



**ADDIS ABABA UNIVERSITY  
SCHOOL OF GRADUATE STUDIES**

**DESIGN OF ENERGY EFFICIENT BUILDINGS  
FOR HOT AREAS OF ETHIOPIA WITH  
RESPECT TO AIR CONDITIONING**

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*October 2004*

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*A thesis submitted to the School of Graduate Studies of Addis Ababa University in partial fulfillment of the Degree of Masters of Science in Mechanical Engineering (Thermal Engineering stream.)*

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# CONTENTS

ACKNOWLEDGMENTS.....	i
LIST OF FIGURES.....	v
LIST OF TABLES .....	vii
CHAPTER ONE .....	1
INTRODUCTION.....	1
1.1. Background .....	1
1.2. Objective of the Thesis.....	3
1.3. Scope and Limitation of the Thesis.....	4
1.4. Organization of the Thesis .....	4
CHAPTER TWO .....	5
BUILDING MATERIALS AND THEIR THERMOPHYSICAL PROPERTIES .....	5
2.1. The Thermophysical Properties of Building Materials.....	5
2.2. Building Materials.....	8
2.2.1. Roof and Ceiling Materials .....	8
2.2.2. Wall Materials .....	12
2.2.3. Building Insulations .....	16
2.2.4. Floor and Floor Finishing Materials .....	21
2.2.5. Windows and Doors.....	22
CHAPTER THREE.....	26
ELEMENTS OF ENERGY EFFICIENT BUILDINGS .....	26
3.1. Introduction.....	26
3.2. Site.....	27
3.3. Landscaping .....	27
3.4. Building Orientation and Layout .....	29
3.4.1. Apparent path of the sun .....	29
3.4.2. Orientation in Northern Hemisphere.....	30
3.5. Building Envelopes .....	31
3.5.1. Windows and Shadings .....	32
3.5.2. Roof and Ceiling .....	34

3.5.3. Walls .....	35
3.5.4. Foundations and Floor.....	36
3.5.5. Insulation.....	37
3.6. Infiltration and Ventilation.....	40
3.7. Air Conditioning Systems.....	41
3.8. Lighting and Appliances .....	41
3.9. Color and Surface Texture .....	42
CHAPTER FOUR.....	44
ENERGYPLUS: BUILDING ENERGY SIMULATION SOFTWARE.....	44
4.1. Introduction.....	44
4.2. EnergyPlus .....	48
4.3. Heat Transfer Modeling of a Building in EnergyPlus .....	52
4.4. EnergyPlus Input Files .....	62
4.5. EnergyPlus Output Data.....	69
CHAPTER FIVE.....	71
A CASE STUDY OF ENERGY SAVING OF BUILDINGS IN GODE.....	71
5.1. Building Description .....	71
5.1.1. Residential building .....	71
5.1.2. Office Building.....	72
5.2. Weather Data for Gode .....	72
5.2.1. Climatic Classification.....	72
5.2.2. Temperatures and Relative Humidity .....	73
5.2.3. Solar Radiation.....	77
5.3. Calculation of Heat Gains .....	84
5.3.1. Heat Gain from Solar Radiation.....	84
5.3.2. Heat Gain through Infiltration.....	85
5.3.3. Heat Gain from People.....	88
5.3.4. Heat Gain from Light.....	89
5.4. Simulation Result and Discussion of the Residential Building .....	90
5.5. Simulation Result and Discussion of Office Building .....	101
5.6. Simulation and Result of a Single Room Building .....	111

5.7. Economic Analysis.....	118
CHAPTER SIX .....	123
CONCLUSION AND FUTURE WORK.....	123
6.1. Conclusion.....	123
6.2. Future Work .....	125
APPENDIX .....	129

