and gypsum board was used as false roof. Air gap maintained for five models were 2 cm, 4 cm, 6 cm, 8 cm and 10 cm. Constant heating was provided for all models during experimentation, since the roofing materials are same in all five models. After identifying the optimum air gap, comparative analysis was carried out between RCC roofed model and the model with optimum air gap for a complete day with the help of the identified operating parameters of these two roofing materials. Schematic diagram of ventilated roof model is depicted in Fig. 5.1.

5.3 Results and Discussion

5.3.1 Experiments under Sunlight

Variation of top and bottom roof surface temperatures for each model is shown in Fig's 5.4 to 5.8. Difference in top and bottom roof surface temperatures was observed during peak temperatures in all models. The difference in temperatures of top and bottom roof surfaces was observed through out the day and night except few meeting points in case of RCC model. Where as a slight difference in top and bottom roof surface temperatures were observed during nights in case of GIS model. Experimental data obtained on 31st March 2013 is analyzed and depicted the variation of top roof surface temperatures and bottom roof surface temperatures of all models in Fig's 5.9 and 5.10 respectively

The temperature variations of top roof surface for mud plate, non-asbestos sheet, corrugated asbestos sheet, GI sheet and reinforced concrete block are shown in Fig. 5.9. From Fig. 5.9, it is observed that FAS roof attains lower temperature at top surface as compared to other roofing materials during peak period i.e., from 10 am to 5 pm. During the first half period i.e, before 12 pm RCC roof and TMT roof temperatures are lower than CAS roof and GIS roof, whereas the reverse phenomenon was observed after 12 pm. The maximum top surface temperature attained by FAS roof is 47°C at 12.00 pm and for concrete block, mud plate, corrugated asbestos sheet and GI sheet are 52°C, 52°C, 56°C and 56°C respectively. These variations in temperatures in roofing materials are because of difference in material properties of roofing materials such as thermal conductivity, solar absorptivity, solar reflectivity. The top surface temperature of FAS model is less than other models due to the high reflectivity of white paint. However, the lowest top surface temperature for all roofing materials are nearly same due to the absence of solar heat at early morning.

The temperature variations of bottom roof surface for mud plate, non-asbestos sheet, corrugated asbestos sheet, GI sheet and reinforced concrete block are shown in Fig. 5.10. From Fig. 5.10, it is observed that concrete block transfers less heat to its bottom surface as compared to all other roofing materials. The maximum bottom surface temperature attained by concrete block was 45°C between 3 pm to 4 pm. The bottom surface temperatures attained by mud plate, flat asbestos sheet and corrugated asbestos sheet were 50.7°C, 44.7°C and 53.2°C between 12 pm to 1 pm respectively. The GI metal sheet attained maximum bottom surface temperature of 57.9°C at same time interval. However, the lowest bottom surface temperature readings for all roofing materials are nearly equal during night. Concrete block reached to minimum temperature of 24°C at 8 am.