## LIST OF FIGURES

Figure 3. 1	Apparent path of the sun in the northern hemisphere.....	29
Figure 3. 2	Different possible installation of insulation in walls .....	39
Figure 3. 3	Installation of roof insulation.....	40
Figure 4. 1	General structure of EnergyPlus .....	50
Figure 4. 2	EnergyPlus Integrated Simulation Manager.....	52
Figure 4. 3	Outside Face Heat Balance Control Volume Diagram.....	54
Figure 4. 4	Inside Face Heat Balance Control Volume Diagram .....	58
Figure 5. 1	Monthly Mean Maximum and Minimum Dry-Bulb Temperature for Gode....	74
Figure 5. 2	Daily Temperature and Relative Humidity profile for the hottest month, March .....	75
Figure 5. 3	Daily Temperature and Relative Humidity Profile for the Month, July.....	76
Figure 5. 4	Monthly Average Sun Shine Hours for Gode.....	77
Figure 5. 5	Daily Total (Beam Plus Diffuse) Solar Radiation Profile for May .....	83
Figure 5. 6	Daily Total (Beam Plus Diffuse) Solar Radiation Profile for July.....	83
Figure 5. 7	Average Monthly Wind speed for Gode.....	87
Figure 5. 8	Overhead fluorescent luminaire configurations.....	90
Figure 5. 9	Cooling Load Variation with Solar Absorptance of External Walls for Residential Building.....	92
Figure 5. 10	Cooling Load Variation with Wall Insulation for Residential Building.....	93
Figure 5. 11	Cooling Load Variation with Roof Insulation .....	95
Figure 5. 12	Cooling Load Variation with Window Shading .....	96
Figure 5. 13	Combined Effects of the Parameters and Orientation on Cooling Load Variation.....	97
Figure 5. 14	Daily Total Cooling Rate Variation of the Residential Building for the Month March. ....	98

Figure 5. 15 Daily Total Cooling Rate Variation of the Residential Building for the Month July.....	98
Figure 5. 16 Cooling Load Variation due to color of External Walls for the Office Building .....	101
Figure 5. 17 Cooling Load Variation due to Wall insulation for the Office Building.....	103
Figure 5. 18 Cooling Load Variation Due to Roof Insulation for the Office Building....	104
Figure 5. 19 Cooling Load Variation Due to Window Glazing and shading for Office Building.....	105
Figure 5. 20 Cooling Load Variation Due to Orientation and Combined effect of the Parameters for the Office Building .....	106
Figure 5. 21 Daily Cooling Rate of Office Building for the Month March .....	107
Figure 5. 22 Daily Cooling Rate of Office Building for the Month September .....	108
Figure 5. 23 Cooling Load Variation Due to Wall Insulation in Case of Small Window	112
Figure 5. 24 Cooling Load Variation Due to Roof Insulation in Case of Small Window	112
Figure 5. 25 Cooling Load Variation Due to Wall Insulation in Case of Large Window	115
Figure 5. 26 Cooling Load Variation Due to Roof Insulation in Case of Large Window	115

## LIST OF TABLES

Table 2.1 Thermal Properties of Roofing Materials .....	12
Table 2.2 Wall and Wall Finishing Materials and Their Thermal Properties.....	15
Table 2.3 Thermal Properties of Insulation Materials .....	21
Table 2.4 Thermal Properties of Floor and Floor Finishing Materials .....	22
Table 2.5 Thermal Properties of Glass Material for Window and Glass Door.....	24
Table 3.1 Absorption coefficient of various colors.....	43
Table 5.1 Climatic zones of area.....	73
Table 5.2 Air Exchange rates (ACH) as a function of airtightness.....	86
Table 5.3 Heat gain from people at different activity level .....	88
Table 5.4 Approximate values of Return Air Fraction, Fraction Radiant, and fraction visible for overhead fluorescent lighting for different luminaire configurations.....	89
Table 5.5 Summary for the residential building in Gode.....	99
Table 5.6 Summary of the results of office building in Gode.....	109
Table 5.7 Summary of simulation results for the one room house with small window size and 4 people. ....	113
Table 5.8 Summary of Simulation Results for the One Room House with Large Window Size and 40 People. ....	116
Table 5.9 Approximate cost for roof insulation in Ethiopia .....	120
Table 5.10 Total cost and Payback Period of Roof Insulation of the Residential Building .....	121
Table 5.11 Total cost and Payback Period of Roof Insulation of the Office Building ....	122

## **ABSTRACT**

This thesis is intended to identify the design improvements of buildings that can be made for the hot region of Ethiopia. A detail literature survey is done on design improvements and those that can be most suitable and economical are suggested. A case study of two different buildings in Gode (one of the hottest area in Ethiopia) was conducted using building energy simulation software to quantify the energy saving from some of the design improvement measures such as using insulation in roof or ceiling and in walls, window glazing and shadings, and orientation. The simulation result verifies that using 75mm insulation in roof or ceilings give a better saving and most economical when the building has small glazing area with respect to the wall size and lower internal cooling load. And when the building has large glazing area using either internal or external window shading is the best way to reduce the annual energy cost of the building and 50mm roof insulation is most economical. In addition to the above results the relation between insulation and different conditions of cooling load in a building is verified. This result shows that when internal load and solar load through window are dominating insulation can have a negative impact to cooling load.

# CHAPTER ONE

## INTRODUCTION

### 1.1. Background

Like in many developing countries, in Ethiopia, modern building construction is growing rapidly. However, due to little awareness of the society, ventilation and air conditioning were rarely used. In fact there are some practices in some of modern buildings in Addis Ababa, modern hospitals, new airport terminal which are constructed these days in different parts of the country, in some buildings in Gambela, Semera, Gode and in some other areas of the country. In the past few years, the demand for these systems has grown rapidly. Accordingly, a few years later, due to the increase in economic and living standard of the society the demand for these systems will increase tremendously. Therefore, it is high time for mechanical engineers and architects in this country to focus on optimum building design.

Air conditioning refers to the control of temperature, moisture content, cleanliness, air quality, and air circulation, as required by occupants, the process, or product in the space. In other words, air conditioning systems create a comfortable and healthy environment for the people. Though it is difficult to define the word comfort because of its subjective nature, some definitions have been given. Among these is the one given by ASHRAE. ASHRAE Comfort Standard 55-74 defines comfort as “*that state of mind which expresses satisfaction with the thermal environment*” but points out that most of the studies regard

comfort as a subjective sensation that is expressed by an individual, when questioned as neither slightly warm nor slightly cool [29]. With the above definition, the factors that influence comfort, in their order of importance are, temperature, radiation, humidity, air motion, and quality of the air with regard to odor, dust, and bacteria. With a complete air conditioning system all of these factors may be controlled simultaneously. It is found that in most cases a reasonably comfortable environment can be maintained when two or three of these factors are controlled. Hence, air conditioning of buildings is mainly concerned with the comfort of people.

Ventilation and air conditioning is a crucial issue in the hot areas of this country like Afar, Gambela, Somali, Dire Dawa, Gode, etc. In fact, in other areas of the country, it is also important in buildings, like conference halls, hospitals, theater halls, hotels, restaurants, churches, schools, in which a large number of people gather.

When we are talking of air conditioning systems, the energy consumption of these systems should be minimized as these systems consume most of the energy consumed by a building. The energy consumed by the air conditioning systems depends on the cooling load on the system which in turn depends largely on the design and materials of the building and building orientation. Thus, the best way to cut energy cost for air conditioning is to design buildings in an energy efficient way which reduces the heat gain or heat loss.

In general, energy efficient buildings provide the benefit of:-

- reduced energy cost for dwellings and commercial buildings.
- greater natural comfort and amenity level to building occupants, and
- by virtue of reduced energy; reduced emissions of carbon dioxide and other greenhouse gases, and thereby reduce impact on the natural environment.