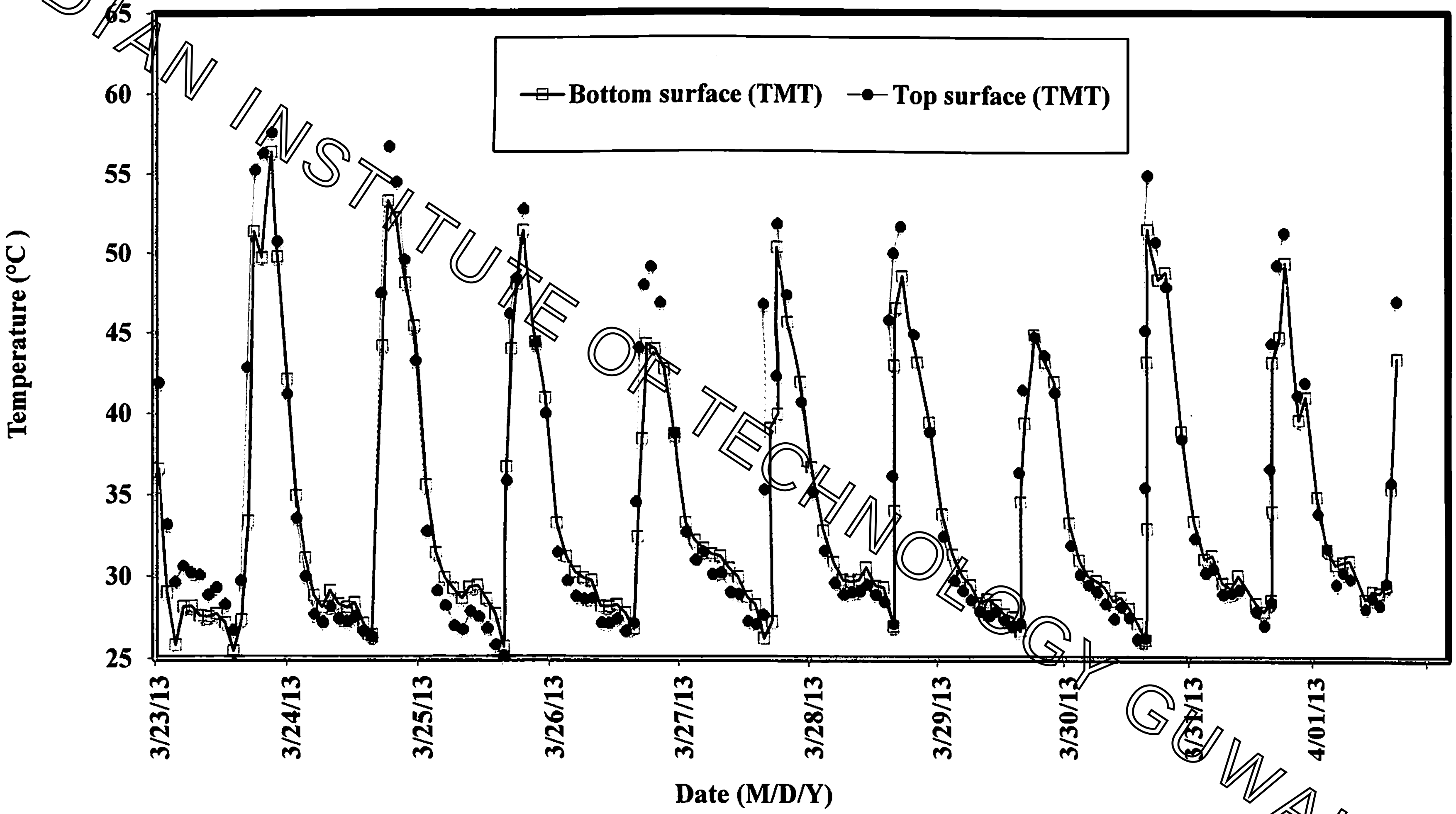

Fig. 5.4: Variation of top and bottom surface temperatures of TMT model

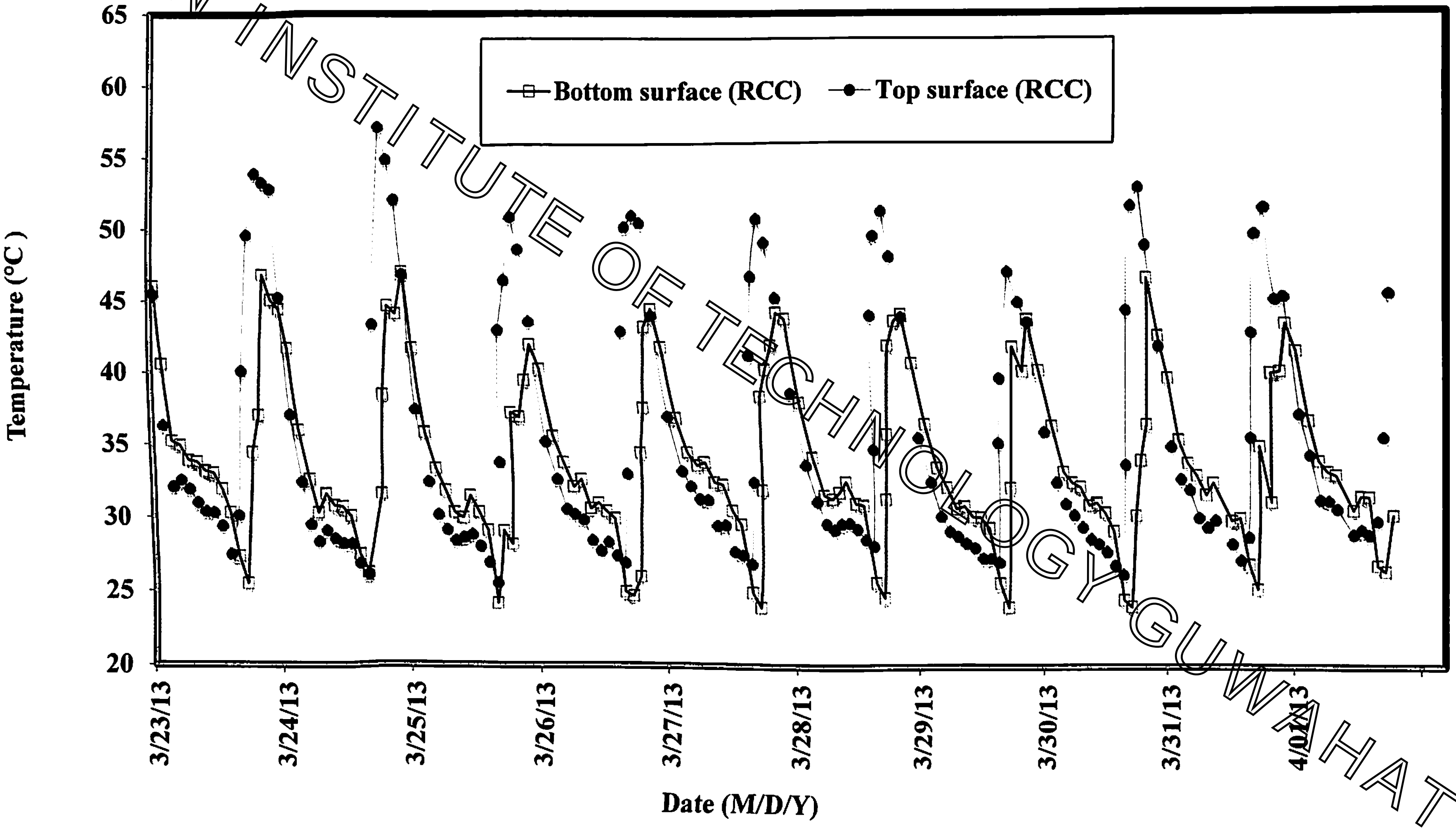

Fig. 5.5: Variation of top and bottom surface temperatures of RCC model

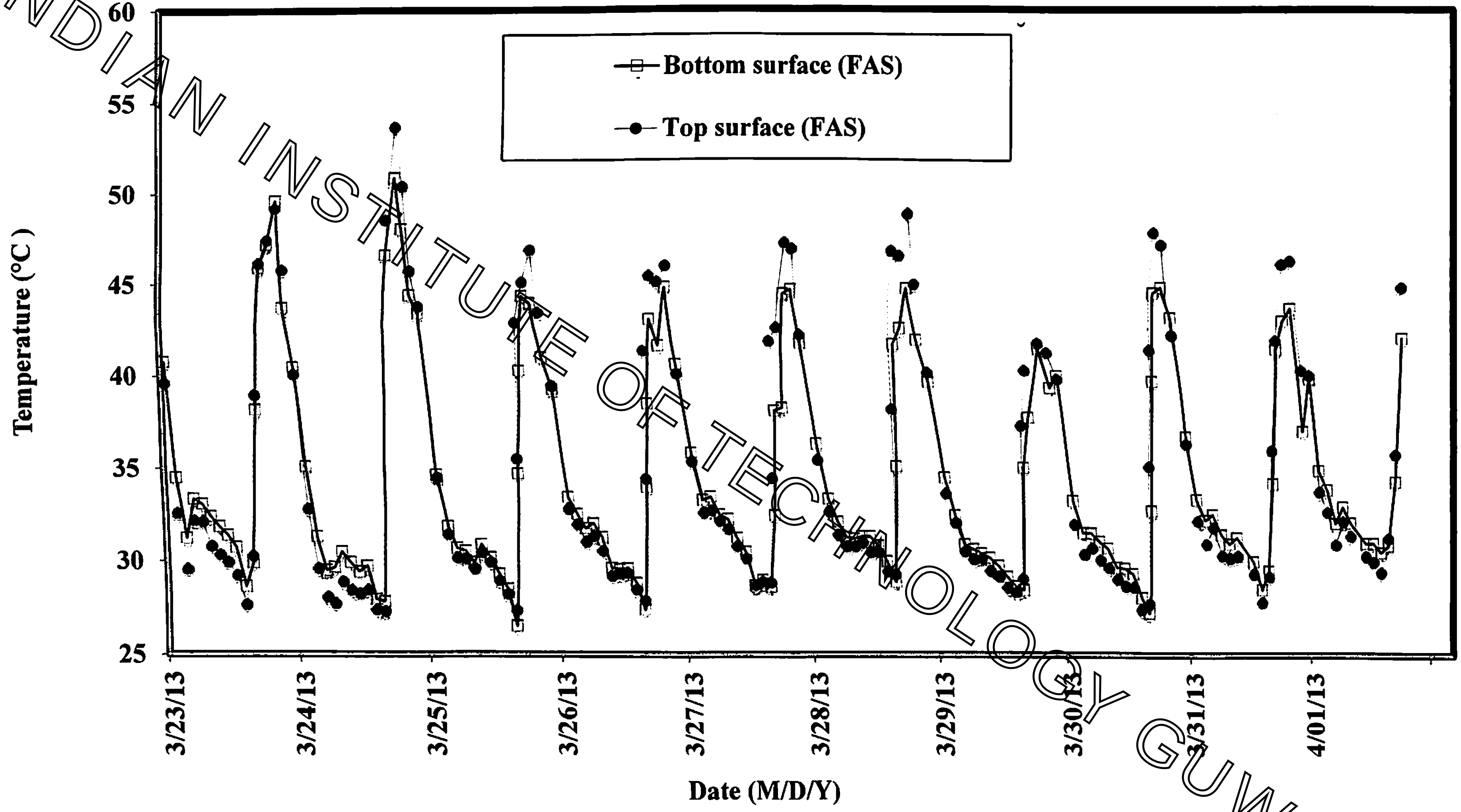

Fig. 5.6: Variation of top and bottom surface temperatures of FAS model

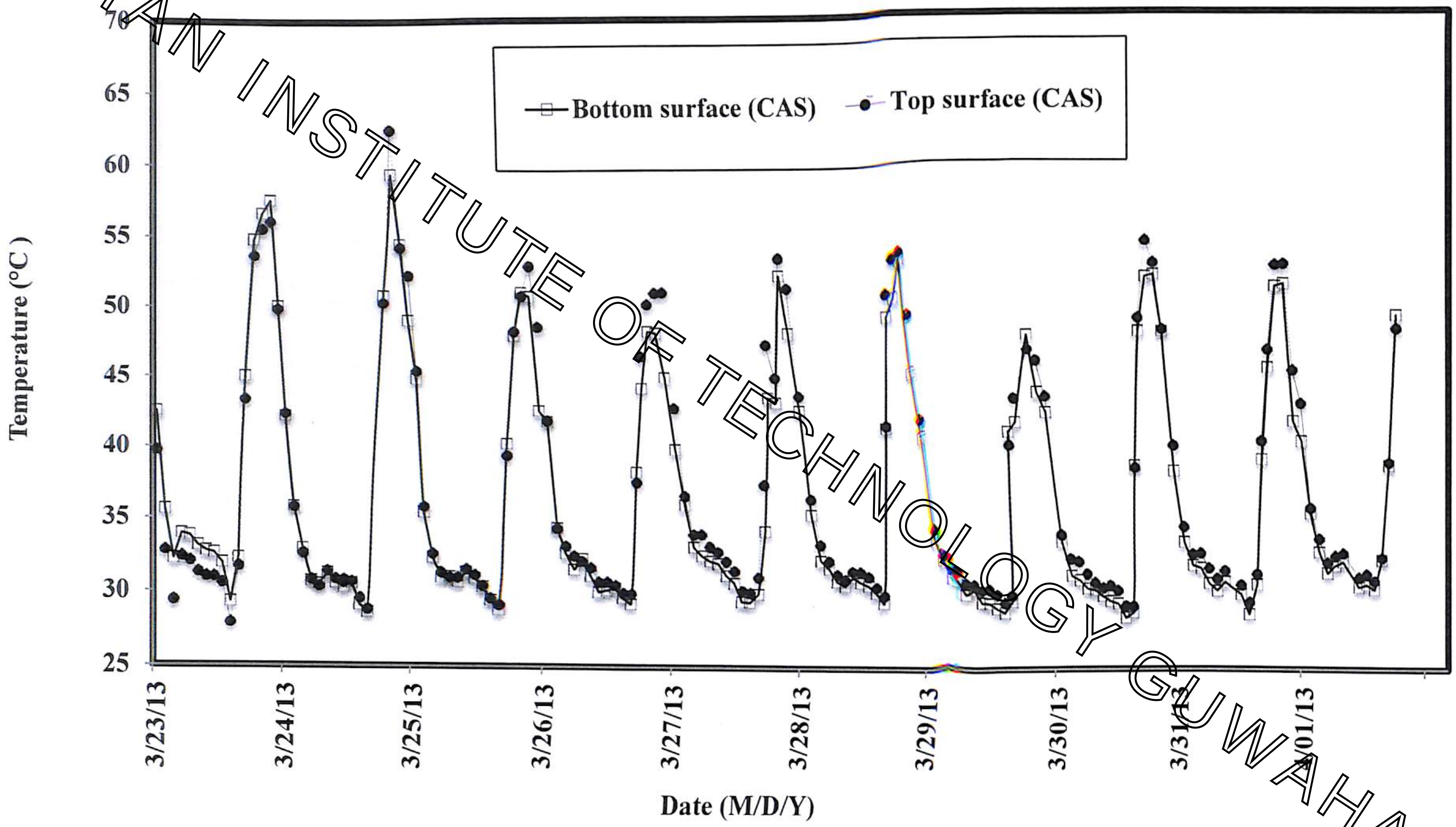

Fig. 5.7: Variation of top and bottom surface temperatures of CAS model

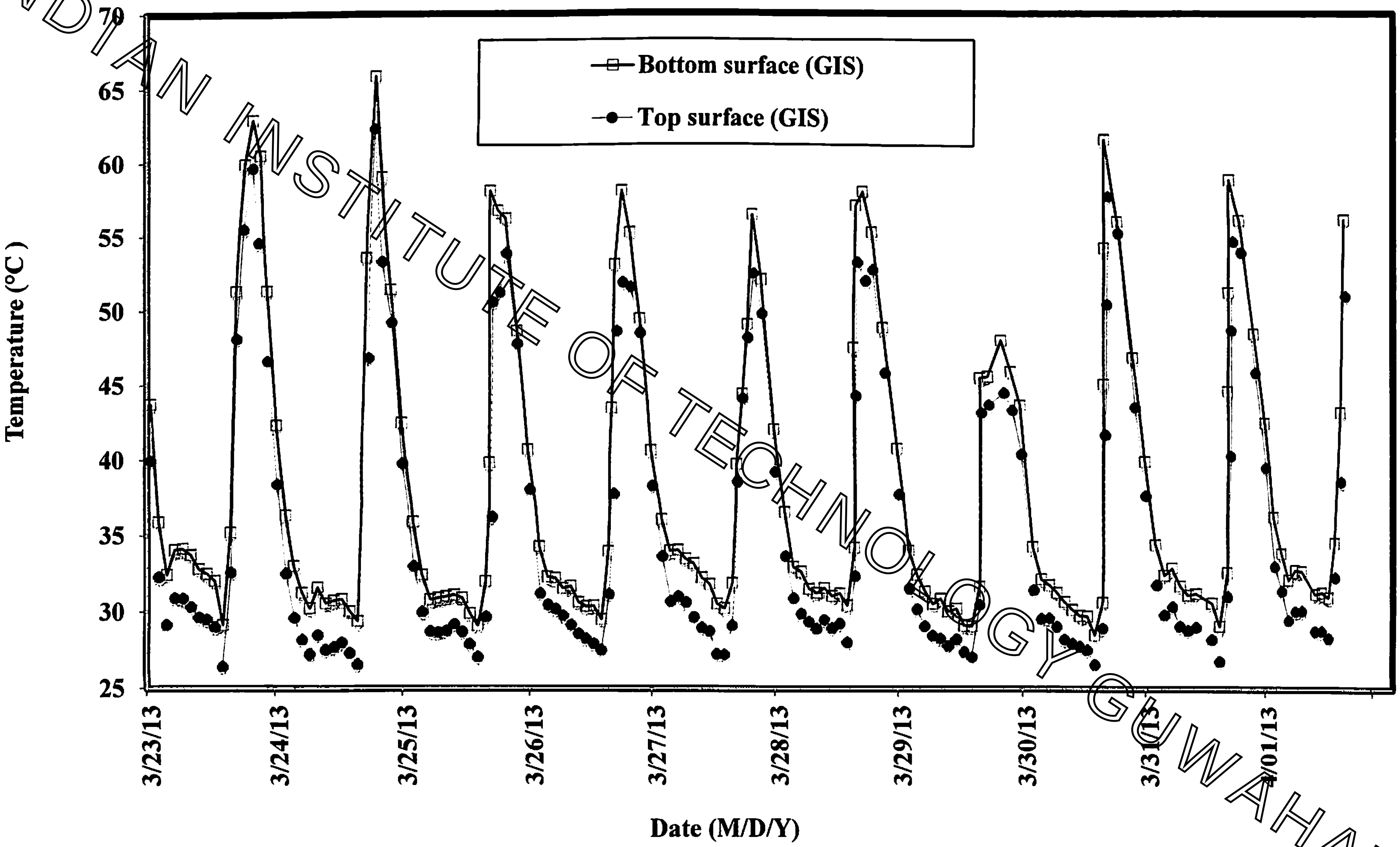

Fig. 5.8: Variation of top and bottom surface temperatures of GIS

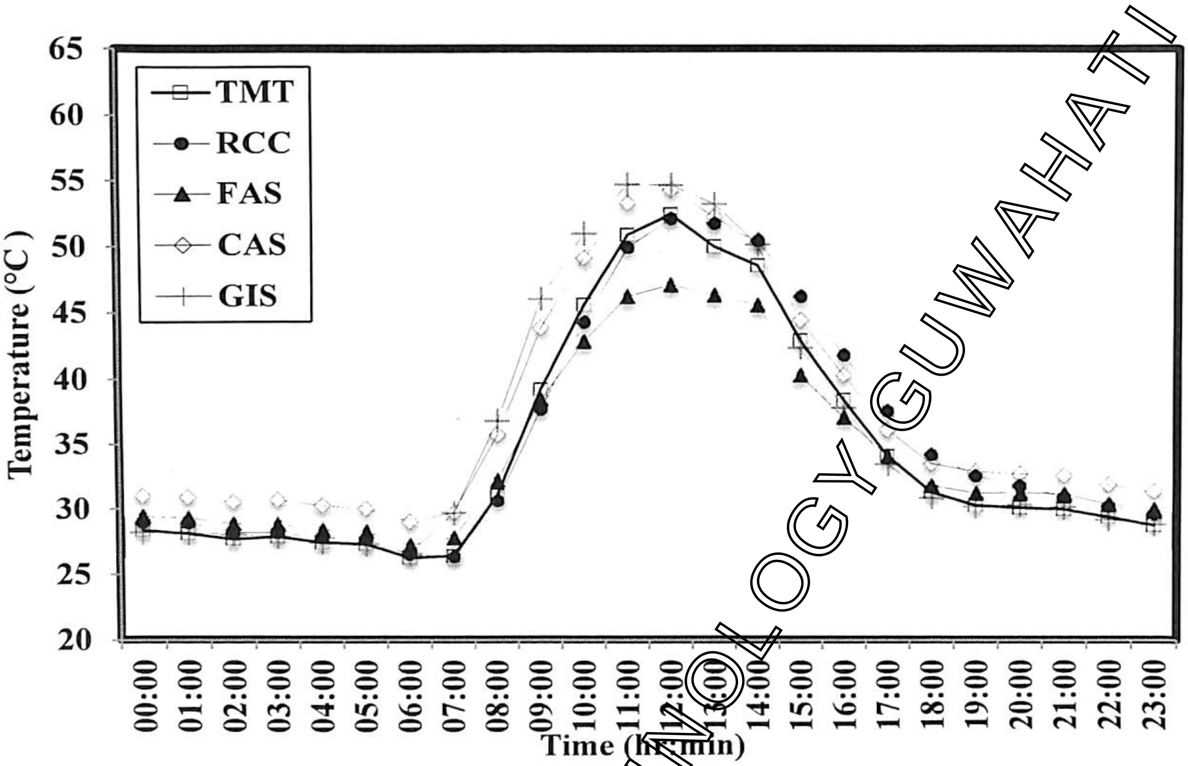

Fig. 5.9: Temperature variations of top roof surface of all models

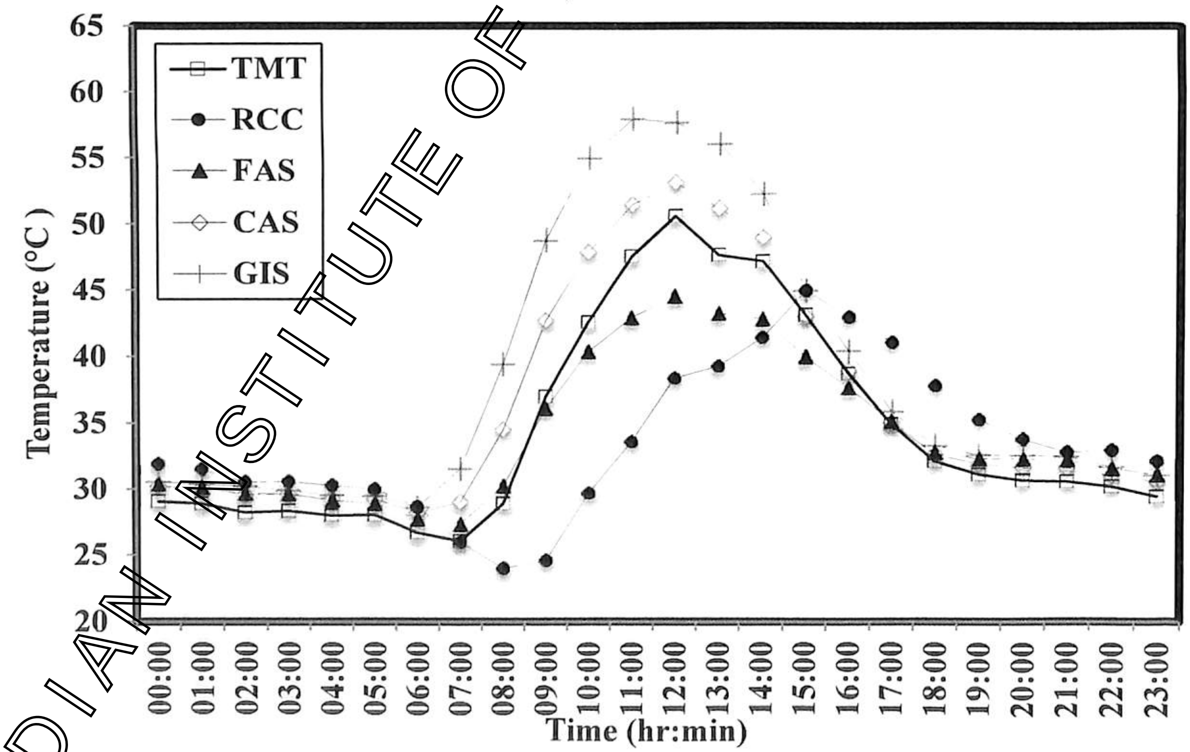

Fig. 5.10: Temperature variations of bottom roof surfaces of all models

From Fig. 5.10, one can conclude that RCC roof is far better than other roofs in zero ventilation conditions. RCC roof performed better in maintaining the bottom surface temperatures less than other roofing materials till 2 pm. The only drawback observed in case of RCC roofed model is that the bottom surface temperatures were reached to maximum of around 44°C between 3 to 4 pm in evening hours and maintained more temperatures than that of other roofing materials after 3 pm. A time lag of 3 to 4 hr was observed in case of RCC roof in attaining maximum bottom surface temperatures when compared with other roofs. The temperature attained by RCC roof is high by 4°C to 6°C, at 5 pm when compared with other roofed models. In remaining four roofed models, temperature variations are in harmony with atmospheric conditions and reached to maximum temperatures around 12 pm. Flat asbestos sheet performed better among the remaining four roofs through out the day and its performance is better than RCC roof after 2 pm. The performance of flat asbestos roof model is comparable with RCC roof model is mainly due to the high reflective nature of white paint.

5.3.2 Experimentation with Artificial Heating

The details of experimental setup for artificial heating is illustrated in Fig. 5.11.

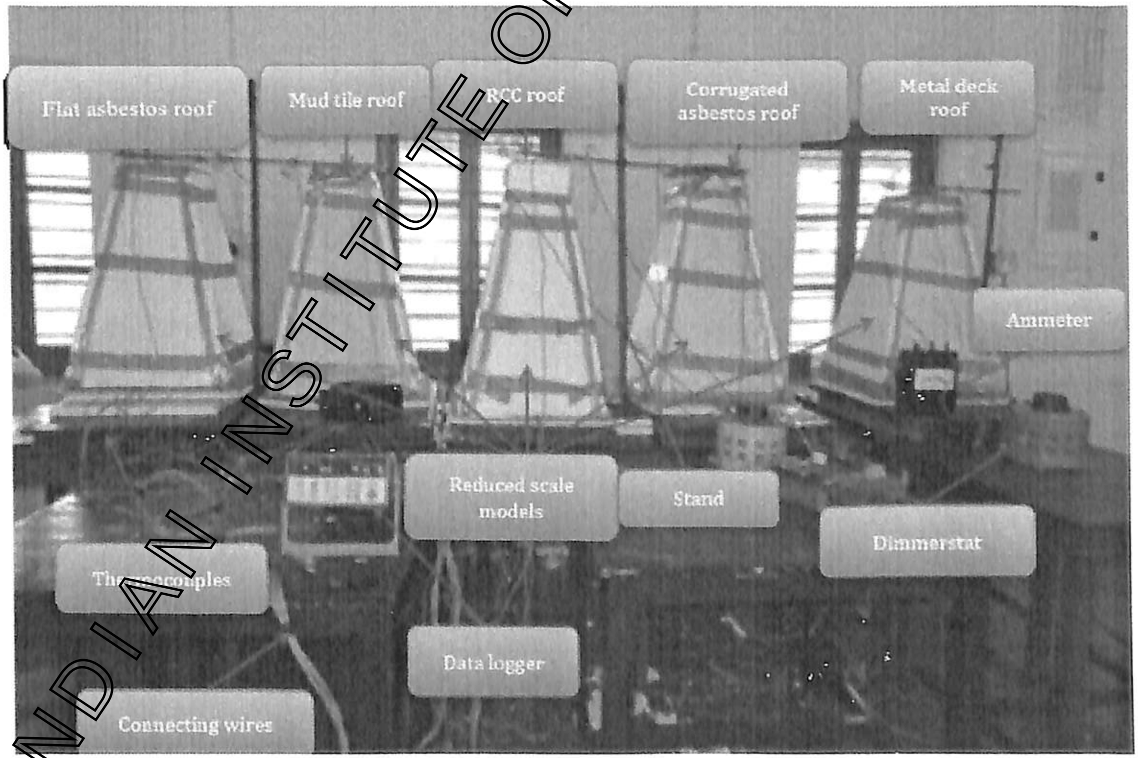

Fig. 5.11:In-house experimentation on reduced scale models with artificial heating

Identified the parameters, current and voltage, need to maintain the required conditions on all the roof materials after rigorous experimentation with artificial heating. Heating effect produced by heating element was controlled using autotransformer with the variation of voltage. Initially constant voltage was applied in steps of 10 volts from 10 volts to 70 volts on RCC model and found the suitable operating range as 30 to 50 volts. Hourly average bottom surface temperature of RCC model based on experiment conducted on 31st March 2013 was obtained and used as reference to replicate the experiment with artificial heating. Voltages required to maintain those temperatures were obtained by conducting series of experiment. Similarly the voltages required to replicate the experiments with asbestos sheet roof were determined in similar lines as explained before. First experiments were conducted to determine the optimum air gap for roof-ventilated model and then conducted for comparative analysis.

5.3.3 Optimum Air Gap for Roof Ventilation

The variations of average temperatures of false roofs (gypsum board) with the air gap are plotted in Fig. 5.12.

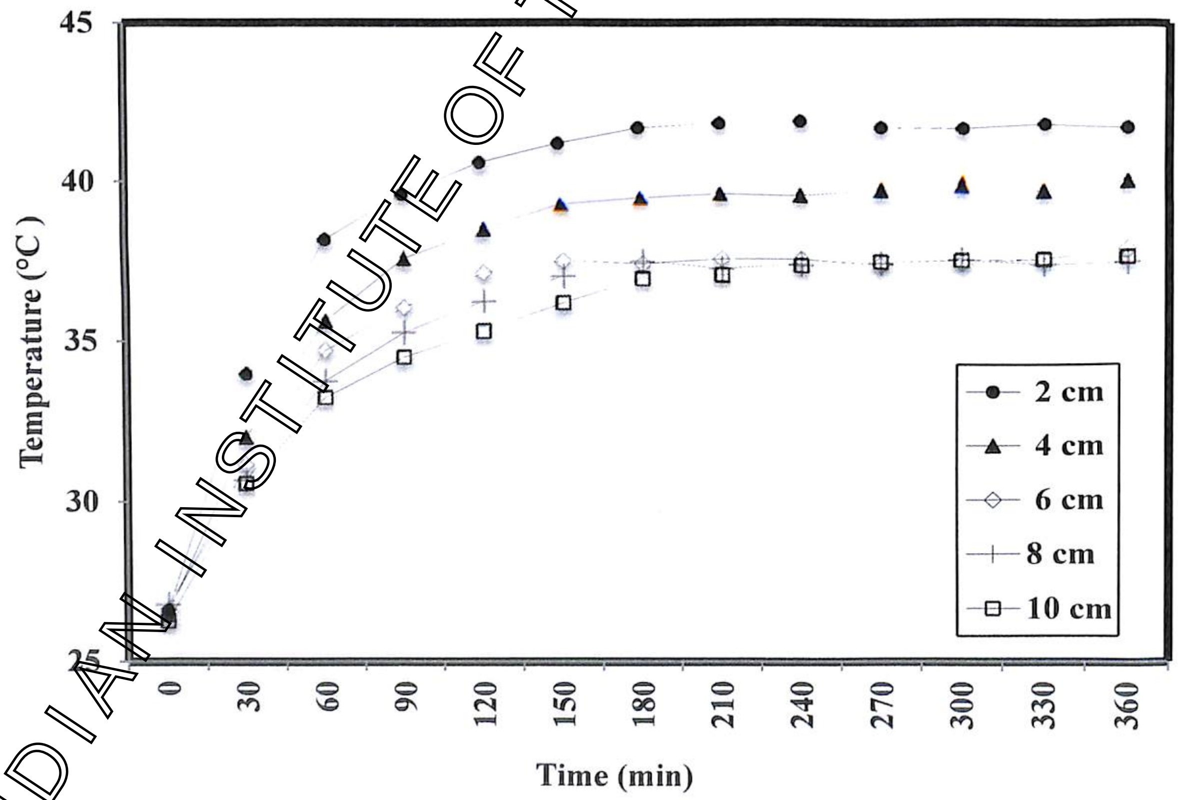

Fig. 5.12: Variation of false roof temperatures of ventilated roof with air gap

Ventilated roofs with air gaps of 2 cm, 4 cm, 6 cm, 8 cm and 10 cm were incorporated in five reduced scale models and all five models were subjected to constant heat flux at 30 volts continuously for 6 hr. Before reaching the steady state, all five ventilated roofs followed the different paths and maintained temperatures inversely proportional to the air gap. After reaching steady state, it is observed that ventilated roofs with 2 cm and 4 cm air gaps maintained different temperatures, but temperatures of ventilated roofs with 6 cm, 8cm and 10 cm air gap were almost same. From this one can conclude that the optimum air gap falls around 6 cm.

5.3.4 Comparative Investigation of Models with RCC Roof and Ventilated Roof

The results obtained in comparative analysis are depicted in Figs. 5.13-5.14. Fig. 5.13 illustrates the variation of temperatures of top and bottom surfaces of RCC roof. The maximum temperatures attained by top surface and bottom surface were 56°C and 46°C respectively. It shows a drop of maximum temperature by 10°C between top surface and bottom surface. A time lag of around 2 hr was observed among them while attaining the maximum temperatures.

Fig. 5.14 illustrates the variation of temperatures of top and bottom surfaces of main roof, flat asbestos cement roof, and the false roof, gypsum board. The maximum temperatures reached by top surface of main roof, bottom surface of main roof and gypsum board were 57°C, 53°C and 42.5°C, respectively. Here a drop of maximum temperature by 14.5°C was observed between main roof and false roof. Time lag observed in this case is not significant; means the temperature variations are in harmony with ambient conditions. Ventilated roof maintained the temperatures less than RCC roof during afternoon and evening times and achieved a maximum difference of 8°C in between 4 to 5 pm.

Thermal performance of RCC roofed model along with ventilated roof model is presented in Fig. 5.15. From Fig. 5.15, one can predict that RCC roof is performing better between 7 am and 12:30 pm, Ventilated roof is performing better than RCC roof during remaining hours.

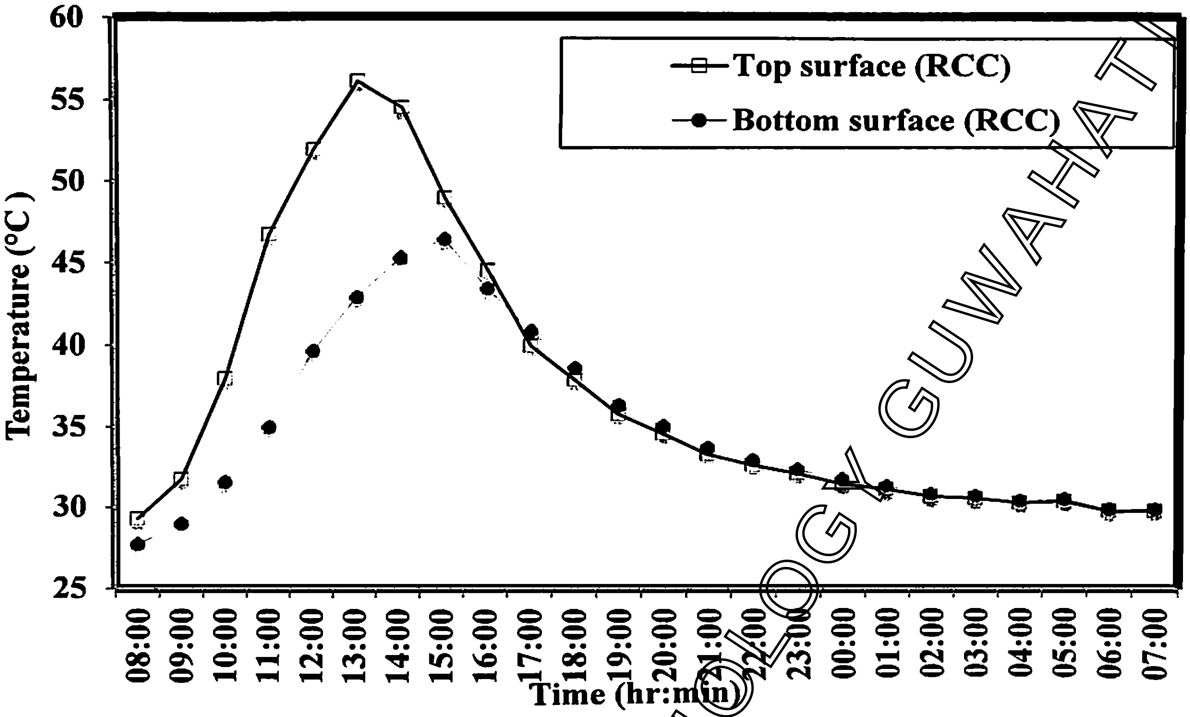

Fig. 5.13: Variation of top and bottom surface temperatures of RCC roof

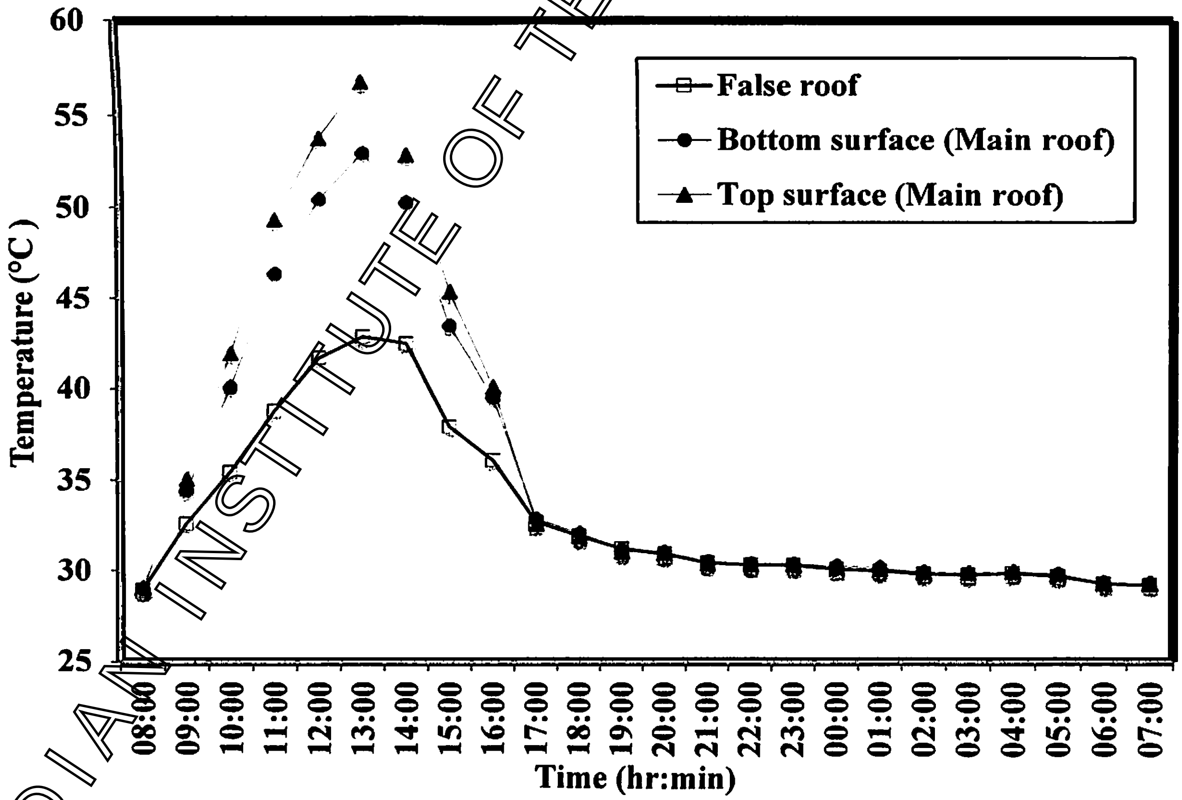

Fig. 5.14: Variation of temperatures of main roof and false roof in ventilated model