## **1.2. Objective of the Thesis**

The objective of this thesis is to investigate design improvements in modern building designs for hot areas of Ethiopia so that cooling load will be minimized in order to minimize energy cost of air conditioning systems or in some cases to eliminate air conditioning requirement while improving the comfort level for the occupants. The design parameters focus mainly on the building envelope which will help in preventing the solar radiation heat from surrounding into the building and the orientation. Actually the best and most economical design depends on individual building parameters such as size, orientation, site, location and the internal loads from light, equipment and people. However, this thesis focuses on two existing buildings in Gode to give some insight on different building design parameters and their effect on energy consumption. The annual cooling energy saving of each parameter is calculated and the economic feasibility of roof insulation is done. Another objective of this thesis is to motivate other researcher to work further on the design of energy efficient building not only in hot areas but also in other parts of the country.

### **1.3. Scope and Limitation of the Thesis**

This thesis covers only design of energy efficient buildings with respect to air conditioning systems. Reduction of energy consumption for air conditioning systems through proper design of the building is only covered. Lighting systems and daylighting, and hot and cold water systems are not covered. The design parameters which are covered in this thesis are improving roof and wall insulations, orientation, window shadings, and colors.

### **1.4. Organization of the Thesis**

The thesis contains six chapters out of which two are on literature review. The first chapter covers the introduction part which deals with the background and objective of the thesis. The second chapter deals with building construction materials and their thermophysical properties like density, thermal conductivity, and specific heat. Chapter three is on literature survey of design of energy efficient buildings. It also covers different design parameters and their thermal effect on the building. The discussion in this chapter is limited to hot areas of the northern hemisphere and gives a general over view on energy efficient building designs. The fourth chapter discusses the building simulation software used to perform the case study. It discusses the general overview of the software (EnergyPlus) and its input and output parameters. The fifth chapter shows the case studies dealt in the study. This chapter shows the energy savings for the different design parameters. In the end, the recommendations and conclusions are forwarded in chapter six.

## CHAPTER TWO

# BUILDING MATERIALS AND THEIR THERMOPHYSICAL PROPERTIES

### 2.1. The Thermophysical Properties of Building Materials

In designing an energy efficient building, the first step is to understand the thermal behavior of the building and materials used in the construction. The relationship between building orientation and the apparent motion of the sun, the heat transfer characteristics of building materials and the response of the building envelop to variation of the outdoor climate are the basic thermal design factors to be considered when selecting building materials. The thermal properties of materials which affect the rate of heat transfer in and out of a building are:

- Thermal conductivity
- Surface characteristics with respect to radiation: absorptivity, reflectivity and emissivity
- Surface convective coefficient
- Heat capacity (density, thickness) and thermal mass
- Transparency to radiation of different wavelengths

***Thermal conductivity:*** is the property of a material which determines the heat flow in unit time by conduction through a unit thickness of a unit area of the material across a unit temperature gradient. The thermal conductivity varies with the density, porosity, moisture

content and absolute temperature. The higher the moisture content, the greater the thermal conductivity is. The thermal conductivity is greater at high than at low temperatures. However, the variation of the thermal conductivity over the range of temperatures commonly occurring in buildings is comparatively small, and thus the thermal-conductivity values measured at normal atmospheric temperature are generally used when considering structural insulation.

In calculations, it is often convenient to use the reciprocal of the thermal conductivity which is called the thermal resistivity. The thermal resistance is a measure of the resistance to heat flow of a material or a combination of materials. The thermal resistance may be regarded as either the time required for the transmission of one unit of quantity of heat through one unit area of material when the temperature difference between surfaces perpendicular to the direction of heat flow is one degree of temperature; or the number of degrees difference in temperature between these surfaces when one unit of quantity of heat flows through one unit area in unit time. If the thickness of the material is increased there is a corresponding proportional increase in its thermal resistance. If several materials are placed together in layers the total thermal resistance of the wall may be obtained by adding the resistances for each component.

***Surface characteristics with respect to radiation:*** The external surface of any opaque material has three properties determining the behavior with respect to radiant heat exchange, namely its absorptivity, reflectivity and emissivity. The color of a surface is the most important factor that determines these properties for solar radiation. The absorptivity decreases and the reflectivity increase with lightness of color; being fully absorbed by a

perfectly back surface and fully reflected by a perfect reflector. Most surfaces, however, absorb only part of the incident radiation, reflecting the remainder. If the absorptivity is denoted by 'a' and the reflectivity by 'r', then,  $r = 1 - a$

The emissivity ( $\epsilon$ ) is the relative power of a material to emit radiant energy. For any specific wavelength, absorptivity and emissivity are numerically equal, i.e.  $a = \epsilon$ . Every surface emits radiation with a spectral distribution and intensity which depend on its temperature.

**Surface coefficient:** The surface coefficients determine the rate of heat exchange between the surface and the surrounding air, and the radiation exchange with other surfaces, or the sky. The surface coefficient is the sum of the radiative coefficient and the convective coefficient. The radiative coefficient is mainly dependent on the surface emissivity, and also to some degree on the mean temperature of the surfaces exchanging radiation. The convective coefficient depends primarily on the velocity of the air near the surface.

**Heat capacity:** This is defined as to the amount of heat required to elevate the temperature of a unit volume of the wall, or the unit area of the surface, by one degree.

**Thermal mass:** Thermal mass is a term used to describe the ability of building materials to store heat (thermal storage capacity). The basic characteristic of materials with thermal mass is their ability to absorb heat, store it, and release it at a later time. Building materials that are heavyweight store a lot of heat so are said to have high thermal mass. Materials that are lightweight do not store much heat and have low thermal mass.

***Transparency to radiation of different wavelength:*** this property is generally applicable to transparent materials like glass in windows and glass doors. This determines the amount of solar radiation entering the building. Materials with high transmissibility allow higher solar radiation than materials with low transmissibility.

## **2.2. Building Materials**

Building materials are those used to construct the building. These include materials used in roofing and ceiling, wall, flooring and foundation, windows and doors, and insulation constructions. They are the envelope which separate the inside from the outside environment and on this way modify or prevent the direct effect of climatic variables such as outdoor air temperature, humidity, wind, solar radiation etc. Their effects depend on the thickness and thermo physical properties of the envelope.

### **2.2.1. Roof and Ceiling Materials**

Different roof designs and materials are used for residential and commercial buildings. Commercial buildings typically use low-slope or flat roofs, while residential roofs are mostly sloped. Some of the common roofing materials available are:

- Asphalt shingles and rolls
- Membrane or/and Single -Ply
- Metal
- Wood
- Concrete and Tiles

### **a. Asphalt**

Asphalt is the most commonly used roofing material in the developed countries but is less frequently used in Ethiopia. Asphalt products include shingles, roll-roofing, and built-up roofing.

*Asphalt shingles* are widely used with flat roofs and can be used in houses with sloping roofs as well. From a reflectance point of view, they are very similar to rolled asphalt roofing, which is often used as the top layer of low slope roofing. These materials are composed of asphalt saturated mats made from organic felts or fiberglass. The asphalt is protected from the sun's ultraviolet light using granules such as crushed granite to protect them from melting.

*Built-Up Roof* is a roof consisting of multiple plies of roof felts laminated together with bitumen. Built-up roof material can consist of bitumen-saturated felt, coated felt, polyester felt or other fabrics. A surfacing is generally applied and can be asphalt, aggregate (gravel or slag), emulsion or a granule-surfaced cap sheet.

### **b. Roofing Membranes or single-ply**

Roofing membranes are fabricated from strong, flexible, waterproof materials which usually contain a fabric made from felt, fiberglass, or polyester. There are three types of membranes: **thermosets**, **thermoplastics**, and **modified bitumens**.