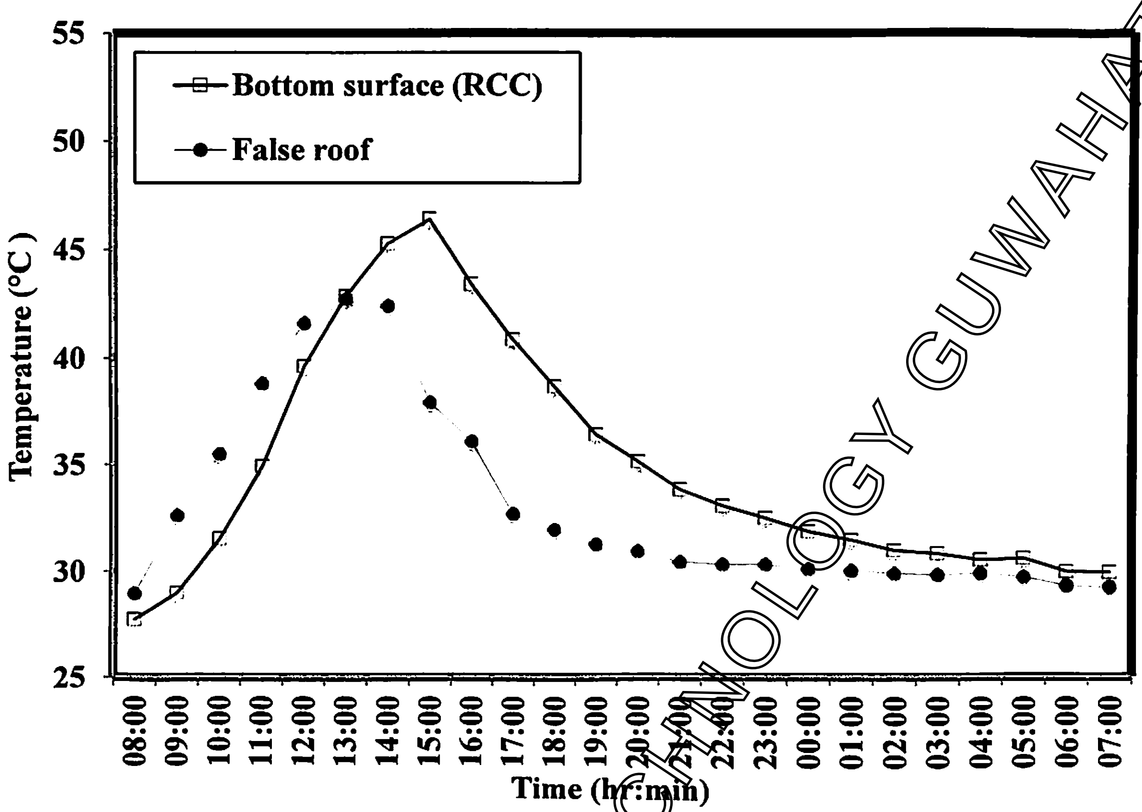

Fig. 5.15: Variation of bottom surface temperatures of RCC and ventilated roof

RCC roof maintained the temperatures less than ventilated roof and achieved a maximum of 4°C low between 10 am and 11 am. Ventilated roof maintained the temperatures less than RCC roof during afternoon and evening times and achieved a maximum of 8°C low during 4 to 5 pm. Overall the performance of ventilated roof is found better than RCC roof.

5.4 Summary

Major observations based on the results obtained from the reduced scale model study are given below:

- RCC roof model performed better than all other simple roof models under zero ventilation conditions.
- RCC roof model failed to maintain low temperatures than other roof models, especially during 3 pm to 8 pm.
- The effect of air gap on thermal performance in ventilated roofs under free

flow conditions are significant up to 6 cm, further increase in air gap has no significant effect on thermal performance.

- Comparative analysis between RCC roofed model and ventilated ACR model showed that by providing suitable roof ventilation technique a better indoor condition than that of RCC roofed model is possible.

Reduced scale model study upheld the results obtained from quantitative analysis. But the experiments conducted in both quantitative analysis and reduced scale model analysis were limited to near zero ventilated conditions. It is not possible to conclude the effect of each roof on thermal comfort without knowing the perception of residents. So, subjective analysis was carried out and the outcome is discussed in the next chapter.

Chapter 6

SUBJECTIVE ANALYSIS

Main objective of the subjective analysis is to know the variation in the response of the residents when subjected to conditions of modern RCC roofed dwelling, TMT roofed dwelling and ACR dwelling. Thermal comfort of human being depends on four physical variables namely, air temperature, air velocity, mean radiant temperature, and relative humidity, along with two personal variables namely, clothing, and activity level. It was decided to conduct subjective analysis during peak period of each season. To identify the peak period in each season a Weather station installed at National Institute of Technology Calicut, Kozhikode, to monitor the environmental conditions of the selected area and its schematic is shown in Fig. 6.1. Field measurements include ambient temperature, relative humidity, wind velocity, wind direction and solar insolation, etc., were measured in all seasons round the year in 2012. Climatic conditions of the selected site were closely monitored throughout the year.

6.1 Field Measurements

Variations in humidity and temperature are depicted in Figs. 6.2 and 6.3 respectively. The extreme conditions of humidity, maximum and minimum, in each month along with monthly average humidity are shown in Fig. 6.2. Maximum relative humidity touched 100% mark during the months from April to November and the same found to be in between 85% to 95% during remaining months. Minimum relative humidity touched 36% and 60% during winter and rainy seasons respectively and it fluctuated between these limits during remaining period. Monthly average humidity, which provides the clear idea about the humidity at the selected area, varied between 65% to 86% with maximum in monsoon and minimum in winter. Minimum average value 65% is observed in the month of January and the value increased month after month and reached to maximum average value 86% in August and then decreased thereafter up to January.

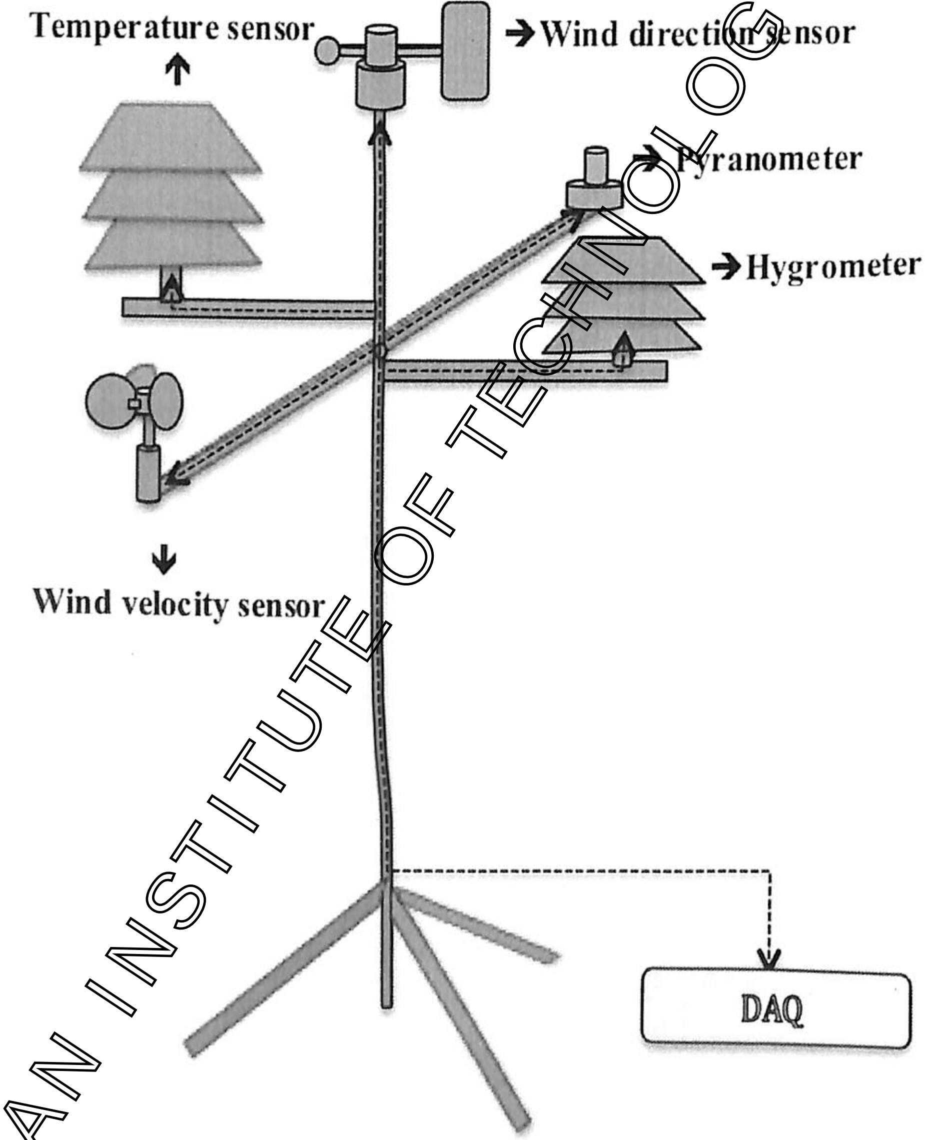

Fig. 6.1: Schematic of weather station

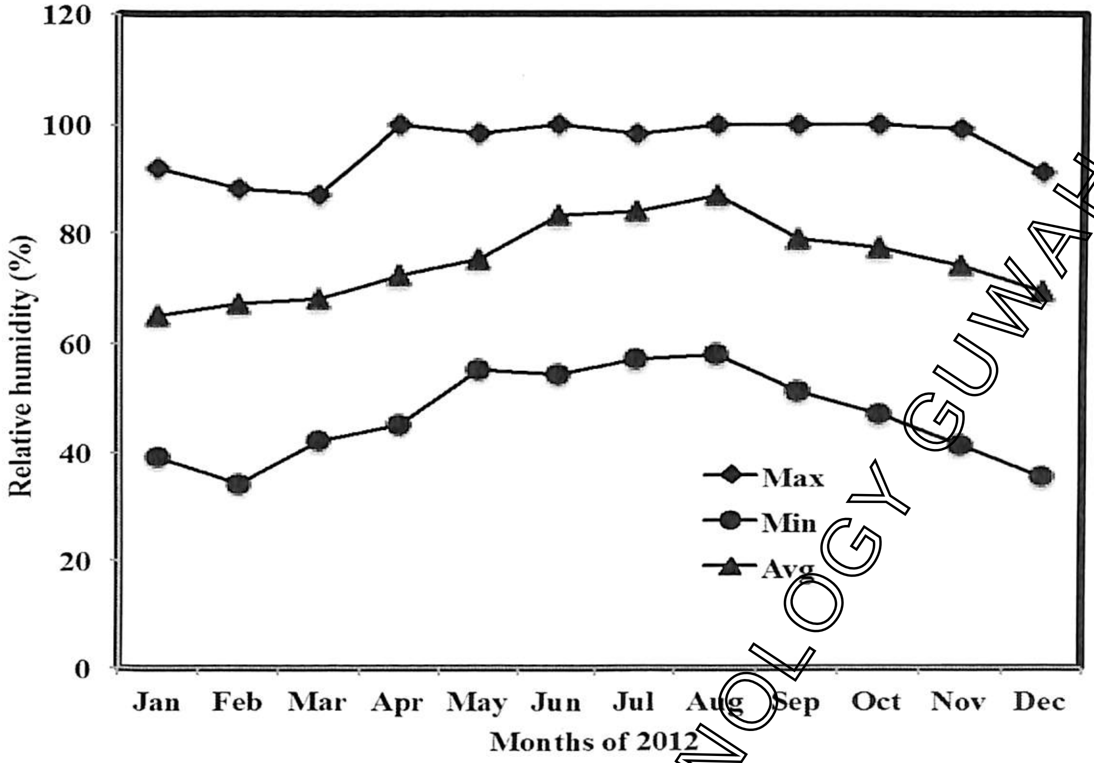

Fig. 6.2: Monthly variation of relative humidity at the selected site

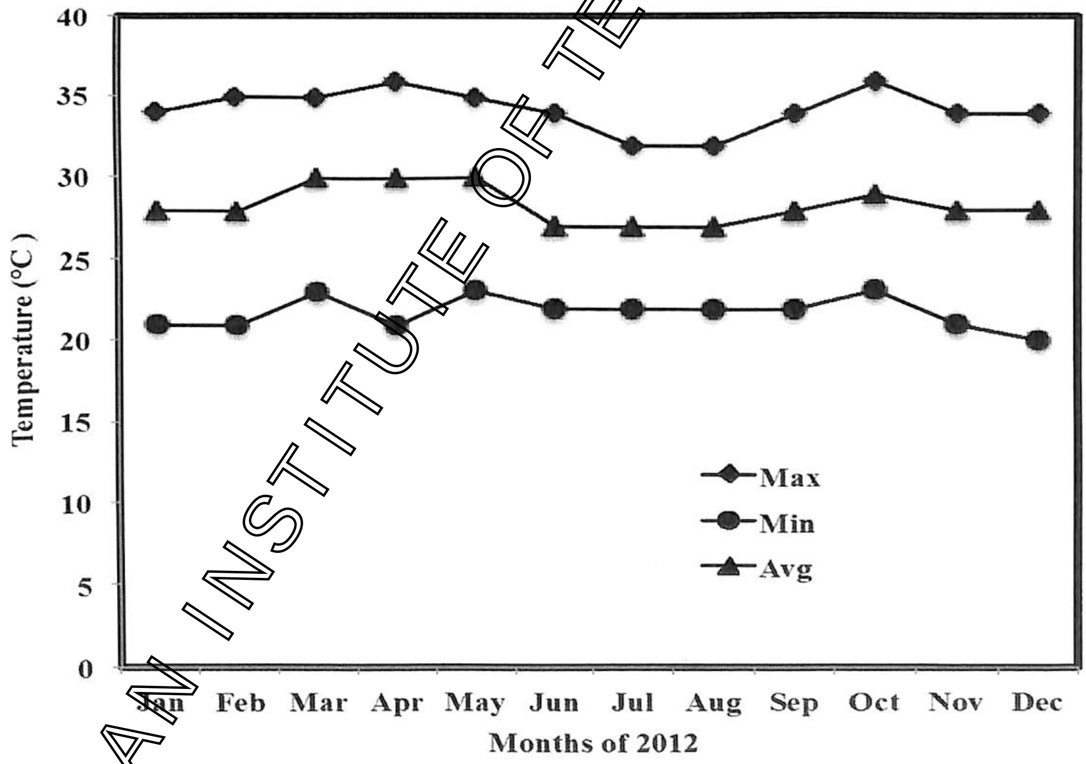

Fig. 6.3: Monthly variation of dry bulb temperature at selected site

The extreme conditions of temperature along with monthly average temperature are presented in Fig. 6.3. Maximum temperature attained in each month is almost constant with 36°C in summer, 34°C in winter and 32°C in monsoon. Minimum temperature of 20°C is observed during onset of monsoon and in winter, and it dipped only up to 22°C during remaining periods. Monthly average temperature variation is observed within the small band of 27°C to 30°C with minimum in monsoon and maximum in summer.

6.2 Survey on Subjects Perception

Based on the data of humidity and temperature, it was decided to conduct subjective analysis in the months of April and May during summer season of 2013, July and August during rainy season of 2013, and December 2013 and January 2014 during winter season. Ten professional students were identified who are staying in and around Kozhikode. Proper instructions were given to them regarding the questionnaire survey. Each student identified six residential buildings, more than 5 year old in their locality, of which three are RCC roofed and other three are mud tile roofed. All together a total of sixty residential buildings were identified, thirty from each type of roofing. Subjective analysis was conducted in all these sixty residential buildings with the help of the ten trained professional students. Due to non-availability of ACR dwellings in all areas, subjective analysis was carried out in the hostel rooms of ACR dwellings located in NIT Calicut.

Survey on subjects was carried out at the peak time of each season in all the sixty selected residential buildings and the data was recorded on the survey sheet. Mainly three details, age, gender and Thermal sensation vote (TSV) on ASHRAE seven-point scale, were taken from the residents of each dwelling, in all seasons. Details of ASHRAE seven point scale along with other questions of the questionnaire are provided in Appendix A.

A total of 936 subjects were participated in survey, in which 402 subjects from TMT roofed residential buildings, 406 subjects from modern RCC roofed residential buildings and remaining 128 subjects were from ACR buildings. Details of age group and gender ratio of subjects are illustrated in Fig. 6.4 and Fig. 6.5, respectively.

Gender ratio was almost maintained constant in case of TMT and RCC dwellings where as male subjects are more in case of ACR dwellings. Subjects participated are more in the age group of 15-30 years.

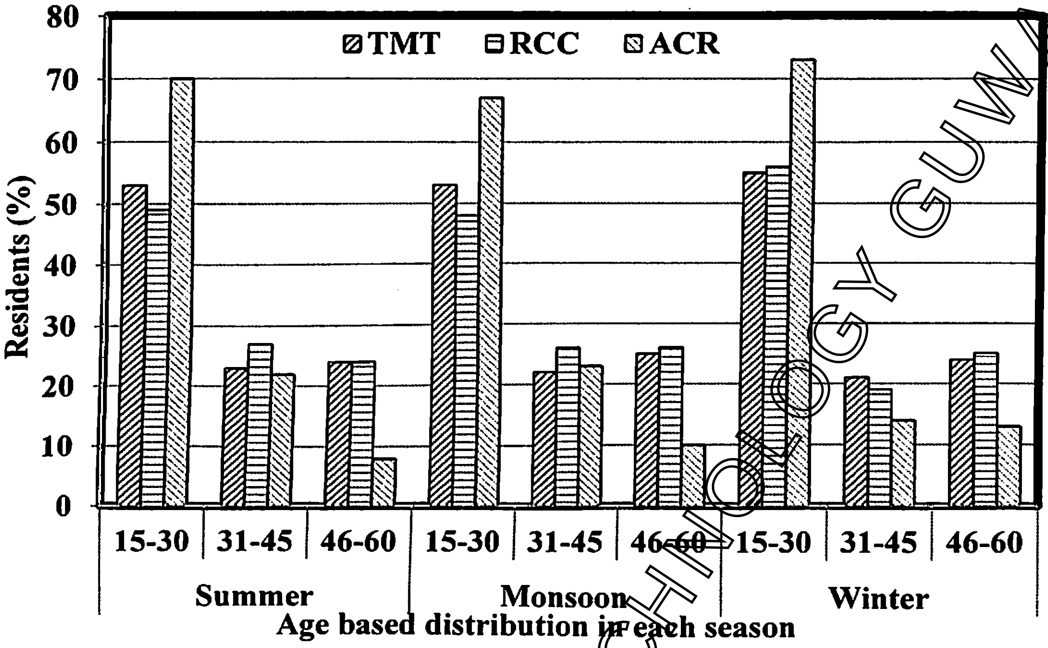

Fig. 6.4: Percentage of residents of different age group participated in survey

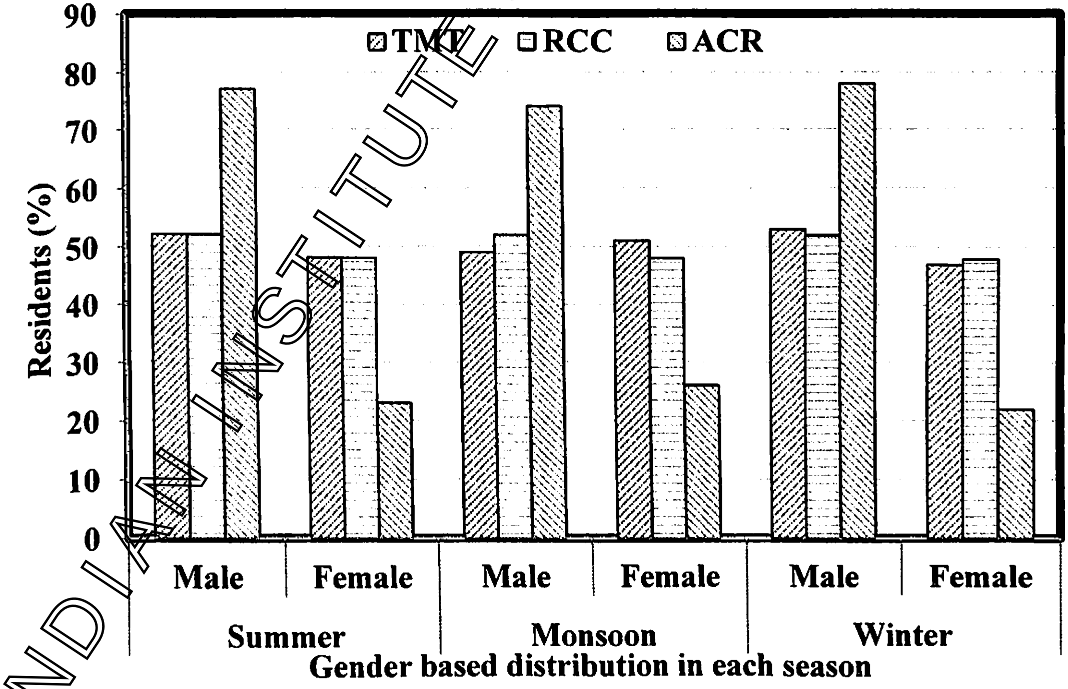

Fig. 6.5: Percentage of residents of different gender participated in survey

Figs. 6.6, 6.7 and 6.8 depict the share of the Thermal Sensation Vote (TSV) based on ASHRAE seven-point scale during summer, monsoon and winter seasons respectively. Subjects felt 100% comfort level during summer, monsoon and winter seasons are 16%, 34%, and 8% respectively in TMT roofed residential buildings; 11%, 47%, and 26% respectively in modern RCC roofed residential buildings and 8%, 41%, and 14% respectively in ACR dwellings. At 85% comfort levels, i.e. by including subjects voted for slightly cool and slightly warm, percentage of subjects felt satisfied during summer, monsoon and winter seasons are 52%, 90%, and 70% respectively in TMT roofed residential buildings; 41%, 93%, and 85% respectively in modern RCC roofed residential buildings and 34%, 95%, and 79% respectively in ACR residential buildings.