*Thermoset membranes* are compounded from rubber polymers. The most commonly used polymer is EPDM (Ethylene Propylene Diene Monomer, often referred to as "rubber roofing"). EPDM membrane thickness ranges from 0.8mm to 2.5mm with the most common thicknesses being 1mm and 1.5mm. *Thermoplastic membranes* are based on plastic polymers. The most common thermoplastic is PVC (polyvinyl chloride) which has been made flexible through the inclusion of certain ingredients called plasticizers. *Modified bitumen membranes* are hybrids that incorporate the high tech formulation and prefabrication advantages of single-ply with some of the traditional installation techniques used in built-up roofing. These materials are factory-fabricated layers of asphalt, "modified" using a rubber or plastic ingredient for increased flexibility, and combined with reinforcement for added strength and stability.

### **c. Metal Roofing**

Metal roofing is the most common and widely used roofing material in Ethiopia. These roofing products consist of corrugated galvanized steel sheets, although some made of aluminum, copper and other metals. Steel is invariably galvanized by the application of zinc or zinc/aluminum coating, which greatly reduces the rate of corrosion. Galvanized steel have low solar absorptance which makes it a good reflector of solar radiation. The metal roofs have high thermal conductivity and most of the heat absorbed by the material will be transferred to the building.

#### **d. Wood**

Wood shakes offer a natural look with a lot of different characters such as color, width, thickness and texture. It offers some energy benefits, like helping in insulating the attic, and it allows the building to breathe by circulating air through the small openings under the felt rows on which wooden shingles are laid. A wood shake roof, however, demands proper maintenance and repair, or it will not last as long as other products. Rot and insects can be a problem. In addition wood shakes are not fire resistance as other roofing materials and can't be recycled. So care must be taken if wood is used as a building envelop.

#### **e. Concrete and Clay Tile Roofing**

Roofing tiles can be ceramic (e.g., clay fired at a high temperature) or fabricated from cement concrete. Some of the lighter types use fibers (e.g., cellulose) added for strength. The color of a tile may be dispersed throughout, or it may be applied in the form of a coating. Perhaps the most venerable type of roof tile is the red barrel tile made from fired clay. The modern version of this tile is sometimes a cement tile with a suitable coating. In either case, the red color is due to the ubiquitous iron oxide material, hematite. Due to wide variety of colors for roofing tiles; more data on the solar reflectance properties are needed. Advantages of tile include fire safety, as they are non-combustible, durability, aesthetically appealing, and low in maintenance. They also provide energy savings and are environmentally friendly. Disadvantages include increased weight and cost compared with some other roofing like low-cost asphalt shingle roofs.

**Table 2.1** Thermal Properties of Roofing Materials

S.No	Material	Density kg/m <sup>3</sup>	Thermal Conductivity W/m K	Specific Heat kJ/kg K	Solar Absorptance
1	Asphalt Rolls	1121.3	0.11	0.83	0.8
2	Asphalt Shingles	1121.3	0.3	0.83	0.7
3	Built-Up roofing	1121.3	0.16	1.46	0.7
4	Bare Aluminum	2139.2	221.38	0.89	0.2
5	Galvanized Steel	7833	45.31	0.5	0.23
6	Roofing Membrane	1121.3	0.19	1.67	0.75
7	Hard Wood	720.83	0.15	1.25	0.78
8	Ply Wood	545	0.11	1.21	0.7
9	Soft Wood	512.6	0.11	1.38	0.78

Source: EnergyPlus data set Materials for Building Construction

**Note** The solar absorptance is given for a normal design of the material but it can vary greatly if the color of the material varies. This property is largely dependent on the color and surface texture.

### 2.2.2. Wall Materials

Walls are required in buildings to divide up spaces into areas of convenient size, keep out dust and rain yet let in air, and provide shade, coolness, privacy and protection. The most common materials used for buildings walls are; stone, concrete, and burnt clay. Other types of wall materials like wood, steel and structural insulated panels are also sometimes used.