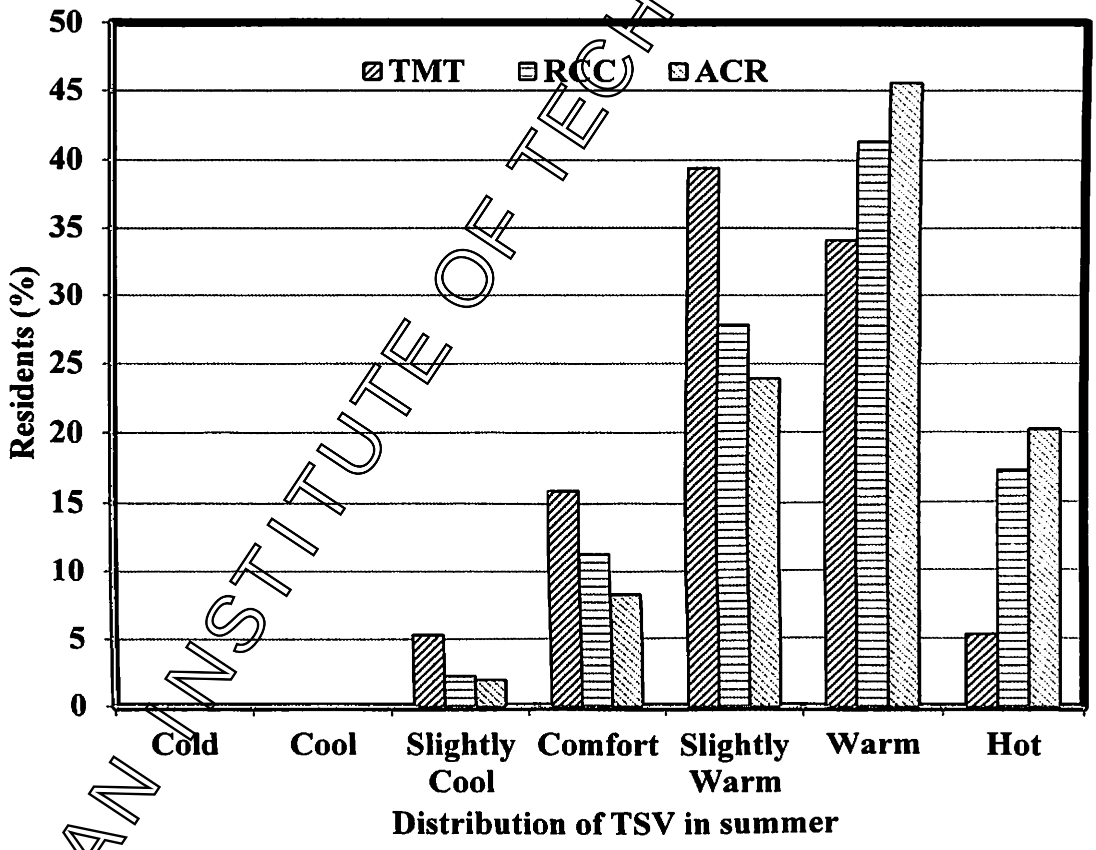

Fig. 6.6: TSV of residents in summer

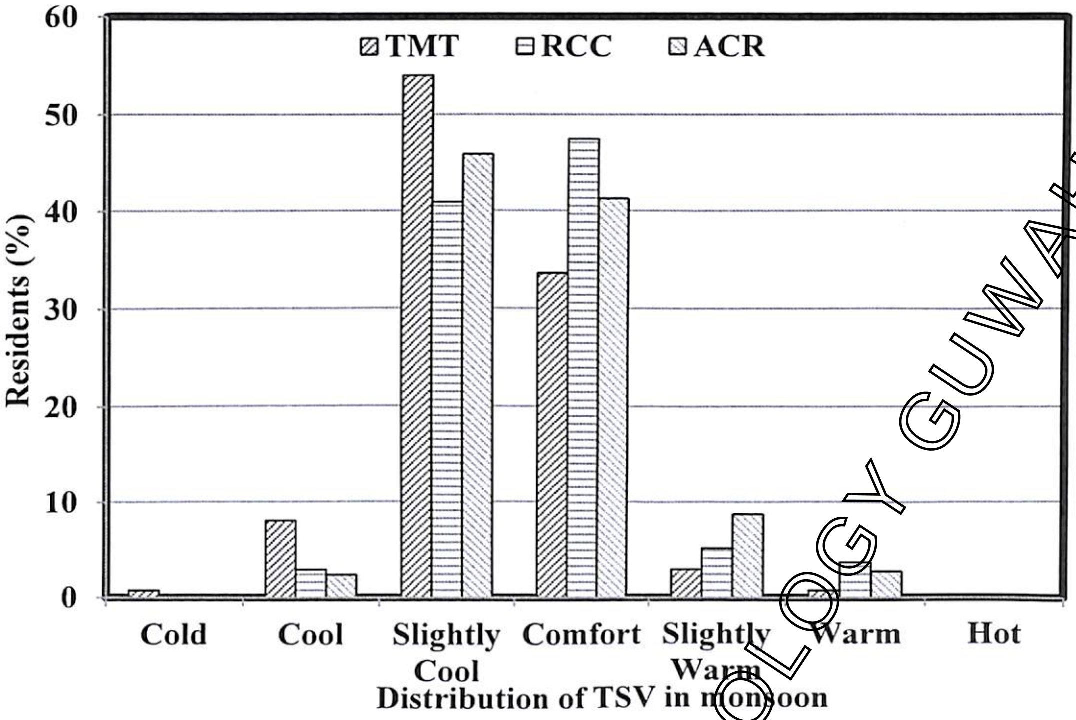

Fig. 6.7: TSV of residents in monsoon

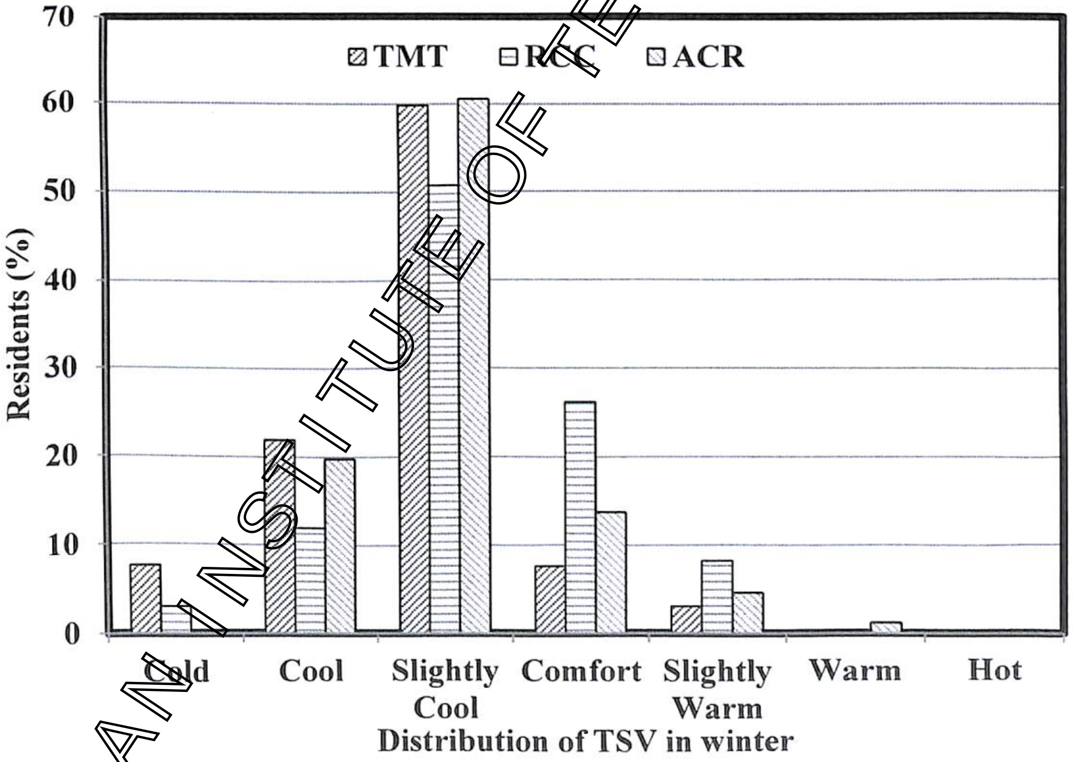

Fig. 6.8: TSV of residents in winter

6.3 Summary

From the subjective analysis, it is found that TMT roofed dwelling performing better in summer followed by RCC roofed dwelling and ACR dwelling in providing thermal comfort. In winter and rainy seasons, RCC roofed dwelling performed better than other dwellings and at the same time ACR dwelling performed better than TMT roofed dwelling. By observing the results closely, one can find that the variation in comfort levels of subjects in three types of dwellings is less than 10%. It is the clear indication that ventilation is playing a major role in providing thermal comfort for the climatic conditions of Kozhikode. Even though there is the effect of roof on thermal comfort, but it is not so significant for climatic conditions of Kerala. The effect of roof may play a major role at elevated temperatures where the provision of ventilation will results into negative effect.

Chapter 7

EVALUATION OF THERMAL COMFORT STANDARDS

7.1 Details of Site and Period of Survey

Kozhikode is located towards the northern part of Kerala at the coastline of Arabian Sea. Here rainy season is severe and lasts over a period of six months in a year, starts with south-west monsoon from June to August and ends with north-east monsoon from September to November. Summer season is moderate and lasts for four months in a year vary from February to May. National Institute of Technology (NIT) Calicut is a technical institute of national importance located in Kozhikode district of Kerala, India. It is located in warm and humid climatic zone of India and its geographical coordinates are 11° 15' North, 75° 46' East. Campus is spread over an area of 12,00,000 m^2 includes academic zone, hostel zone, residential zone and sports zone. The institute houses about 6000 students and 300 families. Fig. 7.1 shows the plan view of campus map.

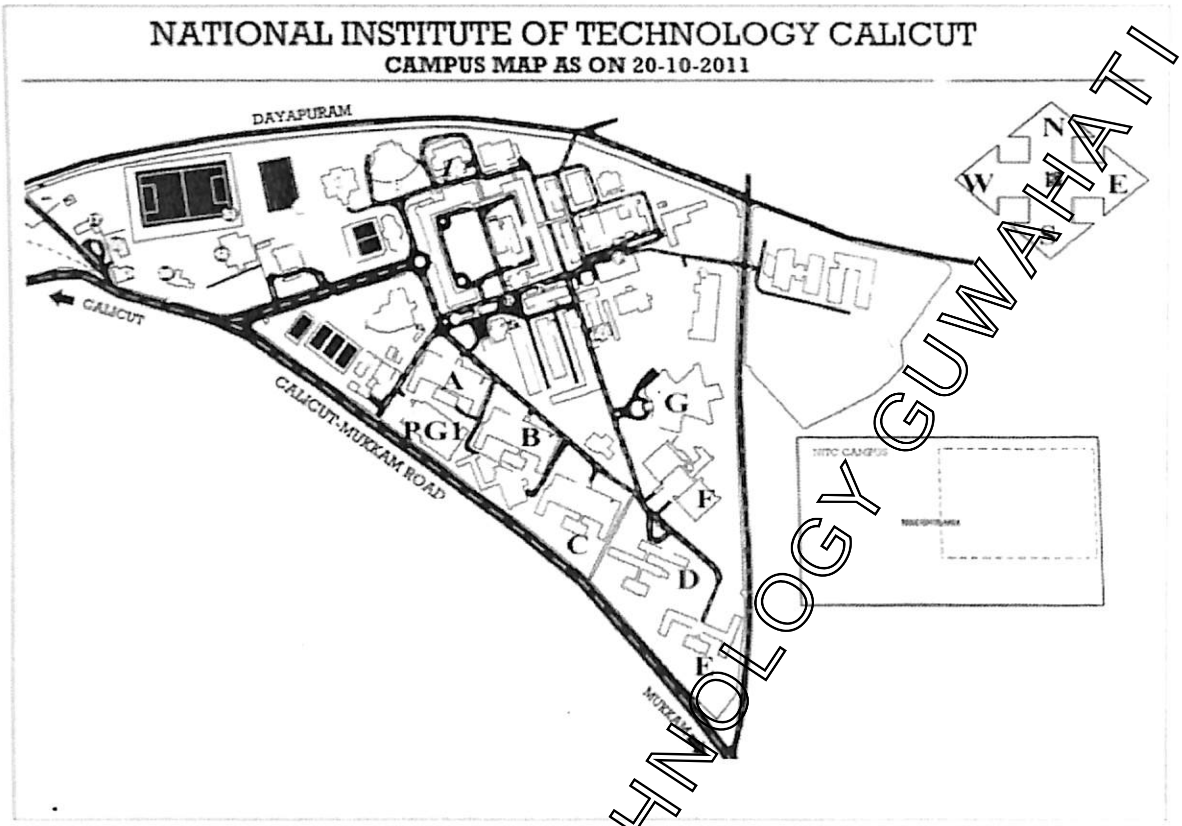

Fig. 7.1: Campus map of NIT Calicut

Among all the seasons prevail here, summer season is the only season that causes a major discomfort due to the presence of high relative humidity at elevated temperatures. Since the temperatures of this region are not much high, the comfort levels would be achieved by maintaining the proper ventilation, which negates the effect of high relative humidity. Due to the availability of buildings with different roof types, National Institute of Technology (NIT) Calicut was considered as a survey site for evaluating thermal comfort standards. It was decided to carry out the thermal comfort analysis in the selected site during the period of summer 2013. Class II protocol was followed for the field survey.

A total of seven differently roofed buildings were considered for the study and the details of the buildings are given below:

- Building A having Traditional mud tile roof with ceiling (TMT_A)
- Building B having Reinforced cement concrete roof (RCC_B)
- Buildings C and D having Pitched reinforced cement concrete roof with paved mud tiles (PRC_C and PRC_D)

- Building E having Reinforced cement concrete roof covered with asbestos cement shingles (RCCC_E).
- Building F having Asbestos cement roof with ceiling (ACR_F)
- Building F having Asbestos cement roof with no ceiling (ACRNC_F)
- Building G having Metal deck roof with ceiling (MDR_G)

Pictures of each type of building is provided in Appendix C. Both field measurements and questionnaire survey were carried out simultaneously for the four months February, March, April and May of summer 2013 to evaluate the thermal comfort standards for the region of Kozhikode.

7.2 Field Measurements

Field measurements include ambient temperature (T_a), globe temperature (T_g), air velocity (V_a), relative humidity (RH) and illuminance were measured using the Comfort Evaluation System, which is shown in Fig. 7.2. Comfort Evaluation System was set to log the measured variables to a memory module continuously with a time step of 15 min. ASHRAE standards were followed during the entire course of measurements. All the sensors were properly installed and data logger logged the measurements. During the survey, all the openings in each selected room were kept open and fans were kept in off condition. Operative temperature was determined by considering both ambient temperature (T_a) and globe temperature (T_g).

Measurements were taken in each building for fourteen days spreading over the entire period, February to May in summer 2013, by using Comfort Evaluation System. Measurements were carried out in each building for seven rounds with a span of two days in each round. In every round of measurements, Comfort Evaluation System was installed for two days in each building and it took a total of seventeen days per round for completing the measurements in all eight buildings. Measurements were carried out in a cyclic order started from building TMT_A and ended with building MDR_G through buildings RCC_B, PRC_C, PRC_D, RCCC_E, ACR_F, ACRNC_F respectively in each round. It took nearly 125 days to complete all the seven rounds of measurements.

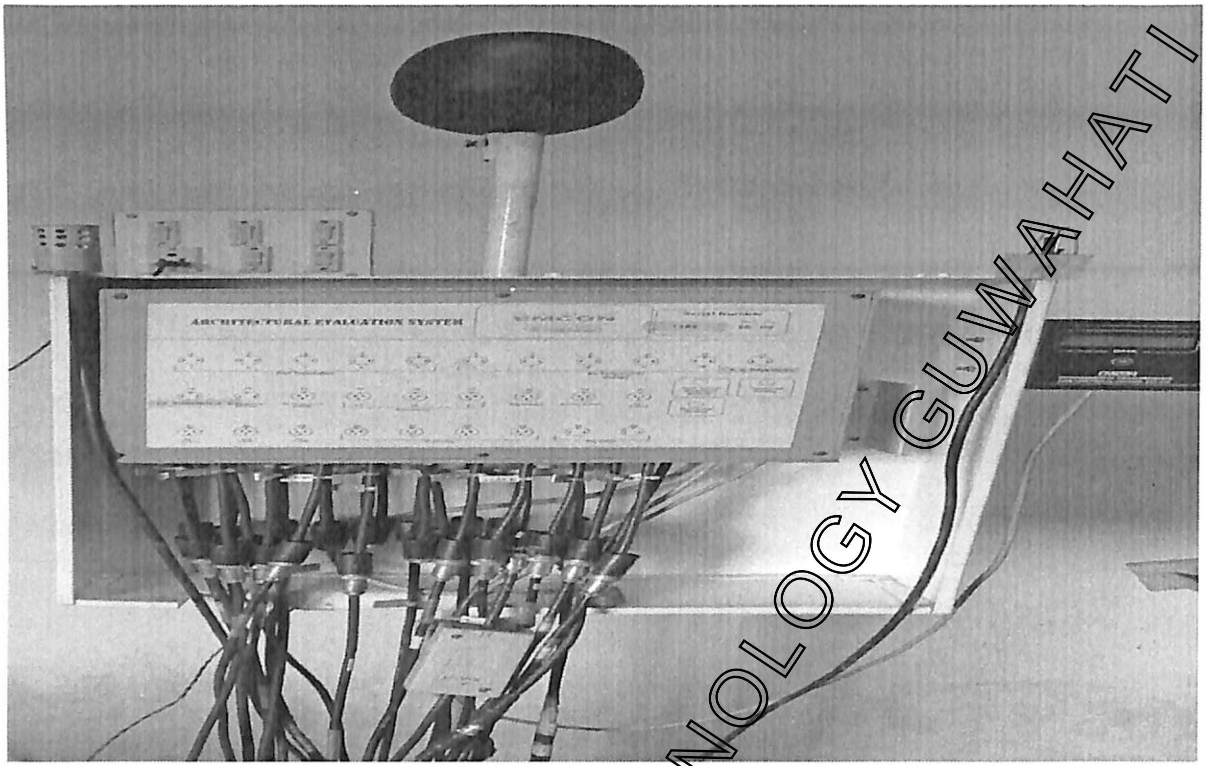

Fig. 7.2: Comfort evaluation system

7.3 Survey

A survey was conducted during the months of February to May in summer 2013 by using questionnaires among the subjects, in the age group 18 - 25 years. Both the field measurements and survey were carried out simultaneously. After careful observation of their clothing pattern clothing insulation level (CLO) was fixed at 0.4 CLO. Metabolic rate (MET) was fixed at 1.0 MET since subjects were held at rest prior to filling the questionnaire. Both the clothing insulation level and metabolic rates were evaluated with the help of ASHRAE data. The subjects filled a total of around 1000 questionnaires during the period of field measurements. In return a total of 835 questionnaires with proper responses were received.