**Stone:** This is the most widely material used in Ethiopia. Stone is available any where and they have high thermal mass which make them suitable in hot areas of the country. It may

be available in the form of limestone, igneous, sandstone, and others. It is durable, and has an aesthetic value.

**Concrete Blocks:** These are also widely used wall materials and are manufactured in many shapes and size. The standard blocks are of 200mm and 150mm thickness, although 75 and 100mm thick are also available. Usually they are made in form of hollow blocks which are machine pressed and lighter than the solid block of the same size. Hollow concrete blocks also improve insulation, and can be handled easily.

**Burnt clay blocks:** They are available as hollow or solid and they are common. They are frequently used as internal partitions and also as outside walls with plain faces.

**Wood:** Of the options available, plywood and oriented strand board (OSB) are the strongest and most durable. Wood sheathing panels add shear and racking strength; the important characteristics that are engineered to help a structure withstand the forces of high winds and earthquakes. Wood-sheathed walls are also easy to build and easy to insulate for high R-values (resistance to heat flow).

**Steel:** Steel is commonly used in the construction of commercial buildings. Steel buildings use nearly the same framing techniques as employed in wood-framed buildings. Construction costs also run about the same. Unlike wood, however, steel is impervious to termites. It provides added resistance to fire and earthquake. Steel ceiling joists can span greater distances than wooden ones, allowing new design possibilities for architects and builders.

### ***Wall Finishing***

Wall finishing materials have a greater impact on the heat gain of a building. Their effect mostly lay on their surface texture and color, because their thickness is very small their thermal resistance can be neglected. Some of the wall finishing materials commonly used are; mortars, stuccos, and gypsum plastering and boards.

***Mortars*** are composed of a cementitious material, fine aggregate, sand, and water. They are used for bedding unit masonry, for plasters and stuccoes, and with the addition of coarse aggregate, for concrete. Properties of mortars vary greatly, being dependent on the properties of the cementitious material used, ratio of cementitious material to sand, characteristics and grading of the sand, and ratio of water to solids. ***Stucco*** is nearly the same in thermal and physical properties as mortars. Stucco is a mixture of sand, portland cement, lime, and water. ***Gypsum plasters*** are also similar to stuccoes except that gypsum is added to the mixture.

***Gypsumboard*** is a product consisting of a core of set gypsum surfaced with specifically manufactured paper firmly bonded to the core. It is designed to be used without addition of plaster for walls, ceilings, or partitions and provides a surface suitable to receive either paint or paper. The types of gypsumboard generally available include wallboard, backing board, coreboard, fire-resistant gypsumboard, water-resistant gypsumboard, gypsum sheathing, and gypsum formboard.

**Table 2. 2** Wall and Wall Finishing Materials and Their Thermal Properties

<b>S.No</b>	<b>Material</b>	<b>Density Kg/m<sup>3</sup></b>	<b>Thermal conductivity W/m K</b>	<b>Specific heat kJ/kg K</b>	<b>Solar Absoptance</b>
1	Asbestos cement	1922.2	0.57	0.83	0.75
2	Brick (common)	1922.2	0.72	0.83	0.76
3	Face Brick	2082.4	1.24	0.92	0.93
4	Clay Tile	1121.3	0.57	0.83	0.82
5	Light Weight concrete Block	608.7	0.38	0.83	0.65
6	Heavy Weight Concrete Block	977.1	0.81	0.83	0.65
7	Light Weight Hollow Concrete Block(150mm)	881	0.37	0.83	0.65
8	Light Weight Hollow Concrete Block(200mm)	720.83	0.57	0.83	0.65
9	Heavy Weight Hollow Concrete Block(150mm)	1361.6	0.95	0.83	0.65
10	Heavy Weight Hollow Concrete Block(200mm)	1105.3	1.04	0.83	0.65
11	Gypsum Plaster	801	0.16	0.83	0.75
12	Plaster Cement, stucco, and mortar	1858.14	0.7	0.83	***
13	Stone, Lime, Sand	2883.6	10.38	0.795	0.6

Source: EnergyPlus Data Sets Materials for Building Construction

\*\*\* Varies from 0.23 to 0.92 depending on the texture and color of the material.