Mean values of various field measurements, details of survey related to Thermal Sensation Vote (TSV), and details of survey related to Thermal Preference Vote (TPV) for eight buildings are presented in Tables 7.1, 7.2 and 7.3 respectively. Survey questionnaire along with ASHRAE thermal sensation scale are provided in Appendix A.

Table 7.1: Details of field measurements

Building	**Number of Participants**	**MET**	**CLO**	**T_{op} [°C]**	**T_{oh} [°C]**	**ET* [°C]**
TMT_A	75	1.0	0.4	31.22	28.81	33.01
RCC_B	126	1.0	0.4	31.76	29.21	33.68
PRC_C	128	1.0	0.4	31.71	29.18	33.61
PRC_D	132	1.0	0.4	31.68	29.15	33.58
RCCC_E	79	1.0	0.4	30.13	27.84	31.4
ACR_F	119	1.0	0.4	32.21	29.55	34.26
ACRNC_F	53	1.0	0.4	32.81	30.03	35.07
MDR_G	123	1.0	0.4	32.32	29.65	34.41

Table 7.2: Details of survey based on TSV

		Thermal sensation vote based on ASHRAE Scale						
Building	**T_{op} [°C]**	**Cold**	**Cool**	**Slightly Cool**	**Neutral**	**Slightly Warm**	**Warm**	**Hot**
TMT_A	31.22	0	0	0	48	16	8	3
RCC_B	31.76	0	0	0	39	60	22	5
PRC_C	31.71	0	0	0	42	64	17	5
PRC_D	31.68	0	0	0	57	39	27	9
RCCC_E	30.13	0	0	0	64	12	3	0
ACR_F	32.21	0	0	0	29	53	26	11
ACRNC_F	32.81	0	0	0	5	7	31	10
MDR_G	32.32	0	0	0	32	48	34	9

Table 7.3: Details of survey based on TPV

Building	Number of Participants	T_{op} [°C]	Thermal Preference Vote (TPV) Cooler Than Present	Present Climate	Warmer Than Present
TMT_A	75	31.22	22.26	77.74	0
RCC_B	126	31.76	26.33	73.67	0
PRC_C	128	31.71	22.78	77.22	0
PRC_D	132	31.68	28.45	71.55	0
RCCC_E	79	30.13	9.08	90.92	0
ACR_F	119	32.21	35.3	64.7	0
ACRNC_F	53	32.81	70.47	29.53	0
MDR_G	123	32.32	44.26	55.74	0

7.4 Results and Discussion

7.4.1 Percentage Dissatisfied (PD) Based on PMV, TSV and TPV

Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) were calculated using Fanger's theory of thermal comfort by utilizing the data obtained from the field measurements. Thermal Sensation Vote (TSV) based on ASHRAE seven point scale obtained from the survey. Percentage dissatisfied in case of Thermal Sensation Vote (TSV) is obtained by utilizing the relation between Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD). Similarly with the help of PMV-PPD relation, Thermal Preference Vote (TPV) is estimated on seven point scale by utilizing percentage dissatisfaction obtained from the survey. Figs. 7.3, 7.4 and 7.5 illustrate the percentage dissatisfied based on Predicted Mean Vote (PMV), Thermal Sensation Vote (TSV) and Thermal Preference Vote (TPV) respectively.

Percentage dissatisfied was found to be 50 to 95% in case of Predicted Mean Vote (PMV), 5 to 70% in case of Thermal Sensation Vote (TSV), and 10 to 70% in case of Thermal Preference Vote (TPV). Percentage dissatisfied based on Predicted Mean Vote (PMV) predicted 25 to 45% more dissatisfaction than that of Thermal Sensation Vote (TSV) and Thermal Preference Vote (TPV), which upholds the Adaptive Thermal Comfort theory. Details of percentage dissatisfied and thermal comfort in eight buildings based on Predicted Mean Vote (PMV), Thermal Sensation Vote (TSV) and Thermal Preference Vote (TPV) are given in Tables 7.4, 7.5 and 7.6 respectively.

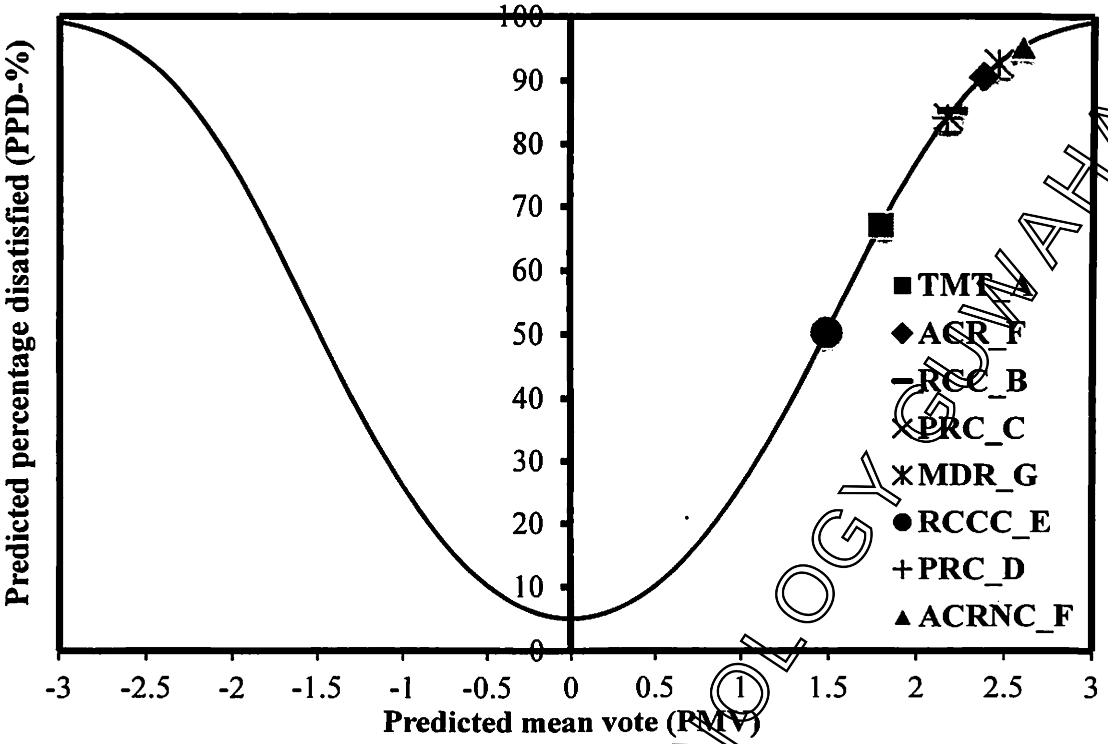

Fig. 7.3: PMV based percentage dissatisfied in eight buildings

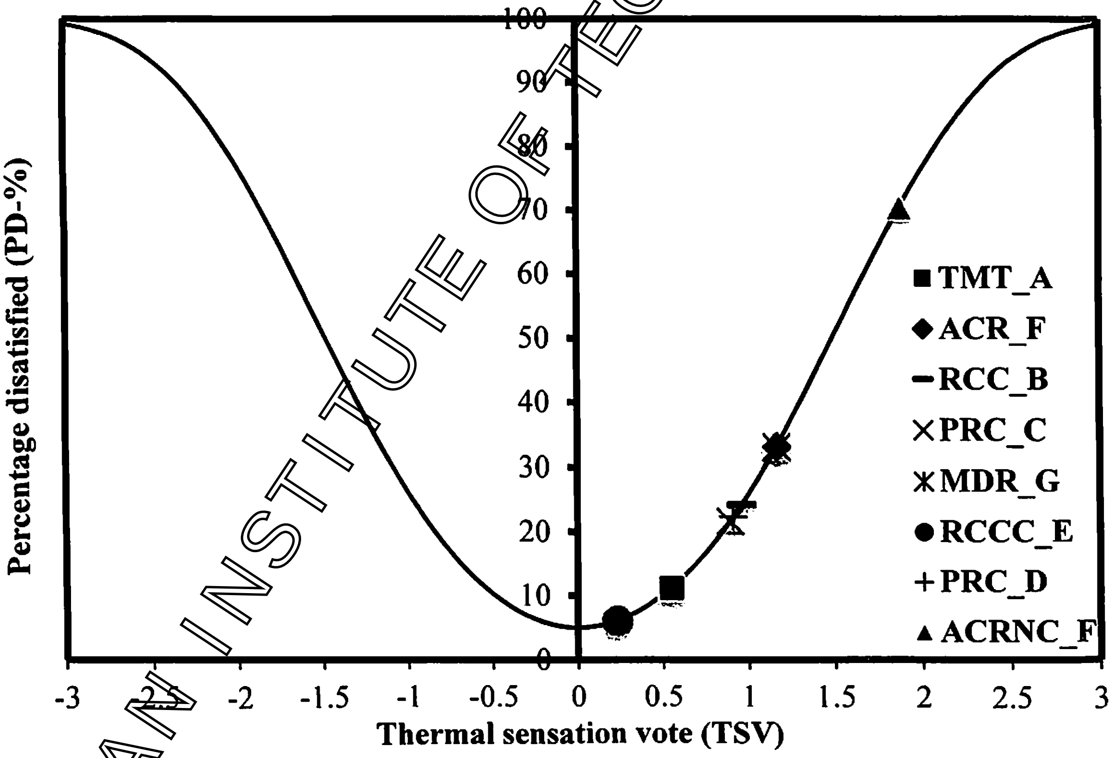

Fig. 7.4: TSV based percentage dissatisfied in eight buildings

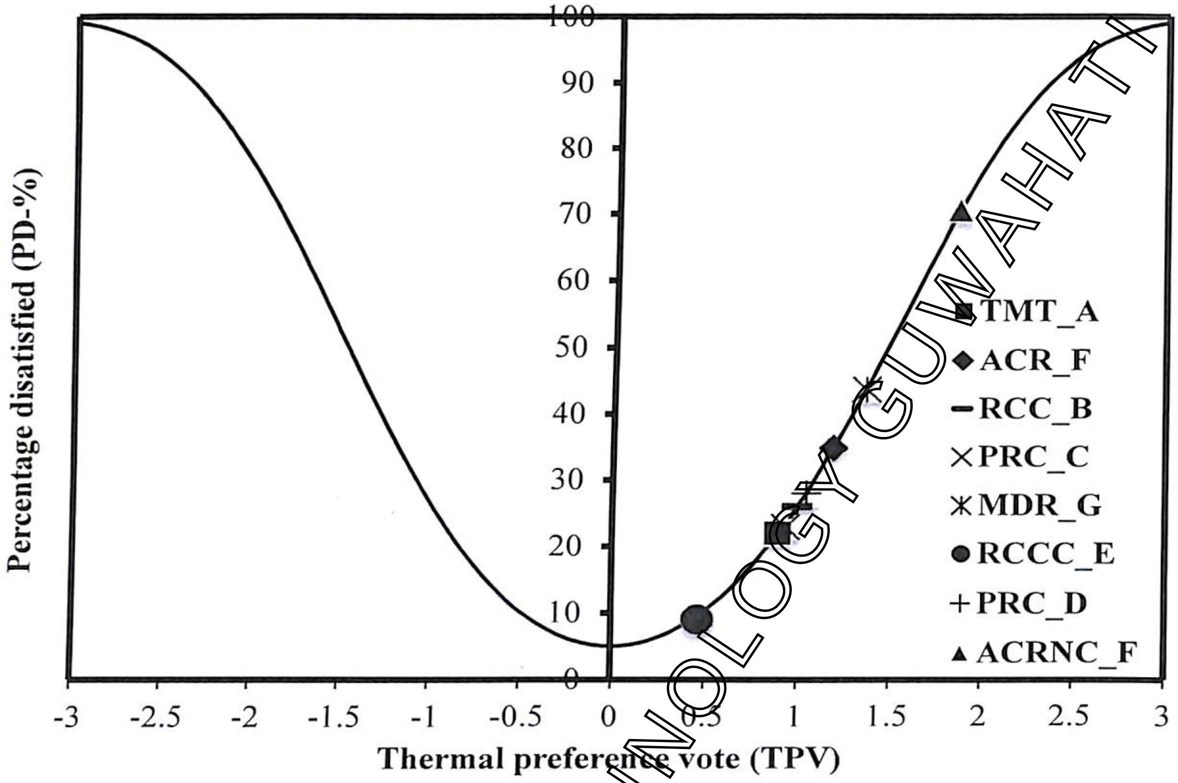

Fig. 7.5: TPV based percentage dissatisfied in eight buildings

Table 7.4: Thermal comfort conditions based on PMV

Building	T_{op} [°C]	T_{oh} [°C]	ET* [°C]	PMV	PPD (%)	Thermal Comfort
TMT_A	31.22	28.81	33.01	1.80	67.31	Warm
RCC_B	31.76	29.21	33.68	2.21	85.29	Warm
PRC_C	31.71	29.18	33.61	2.18	84.40	Warm
PRC_D	31.68	29.15	33.58	2.18	84.20	Warm
RCCC_E	30.13	27.84	31.4	1.49	50.60	Slightly warm
ACR_F	32.21	29.55	34.26	2.38	90.68	Warm
ACRNC_F	32.81	30.03	35.07	2.68	96.47	Hot
MDR_G	32.32	29.65	34.41	2.46	92.73	Warm

Table 7.5: Thermal comfort conditions based on TSV

Building	T_{op} [°C]	T_{oh} [°C]	ET* [°C]	TSV	PD (%)	Thermal Comfort
TMT_A	31.22	28.81	33.01	0.55	11.26	Slightly Warm
RCC_B	31.76	29.21	33.68	0.96	24.33	Slightly Warm
PRC_C	31.71	29.18	33.61	0.88	21.78	Slightly Warm
PRC_D	31.68	29.15	33.58	0.91	22.45	Slightly Warm
RCCC_E	30.13	27.84	31.4	0.23	6.08	Comfort
ACR_F	32.21	29.55	34.26	1.16	33.30	Slightly Warm
ACRNC_F	32.81	30.03	35.07	1.87	70.47	Warm
MDR_G	32.32	29.65	34.41	1.16	33.26	Slightly Warm

Table 7.6: Thermal comfort conditions based on TPV

Building	T_{op} [°C]	T_{oh} [°C]	ET* [°C]	TPV	PD(%)	Thermal Comfort
TMT_A	31.22	28.81	33.01	0.89	22.26	Slightly Warm
RCC_B	31.76	29.21	33.68	1.00	26.33	Slightly Warm
PRC_C	31.71	29.18	33.61	0.93	22.78	Slightly Warm
PRC_D	31.68	29.15	33.58	1.05	28.45	Slightly Warm
RCCC_E	30.13	27.84	31.4	0.46	9.08	Comfort
ACR_F	32.21	29.55	34.26	1.19	35.3	Slightly Warm
ACRNC_F	32.81	30.03	35.07	1.87	70.47	Warm
MDR_G	32.32	29.65	34.41	1.37	44.26	Slightly Warm

7.4.2 Correlations to Calculate TSV and TPV

Linear regression analysis was carried out for Predicted Mean Vote (PMV) and Thermal Sensation Vote (TSV) as well as Predicted Mean Vote (PMV) and Thermal Preference Vote (TPV). Linear equation between Predicted Mean Vote (PMV) and Thermal Sensation Vote (TSV) was evaluated by the regression analysis as PMV = 0.746* TSV + 1.454. It shows a strong correlation at $R^2 = 0.92$. Linear equation for PMV = 0.852* TPV + 1.239, was evaluated in case of Predicted Mean Vote (PMV) and Thermal Preference Vote (TPV) with a strong correlation at $R^2 = 0.856$. Figs. 7.6 and 7.7 illustrate the fit between Predicted Mean Vote (PMV) and Thermal Sensation Vote (TSV), and Predicted Mean Vote (PMV) and Thermal Preference Vote (TPV), respectively.

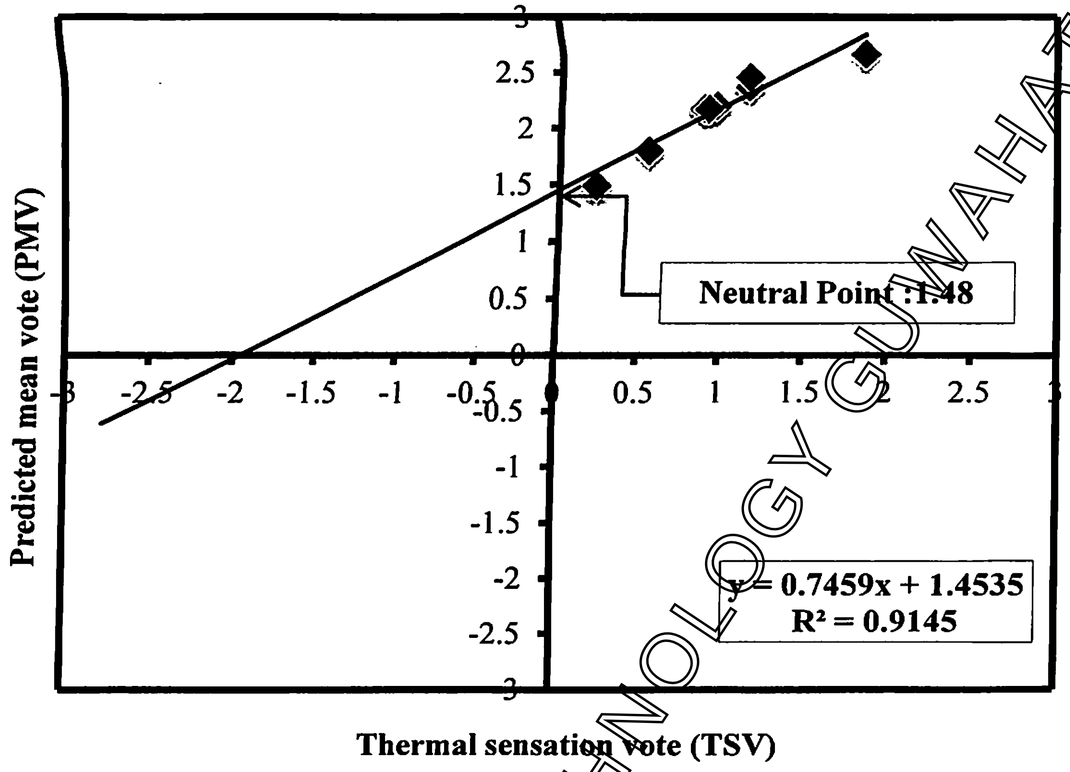

Fig. 7.6: Correlation between PMV and TSV

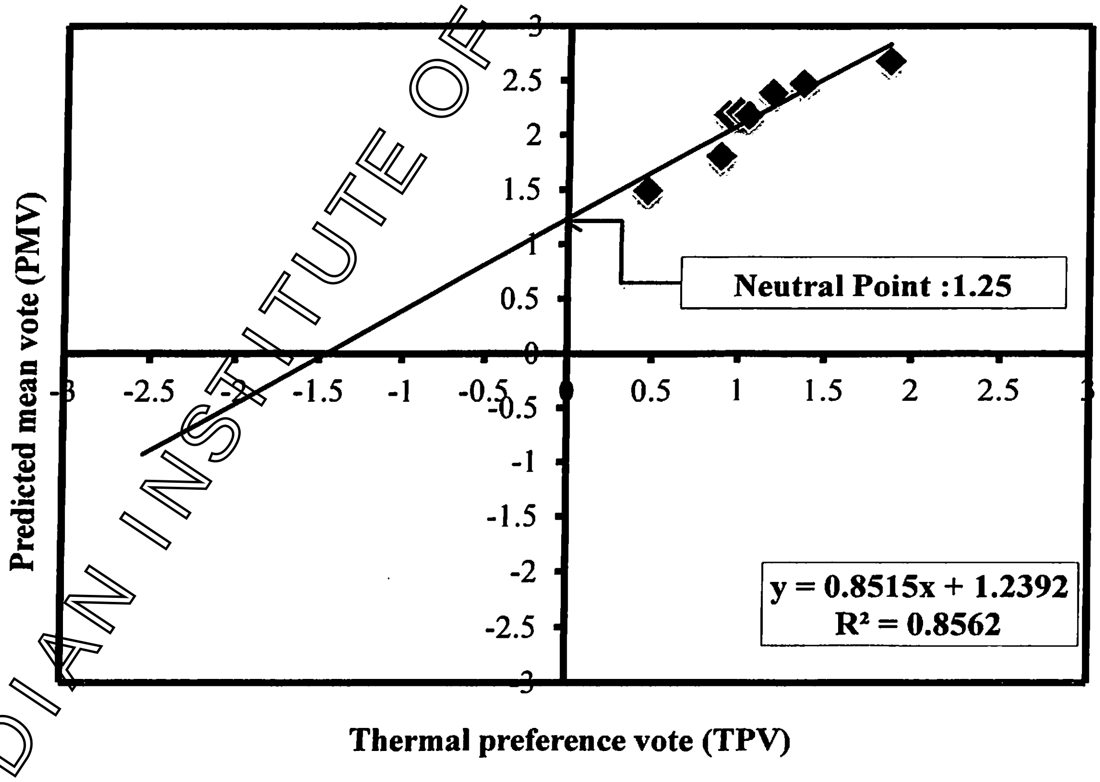

Fig. 7.7: Correlation between PMV and TPV

It is clear that both Thermal Sensation Vote (TSV) and Thermal Preference Vote (TPV) were showing similar results with slight variation whereas the Predicted Mean Vote (PMV) analysis demanded more thermal comfort than that of actual. The shift of neutral point in ASHRAE seven point scale was also identified, as +1.48 for Thermal Sensation Vote (TSV) and +1.25 for Thermal Preference Vote (TPV), in comparison with Predicted Mean Vote (PMV).

7.4.3 Preferred Operative Temperature Based on PMV, TSV and TPV

Figs. 7.8, 7.9 and 7.10 depict the variation of Predicted Mean Vote (PMV), Thermal Sensation Vote (TSV) and Thermal Preference Vote (TPV) respectively with the change of operative temperature. It was observed that Predicted Mean Vote (PMV) failed in predicting the required thermal comfort conditions and showed the preferred operative temperature as 27°C, which is nearly 3°C less than that of obtained from either Thermal Sensation Vote (TSV) or Thermal Preference Vote (TPV). Preferred operative temperatures obtained based on Thermal Sensation Vote (TSV) and Thermal Preference Vote (TPV) were 30°C and 29.4°C, respectively and the variation among these preferred temperatures is limited to 0.6°C only. So either Thermal Sensation Vote (TSV) or Thermal Preference Vote (TPV) can be used for predicting the thermal comfort in naturally ventilated hostels.

7.4.4 Neutral Effective Temperature Based on PMV, TSV and TPV

The effective temperature is the temperature at 50% relative humidity that yields the same total heat loss from the skin as for the actual environment. Effective temperatures were determined for each building and determined the neutral effective temperature for the study area. Figs.7.11, 7.12 and 7.13 show the variation of Predicted Mean Vote (PMV), Thermal Sensation Vote (TSV) and Thermal Preference Vote (TPV) respectively with the change of effective temperature. Neutral effective temperature obtained based on Thermal Sensation Vote (TSV) and Thermal Preference Vote (TPV) were 31.3°C and 30.4°C respectively and the variation among these preferred temperatures is limited to 0.9°C only. Whereas, in case of Predicted Mean Vote (PMV), the neutral effective temperature was identified as 27.2°C and is nearly 4°C less than that of obtained from that of Thermal Sensation Vote (TSV).

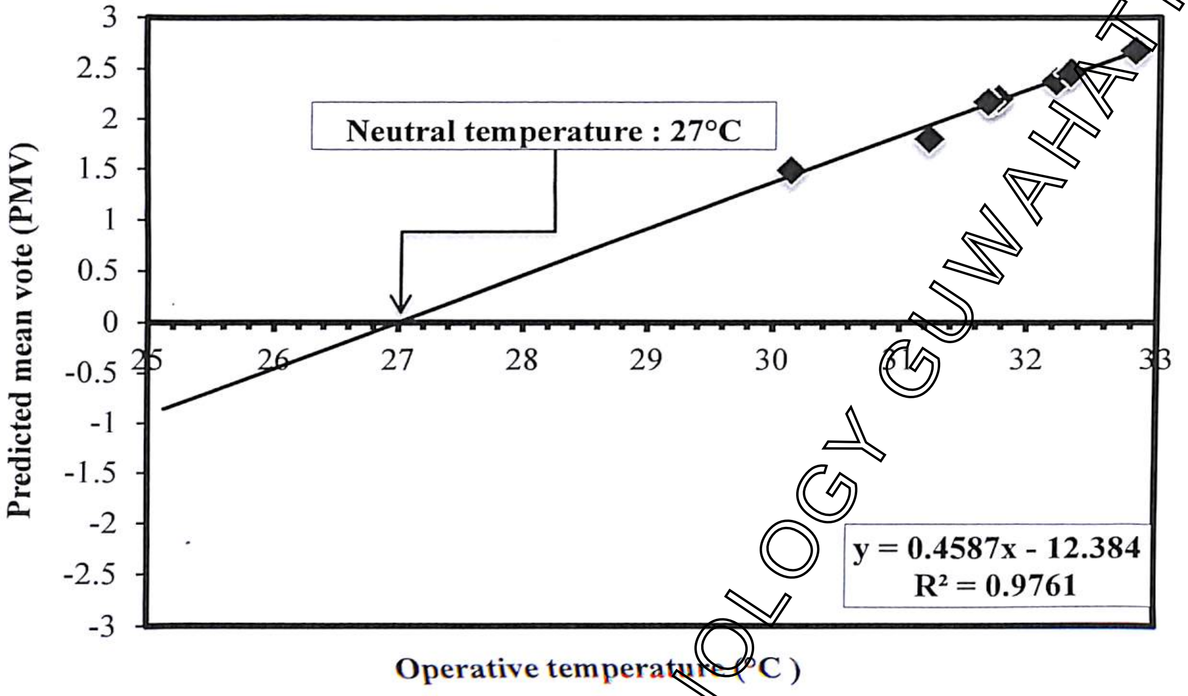

Fig. 7.8: Variation of PMV with operative temperature

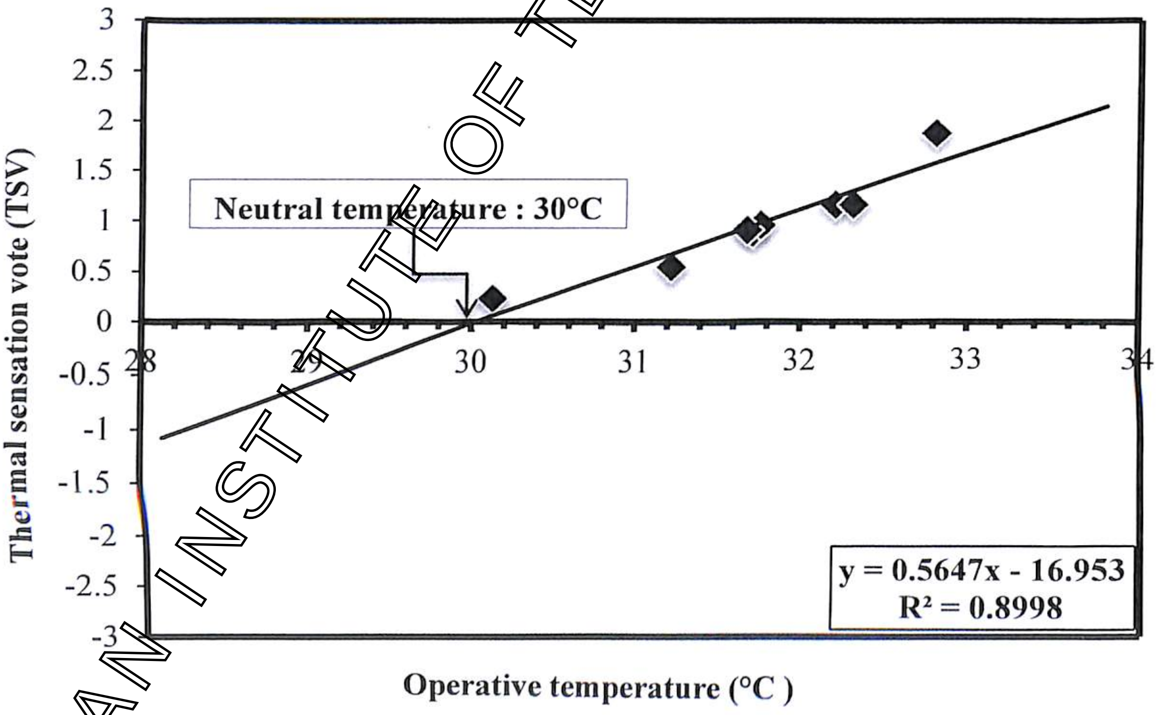

Fig. 7.9: Variation of TSV with operative temperature

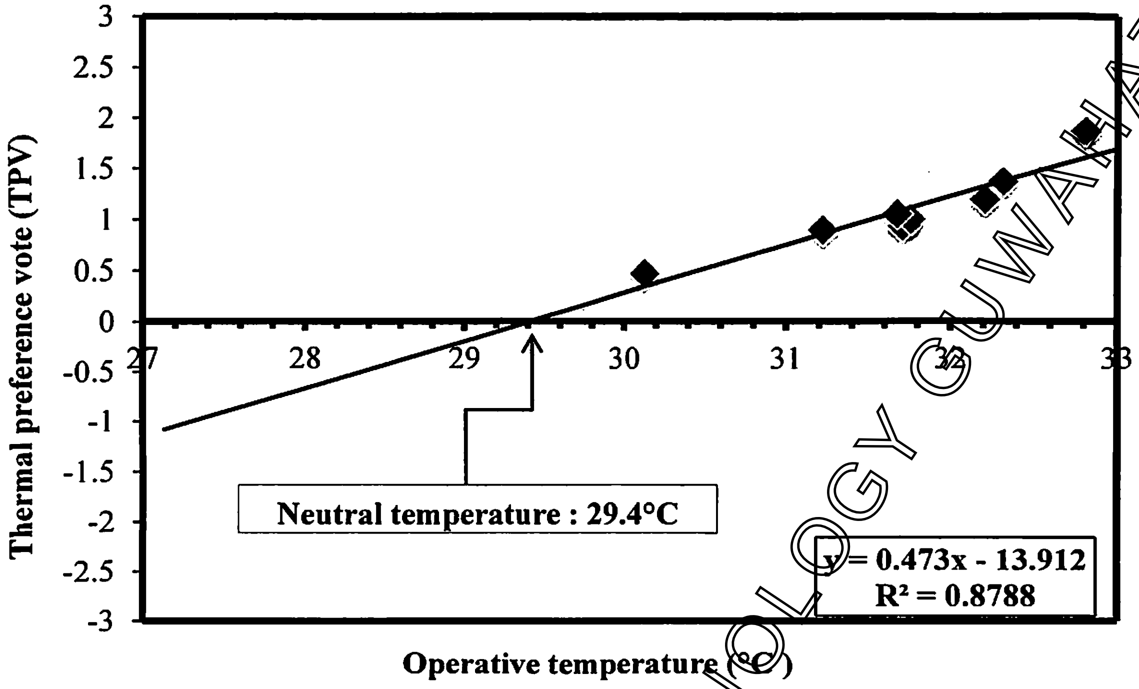

Fig. 7.10: Variation of TPV with operative temperature

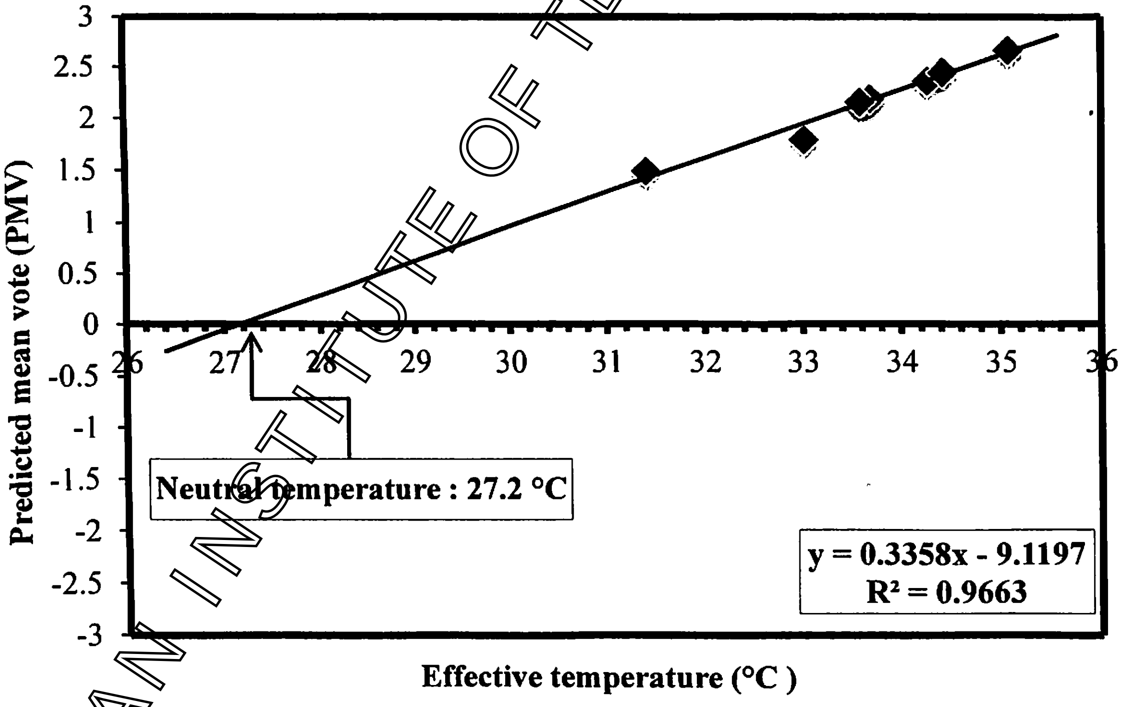

Fig. 7.11: Variation of PMV with effective temperature

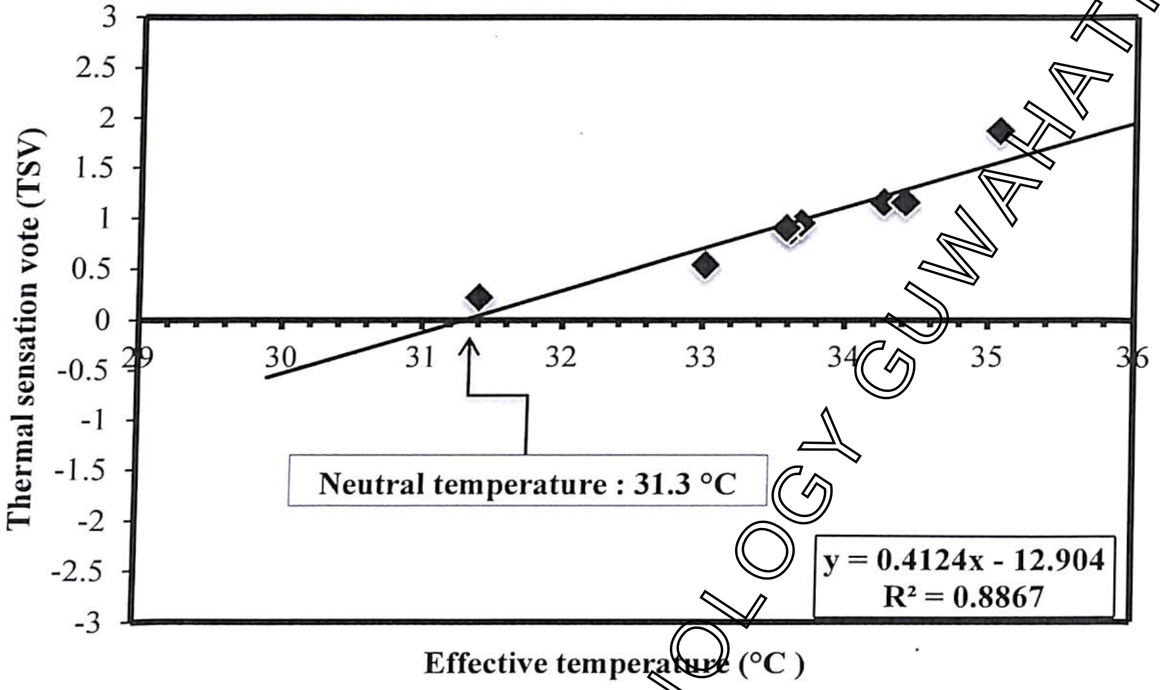

Fig. 7.12: Variation of TSV with effective temperature

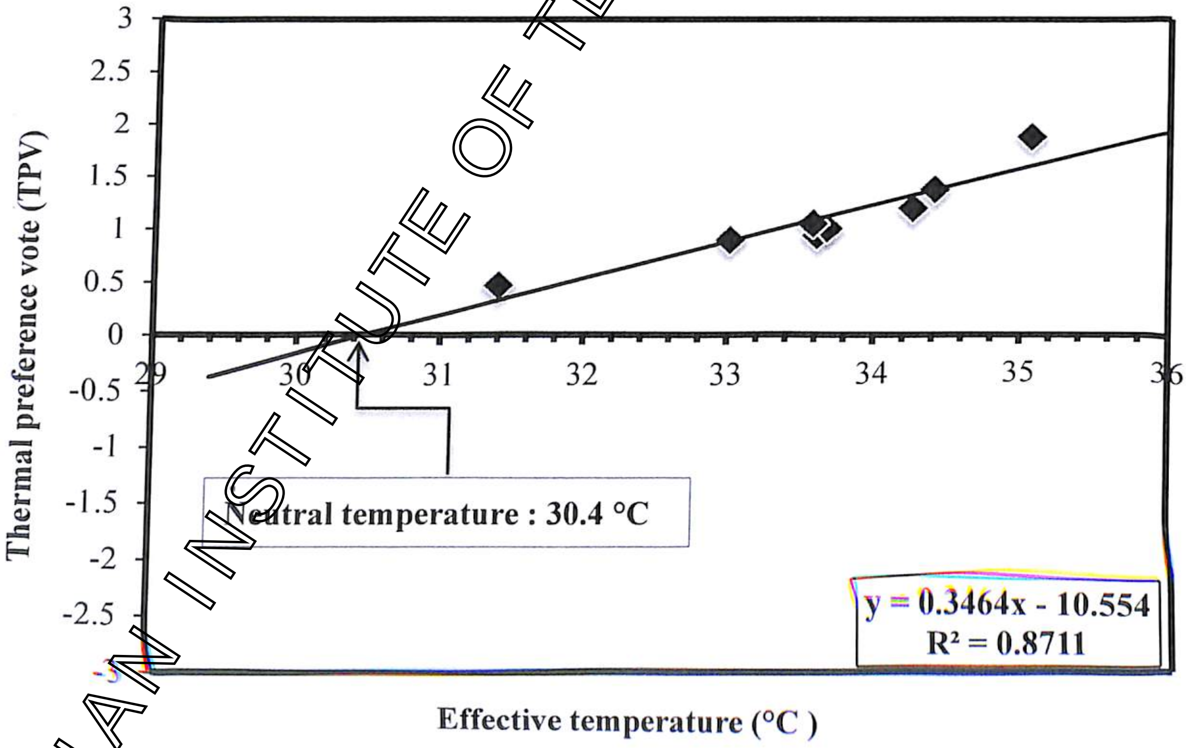

Fig. 7.13: Variation of TPV with effective temperature

7.4.4 Neutral Humid Operative Temperature Based on PMV, TSV and TPV

The humid operative temperature is the temperature at 100% relative humidity that yields the same total heat loss from the skin as for the actual environment. Humid operative temperatures were determined for each building and determined the neutral humid operative temperature for the study area. Figs.7.14, 7.15 and 7.16 shows the variation of Predicted Mean Vote (PMV), Thermal Sensation Vote (TSV) and Thermal Preference Vote (TPV) respectively with the change of humid operative temperature. Neutral humid operative temperature obtained based on Thermal Sensation Vote (TSV) and Thermal Preference Vote (TPV) were 27.8°C and 27.3°C respectively and the variation among these preferred temperatures is limited to 0.5°C only. Whereas, in case of Predicted Mean Vote (PMV), the neutral humid operative temperature was identified as 25.3°C and is nearly 2.5°C less than that of obtained from that of Thermal Sensation Vote (TSV).

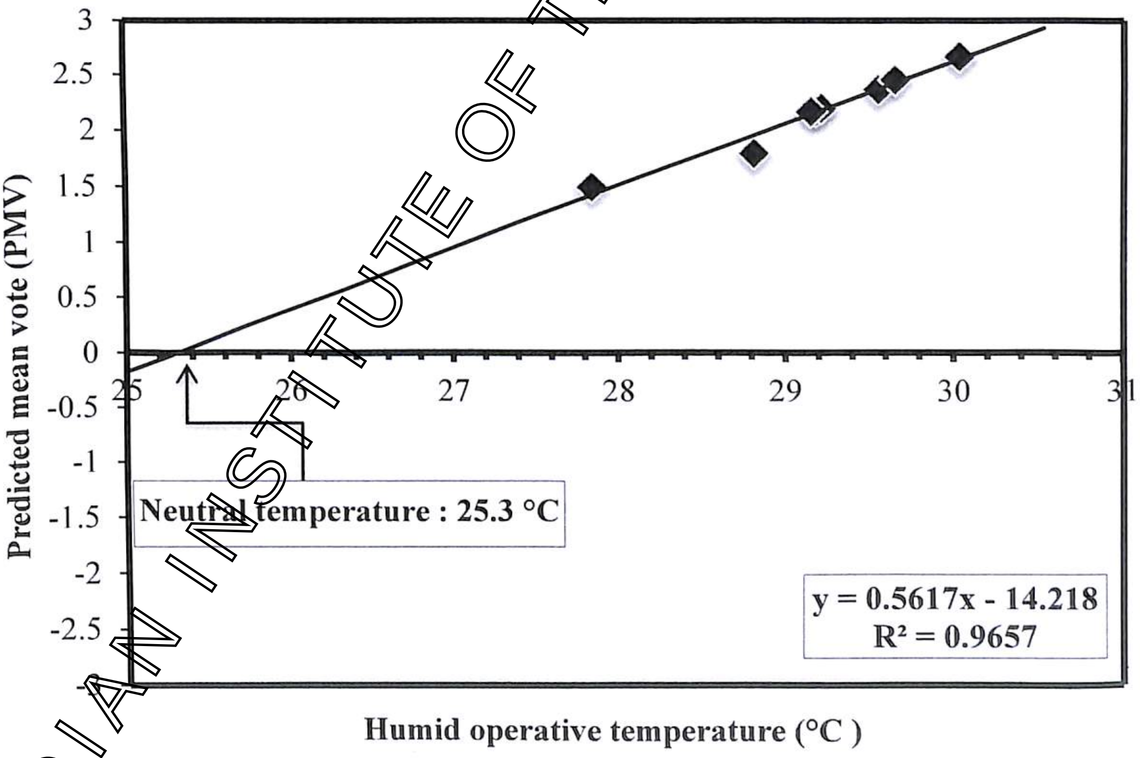

Fig. 7.14: Variation of PMV with humid operative temperature

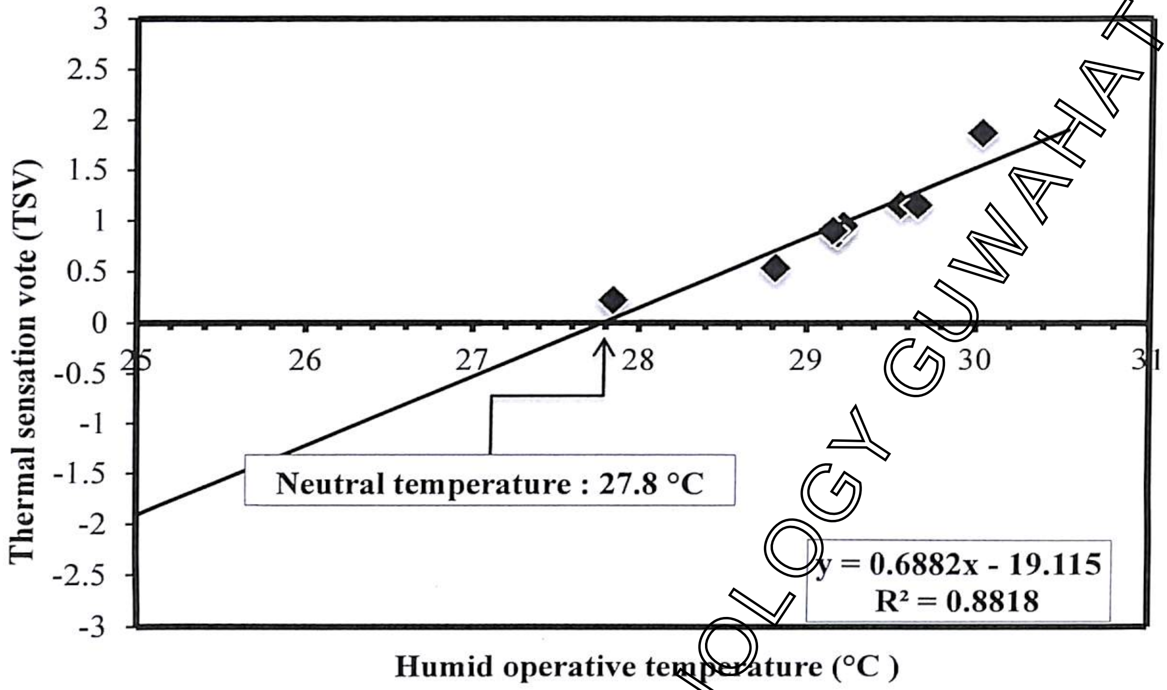

Fig. 7.15: Variation of TSV with humid operative temperature

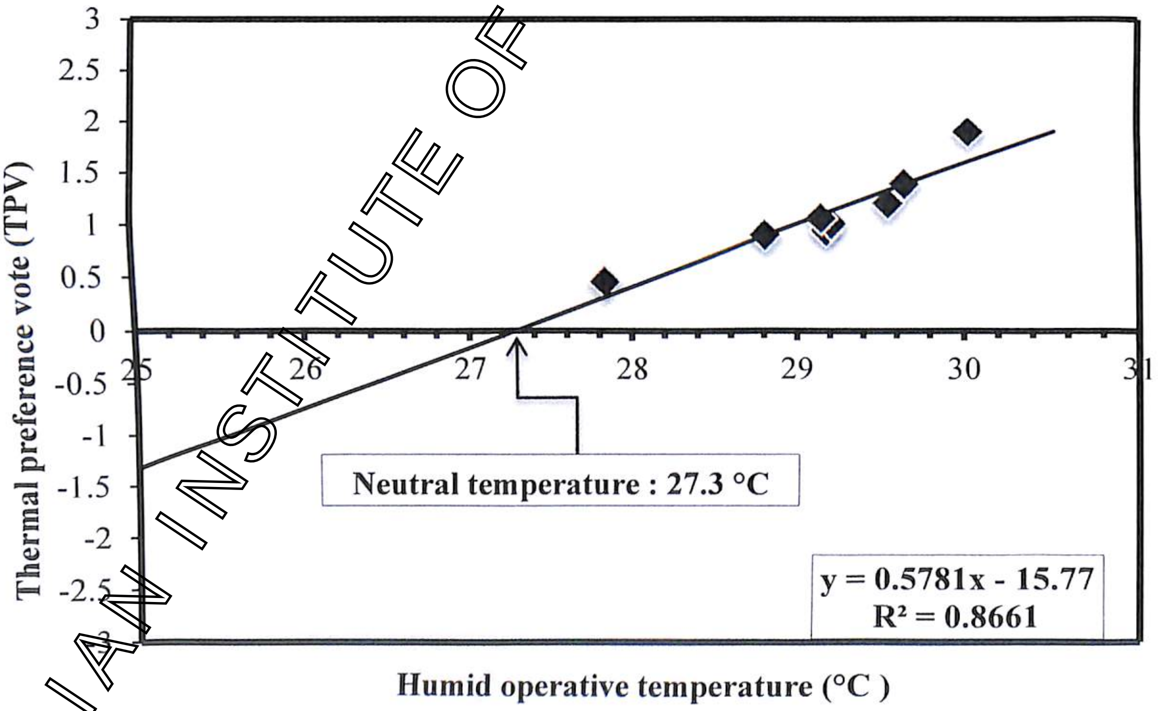

Fig. 7.16: Variation of TPV with humid operative temperature

7.4.5 Adaptive Thermal Comfort Model

Monthly mean out door temperature (30°C) was used and evaluated comfort temperature for each available model. Comfort temperature obtained based on Thermal Sensation Vote (TSV) was 30°C and is equal to monthly mean out door temperature. Based on the present study comfort temperature for climatic conditions of Kozhikode, Kerala is obtained as 30°C.

Based on the comfort standards obtained by the present research work, it is concluded that Adaptive comfort models proposed by ASHRAE Std 55 (Dear and Brager, 2002) and EN15251 (Nicol and Humphreys, 2010) are not suitable to predict comfort temperature for climatic conditions of Kozhikode, whereas the remaining three models proposed by Indraganti et al (2014), Nguyen et al (2012), and Toe and Kubota (2013) able to predict comfort temperature with minimum deviation from the present value. Adaptive thermal comfort models along with the comfort temperatures obtained from each model and its deviation from the actual comfort temperature are tabulated in Table 7.7.

Table 7.7: Comfort temperatures based on different adaptive comfort models

Adaptive comfort model	**Reference**	**Comfort temperature T_c [°C]**	**Deviation from the present model [°C]**
$T_c = 0.31\ T_o + 17.38$	Dear and Brager (2002)	26.68	3.32
$T_c = 0.33\ T_o + 18.8$	Nicol and Humphreys (2010)	28.7	1.3
$T_c = 0.26\ T_o + 21.4$	Indraganti et al (2014)	29.2	0.8
$T_c = 0.34\ T_o + 18.83$	Nguyen et al (2012)	29.03	0.97
$T_c = 0.57\ T_o + 13.8$	Toe and Kubota (2013)	30.9	- 0.9

From the above table, it is observed that few models are over predicting and few models are under predicting the thermal comfort conditions when compared to that of actual comfort conditions obtained from the present study. If someone what to choose one of the available models to predict thermal comfort conditions, then the first question arises in mind is whether to go for under predicted model or to go for over predicted model. It is always better to go for under predicting model since it minimizes the energy requirement when compared to over predicting model with same discomfort level.

7.5 Summary

From the present work it was observed that PMV is over predicting the thermal comfort conditions in naturally ventilated buildings and the predicted neutral temperature is 2 to 3°C more when compared to that of TSV and TPV. It indicates that Adaptive Comfort theory is best suitable for predicting the thermal comfort conditions of naturally ventilated buildings in warm and humid climatic zone. Thermal comfort standards obtained from this study may be applicable to all type of naturally ventilated buildings irrespective of roof type. These standards may be refined by conducting similar studies in this region by incorporating more no of subjects and more no of variables.

Chapter 8

CONCLUSIONS AND FUTURE SCOPE

8.1 Quantitative Analysis

Quantitative analysis gave the clear picture of the role of roof in maintaining thermal comfort inside buildings. It is found that RCC roof under non-ventilated conditions failed to maintain the inside temperatures below the ambient temperatures. Most of the time, inside temperatures of the RCC building are above the ambient and reached to a maximum of 40°C which is 4°C more than ambient. At the same time TMT roofing maintained the inside temperatures well below the ambient at peak time and reached a maximum of 33.6°C which is 2.4°C less than ambient. Interesting observation is that even ACR building performed better than RCC roofed building under non-ventilated conditions. It also found from the quantitative analysis conducted on ACR house that the maximum temperature in living space is slightly more than that of ambient temperature. Detailed analysis of ACR building provided the avenues for improvement of the thermal comfort levels inside the dwelling.

8.2 Reduced Scale Model Analysis

Major conclusions based on the results obtained from the model study are given below:

- RCC roof model is performing better than all other models followed by mud tile roof under zero ventilation conditions.

- RCC roof model failed to maintain low temperatures than other roof models, especially during 3 pm to 6 pm.
- The effect of air gap on thermal performance in ventilated roofs under free flow conditions are significant up to 6 cm, further increase in air gap has no significant effect on thermal performance.
- Comparative analysis between RCC roofed model and ventilated roof model shows that better indoor condition than that of RCC roofed model is possible by providing suitable roof ventilation technique.

8.3 Subjective Analysis

Subjects felt 100% comfort level during summer, monsoon and winter seasons are 16%, 34%, and 8% respectively in TMT roofed residential buildings; 11%, 47%, and 26% respectively in modern RCC roofed residential buildings and 8%, 41%, and 14% respectively in ACR dwellings. At 85% comfort levels, i.e. by including subjects voted for slightly cool and slightly warm, percentage of subjects felt satisfied during summer, monsoon and winter seasons are 52%, 90%, and 70% respectively in TMT roofed residential buildings; 41%, 93%, and 85% respectively in modern RCC roofed residential buildings and 34%, 95%, and 79% respectively in ACR residential buildings. Subjective analysis showed that ACR dwellings, RCC roofed residential buildings and mud tile roofed residential buildings succeeded in providing comfort conditions with more than 70% of residents are found comfortable with 85% satisfaction level during winter and monsoon seasons. But in summer the percentage of satisfied residents fall to 41% and 34% in case of RCC roofed dwelling and ACR dwelling, at the same time mud tile roofed dwelling able to provide satisfaction to more than 52% subjects. People satisfied with thermal comfort is observed in mud tiled roofed dwelling in comparison with RCC roofed dwelling and ACR dwelling is mere 11% and 18% more respectively.

In case of quantitative analysis, the difference observed in inside temperatures of RCC roofed residential buildings when compared to TMT and ACR houses are huge and reached to a maximum of 7.5°C and 4°C respectively. But in case of subjective analysis all the selected roofs are performing similar with little variation in thermal comfort. This variation in results is mainly due to the following two reasons:

- Quantitative analysis is carried out at near zero ventilation by closing all the openings in living space, i.e. RCC roofed dwelling lost its convective means of interaction with the environment but the attic space of ACR and TMT roofed dwellings still has the convective means of interaction. This may be the reason for enhanced variation in living space temperatures.
- Less variation is observed in case of subjective analysis. This is mainly due to the adaptive nature of the residents to the subjected environment. Since residents have been staying in their dwellings from last five years, they showed the tendency of voting towards comfort because of adaptive nature.

Subjective analysis upholds the adaptive thermal comfort theory, which suggests that thermal comfort not only depends on temperature, humidity etc. but also on factors like physiological, psychological and behavioral adaptations.

8.4 Thermal Comfort Standards

Thermal comfort conditions of student residence zone of NIT Calicut, Kerala, India were obtained. In the present study, it was clearly observed that PMV-PPD analysis based on Fanger's theory of thermal comfort failed in exact prediction of the comfort conditions in naturally ventilated hostels. The Predicted Mean Vote (PMV) based preferred operative temperature was found to be 27°C and neutral effective temperature was found to be 23.5°C. The preferred operative temperature and neutral effective temperature obtained based on Thermal Sensation Vote (TSV) were 30°C and 25.8°C respectively, whereas 29.4°C and 25.3°C respectively were obtained in case of Thermal Preference Vote (TPV). Results obtained from Thermal Sensation Vote (TSV) and Thermal Preference Vote (TPV) was found to be in line with each other.

The acceptable range of operative temperature for 85% satisfaction was found to be 25.1 to 28.9°C in case of Predicted Mean Vote (PMV), 28.5 to 31.5°C in case of Thermal Sensation Vote (TSV) and 27.6 to 31.2°C in case of Thermal Preference Vote (TPV). Similarly, the acceptable range of effective temperature for 85%

satisfaction was found to be 22.1 to 24.9°C in case of Predicted Mean Vote (PMV), 24.6 to 27°C in case of Thermal Sensation Vote (TSV) and 23.9 to 26.7°C in case of Thermal Preference Vote (TPV).

A linear relationship, PMV = 0.746*TSV + 1.454, was developed for obtaining Thermal Sensation Vote (TSV) in terms of Predicted Mean Vote (PMV) for warm humid climatic conditions of Kerala. Similarly a linear relationship, PMV = 0.852* TPV + 1.239, was developed for obtaining Thermal Preference Vote (TPV) in terms of Predicted Mean Vote (PMV) for warm humid climatic conditions of Kerala.

Present research work provided the thermal comfort standards for the naturally ventilated buildings in the region of Kozhikode. These key findings help in filling the research gap of non-availability of thermal comfort standards based on the local comfort survey, which considers the factors like psychological, physiological and adaptive nature of residents apart from the comfort measurements. The outcomes of the present research work are in accordance with the adaptive thermal comfort theory. These outcomes provide useful guidelines for the building engineers, air-conditioner engineers and architectures in decision making while designing energy efficient buildings particularly in the state of Kerala.

8.5 Scope for the Future Work

The scope for future work is outlined below:

- Conducting quantitative analysis on full-scale buildings by varying different influential parameters is not an easy task. To overcome this difficulty one can develop the numerical model with the help of the reported results and there by the same model can be used for predicting the influence of each parameter under different climatic conditions.
- One can also use the already available Design and simulation software's to predict the thermal performance of buildings like
    - Therm Version 1.0: Thermal evaluation tool for buildings
    - TADISM: Tools for architectural design and simulation
    - TRNSYS: Dynamic simulation tool
    - DOE-2.1E: Design of experiments software

  - Energy plus and e QUEST softwares

  By using the above software tools, the effects of various parameters and variables like building materials, type of openings, orientation, natural ventilation, relative humidity and internal gains through convection and radiation on the thermal comfort can also be analyzed apart from the overall thermal performance of buildings.

- Strengthen the standards obtained in present work by conducting similar studies by incorporating more subjects. As the number of comfort studies increases, the refinement of standards will be possible.
- Thermal comfort standards obtained in present work are limited to young subjects with fixed clothing level and metabolic activity. This limitation may be overcome by conducting survey among different age groups with variable clothing level and metabolic activity. There is also a scope of work to predict the effect of gender on thermal comfort.
- This work may be extended for determining comfort standards for buildings in commercial sector like industrial buildings, office buildings etc.
- There is a scope for developing different passive techniques to rectify the negative aspects observed in each type of roof.
- One can work on design aspects of RCC and ACR buildings to overcome the observed drawbacks by incorporating best aspects of TMT roofed buildings.

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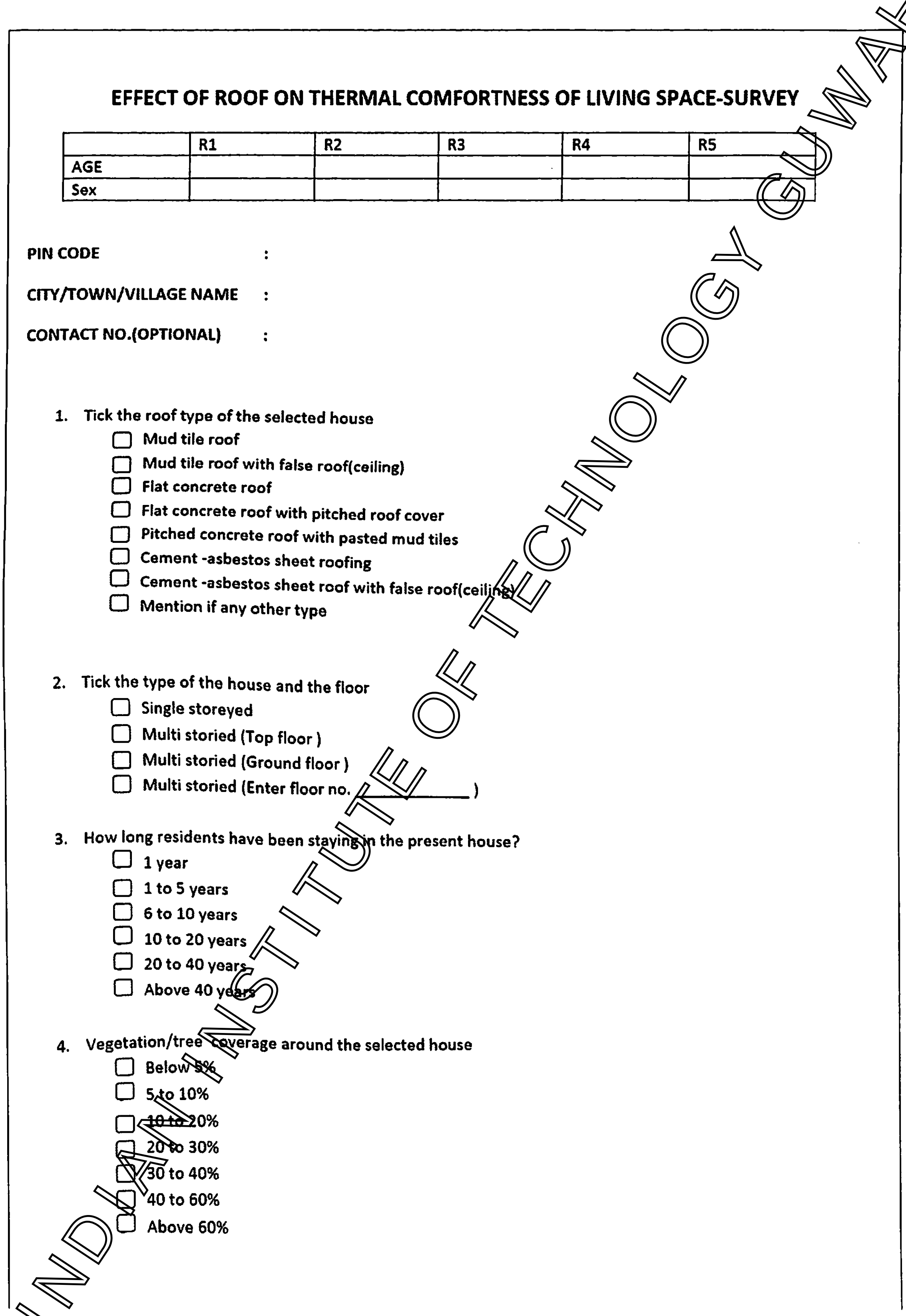
APPENDIX A
SURVEY QUESTIONNAIRE



EFFECT OF ROOF ON THERMAL COMFORTNESS OF LIVING SPACE-SURVEY

	R1	R2	R3	R4	R5
AGE					
Sex					

PIN CODE :

CITY/TOWN/VILLAGE NAME :

CONTACT NO.(OPTIONAL) :

1. Tick the roof type of the selected house
   - ☐ Mud tile roof
   - ☐ Mud tile roof with false roof(ceiling)
   - ☐ Flat concrete roof
   - ☐ Flat concrete roof with pitched roof cover
   - ☐ Pitched concrete roof with pasted mud tiles
   - ☐ Cement -asbestos sheet roofing
   - ☐ Cement -asbestos sheet roof with false roof(ceiling)
   - ☐ Mention if any other type

2. Tick the type of the house and the floor
   - ☐ Single storeyed
   - ☐ Multi storied (Top floor)
   - ☐ Multi storied (Ground floor)
   - ☐ Multi storied (Enter floor no. ________)

3. How long residents have been staying in the present house?
   - ☐ 1 year
   - ☐ 1 to 5 years
   - ☐ 6 to 10 years
   - ☐ 10 to 20 years
   - ☐ 20 to 40 years
   - ☐ Above 40 years

4. Vegetation/tree coverage around the selected house
   - ☐ Below 5%
   - ☐ 5 to 10%
   - ☐ 10 to 20%
   - ☐ 20 to 30%
   - ☐ 30 to 40%
   - ☐ 40 to 60%
   - ☐ Above 60%

5. How is the thermal comfort in your house during the following seasons?

○ Summer

Options	Too cool	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
R1							
R2							
R3							
R4							
R5							

○ Winter

Options	Too cool	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
R1							
R2							
R3							
R4							
R5							

○ Rainy/Monsoon

Options	Too cool	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
R1							
R2							
R3							
R4							
R5							

6. Which climate would you prefer

Season	Summer			Winter			Rainy/Monsoon		
Options	Cooler than now	Present climate	Hotter than now	Cooler than now	Present climate	Hotter than now	Cooler than now	Present climate	Hotter than now
R1									
R2									
R3									
R4									
R5									

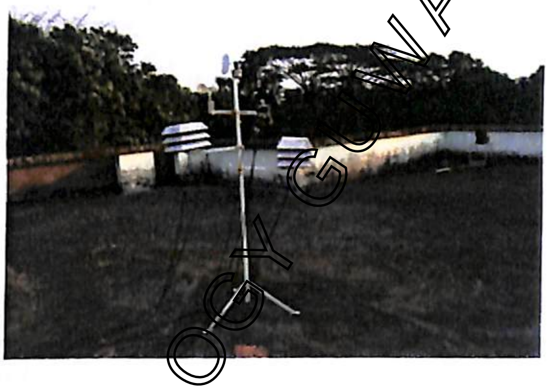
THANK YOU

APPENDIX B

INSTUMENTATION AND SENSORS

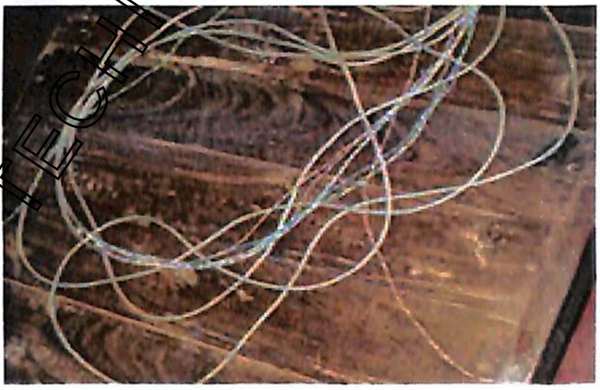
Comfort evaluation system

Weather station

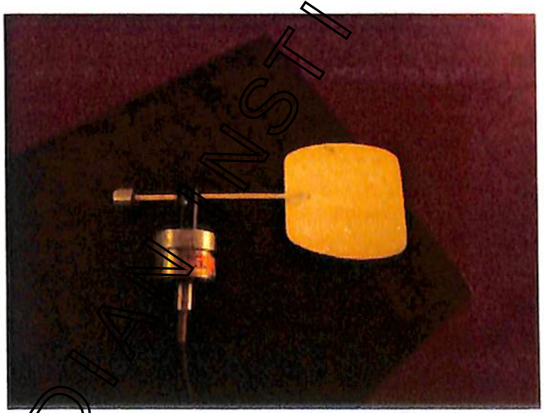


Globe temperature sensors

Thermocouples



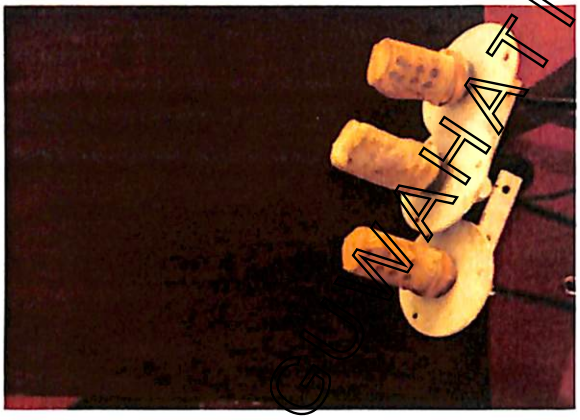
Wind direction sensor



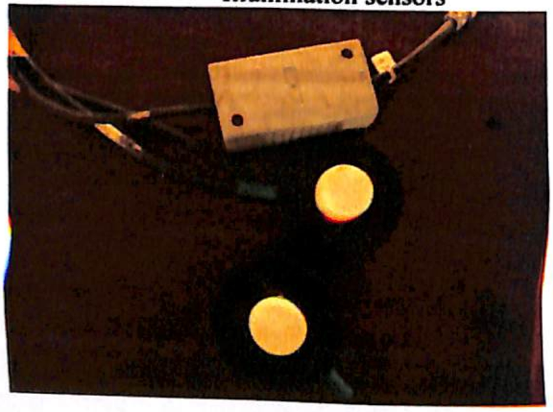
Wind velocity sensor

Solar radiation sensors

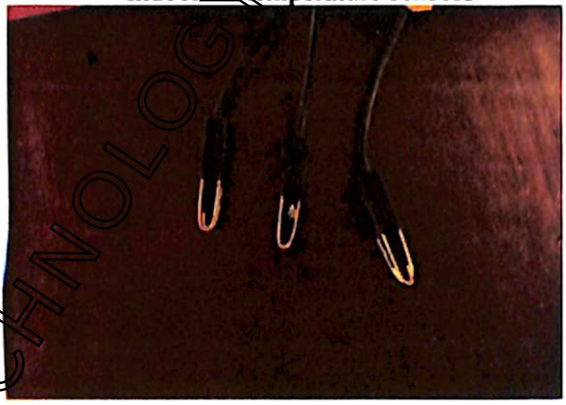
Humidity sensors



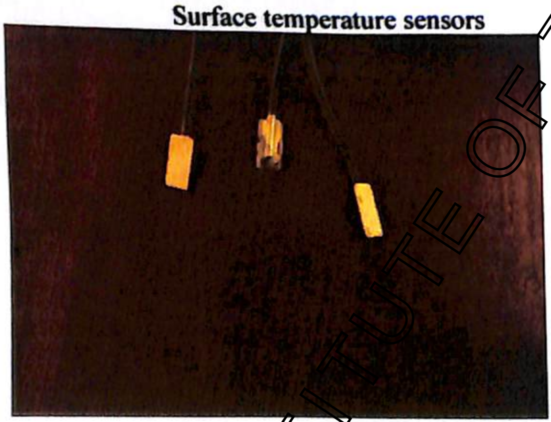
Illumination sensors



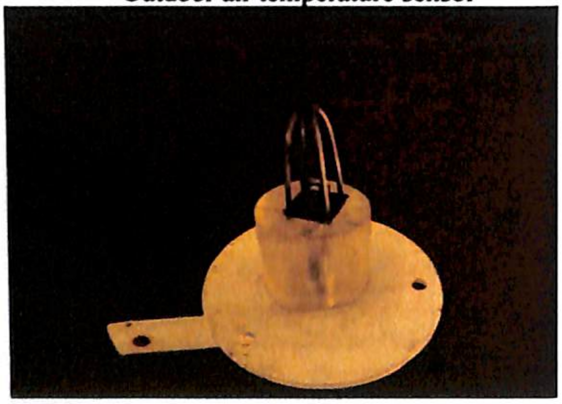
Indoor air temperature sensors



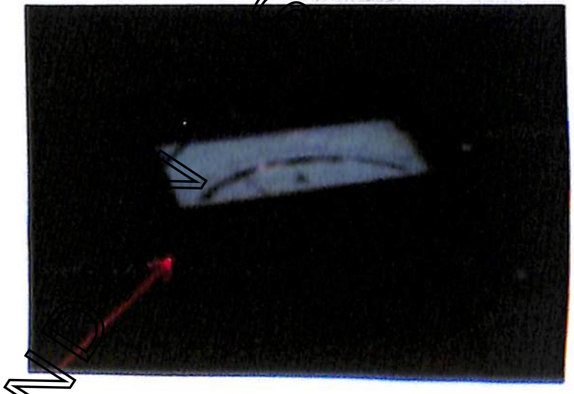
Surface temperature sensors



Outdoor air temperature sensor

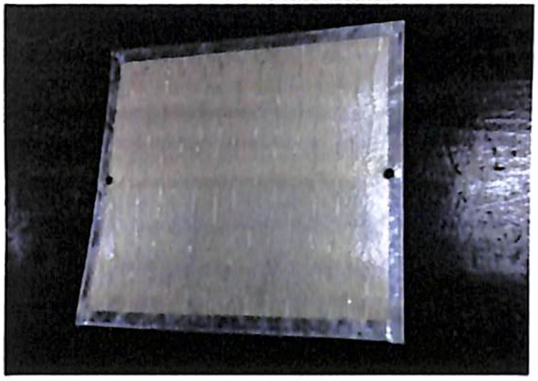


Ammeter



Auto transformer

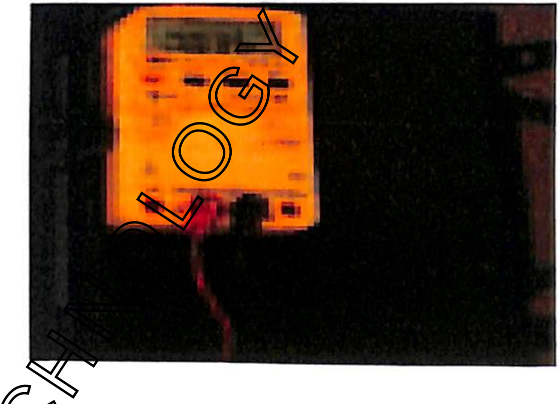
Plate heater



Vane anemometer

Data logger

Multi meter



APPENDIX C

DETAILS OF INSTRUMENTATION

The important details of the various instruments and sensors used in the experiments are given below:

C.1 Data logger

Make :	Agilent technologies
Model :	Agilent 34970 A
Reading rate :	600 readings/second
Scanning rate :	60 channels/second
Scan intervals :	0 to 99 hours; 1ms step size.

C.2 Comfort Evaluation System

Make :	Emcon
Model :	1385
Capacity :	32 Channels
Globe temperature :	2 sensors
Illumination :	3 sensors
Indoor Air temperature :	5 sensors
Outdoor Air temperature :	2 sensors
Relative humidity :	4 sensors
Solar Radiation :	2 sensors
Surface temperature :	5 sensors
Wind Direction :	2 sensors
Wind velocity :	4 sensors

C.3 Wane Anemometer

Make : Lutron

Model : AM-4201

Range : 0.4 to 30 m/s

Resolution : 0.1 m/s

Accuracy : ± 2%

C.4 Teflon sheathed T type thermocouples

Type : Thermoelectric

Range : -160 to 400°C

Sensitivity : ± 0.1°C

Accuracy : ± 0.5°C

C.5 Indoor air temperature Sensor

Type : Semiconductor

Range : 0 to 60°C

Accuracy : ± 0.1°C

Response : 1 s

C.6 Outdoor air temperature Sensor

Type : RTD

Range : 0 to 60°C

Accuracy : ± 0.1°C

Response : 3 s

C.7 Relative humidity Sensor

Type :	Semiconductor
Range :	0 to 100%
Accuracy :	2%
Response :	1 s

C.8 Surface temperature sensor

Type :	Semiconductor
Range :	0 to 60°C
Accuracy :	± 0.1°C
Response :	1 s

C.9 Solar radiation sensor

Type :	Semiconductor
Range :	0 to 1500 W/m^2
Accuracy :	± 1%
Response :	1 s

C.10 Illumination

Type :	Semiconductor
Range :	0 to 50000 Lux
Accuracy :	± 1%
Response :	1 s

C.11 Wind direction sensor

Type :	Single vane type
Range:	0 to 360°
Accuracy:	± 1°

C.12 Wind velocity sensor

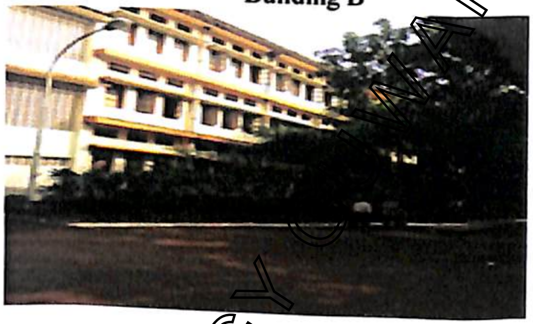
Type :	Three cup infrared type
Range :	0 to 27 m/s
Accuracy :	± 1%

Appendix D

BUILDINGS CONSIDERED FOR STUDY

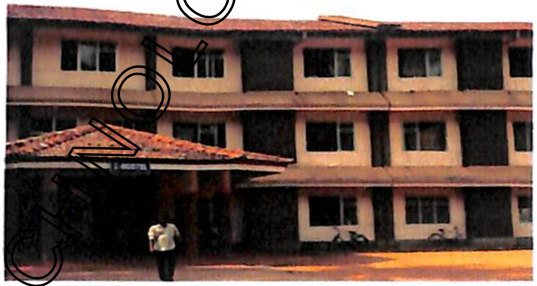
Building A

Building B



Building C

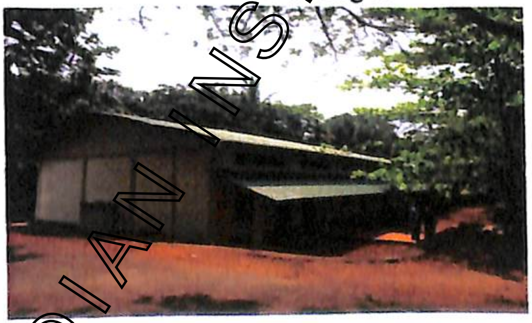
Building D



Building E

Building F

Building G



APPENDIX E

PICTURES TAKEN DURING STUDY

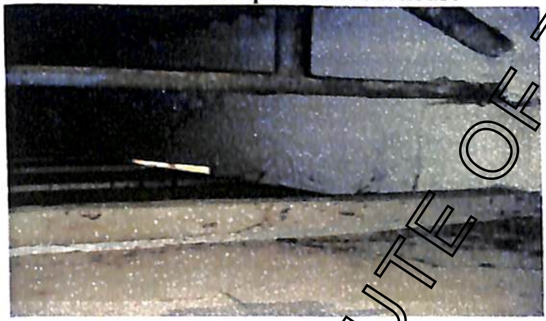
Measuremets during survey

Reduced scale model analysis

Quantitative analysis_TMT house

Sensors fixed at sitting level

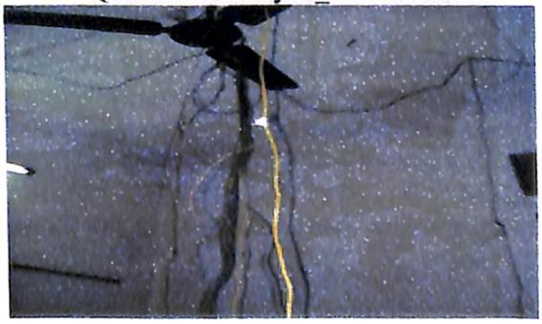
Attic space of ACR house



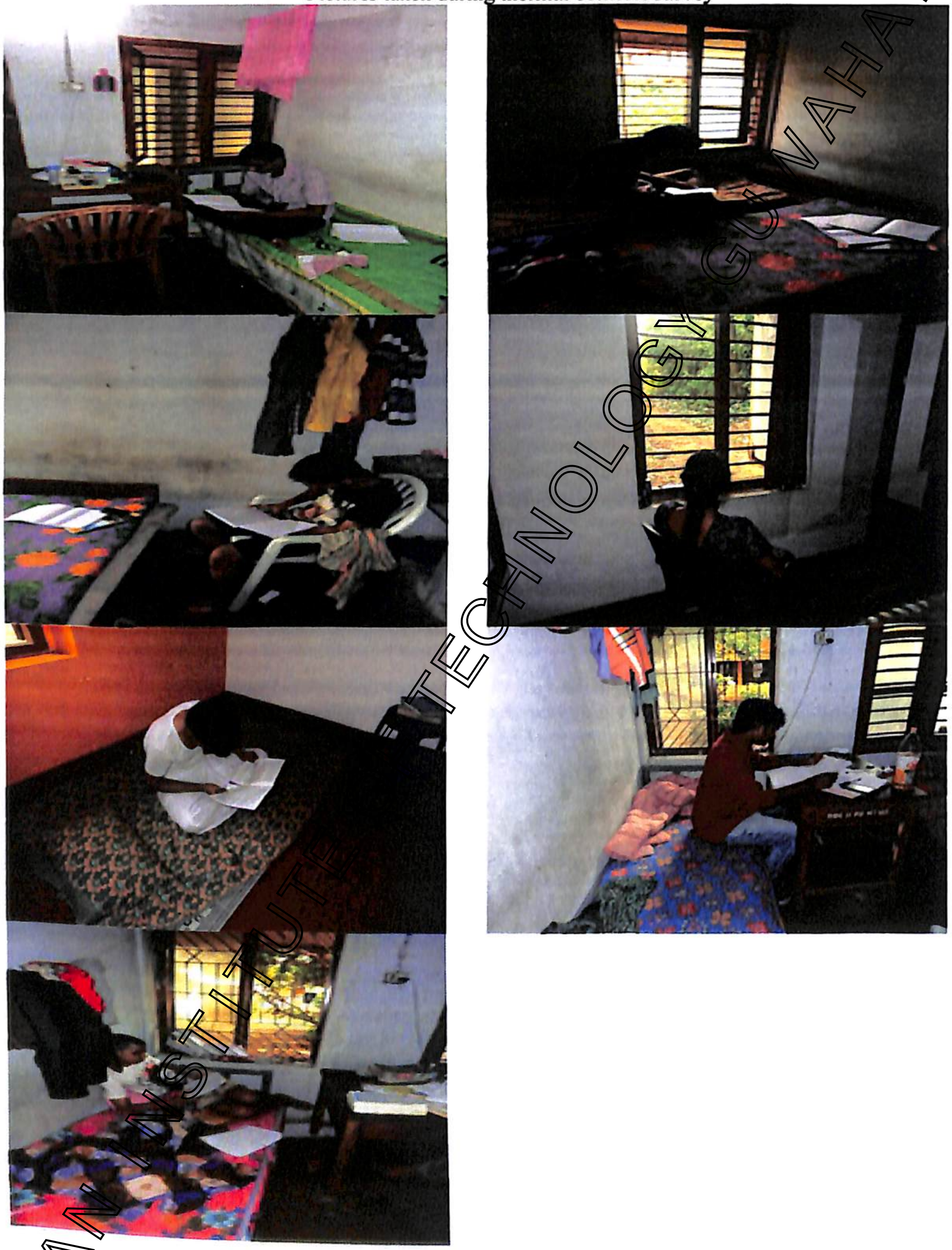
Downloading data to Laptop

Quantitative analysis_ACR house

Quantitative analysis_RCC house



Pictures taken during thermal comfort survey



LIST OF PUBLICATIONS

Accepted

- Lachireddi GKK, Muthukumar P, Sudhakar S. Thermal Performance of a residential building with Asbestos Cement roof, Journal of Applied and Engineering Sciences, 2014.

Communicated

- Lachireddi GKK, Muthukumar P. Thermal Comfort of Residential Buildings in Kozhikode, Building and Environment, (Revised Manuscript submitted on 17th October 2015).
- Lachireddi GKK, Muthukumar P, Sudhakar S. Thermal Comfort Analysis of Hostels in National Institute of Technology Calicut, India, Sadhana - Academy Proceedings in Engineering Science (Submitted on 3rd April 2014).
- Lachireddi GKK, Muthukumar P, Sudhakar S. Comparative studies on thermal performance of RCC roof with ventilated roof: A reduced scale model analysis, Journal of The Institution of Engineers (India): Series A (Submitted 20th June 2014).