### **2.2.3. Building Insulations**

Insulation works by slowing down heat as it travels through the material. The amount of insulation one needs depends on the building design and location. When selecting insulation products, several performance characteristics are important. Some of them are: insulating capacity, fire resistance, moisture control, weight, convective heat loss, settling and loss of insulating capacity, and cost. Insulation is rated in terms of its resistance to heat flow, called R-value. The higher the R-value, the greater is its thermal resistance. The R-value of thermal insulation depends on the type of material, its thickness, and density. Insulation is available in a variety of materials and forms:

- Fiber glass insulation
- Cellulose insulation
- Mineral wool insulation
- Rigid insulation
- Sprayed foam insulation
- Radiant Barriers and Reflective Insulations

#### **a. Fiber Glass Insulation**

The most commonly used insulation in modern buildings is fiberglass. Fiberglass is chemically stable, will not rot and is nonflammable. It does melt with enough heat, so it offers no fire retardant properties to the building. It is also permeable and will readily absorb moisture, making it a poor choice in damp or wet locations.

Fiberglass insulation is manufactured in a number of useful forms such as fiber glass rolls, fiber glass batts, fiber glass blankets, and fiber glass loose-fill.

***Roll and Batt Insulations*** are available in widths suited to standard spacing of wall studs and attic or floor joists. Continuous rolls can be hand-cut and trimmed to fit. They are available with or without vapor retarder facings. Batts with a special flame-resistant facing are available in various widths. This type of insulation will be damaged if it gets wet and therefore flexible batts should be installed after a building is enclosed and weather tight. If batt insulation is compressed to fit into a space, its thermal efficiency will be reduced. Both have an attached vapor barrier facing to protect them from moisture. This facing is designed to be stapled onto framing studs to keep the insulation in place prior to the installation of the wallboard or plaster. Paper is the most common facing, but there is also an aluminum facing which adds additional heat reflective properties to the insulation.

***Fiberglass blankets*** are similar to batts in that they are sold in precut lengths, but do not have a vapor barrier facing. They are designed to be installed over the top of existing insulation in attic floors to increase the resistance, not as the primary insulation layer.

***Loose fill fiberglass*** can be poured or mechanically blown onto spaces, making this the fiberglass product of choice for quick retrofitting of insulation into older buildings or into areas with limited access for the installation of batts. This insulation is well suited for places where it is difficult to install other types of insulation. Additional resistance to air infiltration can also be provided if the insulation is sufficiently dense or thick. Loose fill

insulation is not only made from fiberglass but it can be made up of mineral wool fibers and cellulose fibers.

#### **b. Cellulose Insulation**

Cellulose insulation is a byproduct of the paper industry, using up to 75% recycled newsprint. Cellulose and fiberglass share similar R-values at normal temperatures, but cellulose has greater insulating properties at lower temperatures than fiberglass or mineral wool making it the better insulation choice in the colder climates. Cellulose is also less permeable to air movement than fiberglass and is less affected by packing and fluffing, making it a better insulation for blowing into uninsulated walls or other building cavities. They are available as loose-fill products and they have none of the irritating properties of fiberglass, and so far have not been shown to have any deleterious effects.

#### **c. Mineral Wool**

Mineral wool, also known as rock wool, is an insulation product manufactured from steel slag. The slag, a byproduct of steel manufacturing consisting of dirt and limestone, is combined with other chemicals, heated and spun into a fibrous material that is an excellent insulator. It is permanent, will not rot, does not burn or melt, does not absorb moisture, and will not support mold or mildew. It is available in batts or as a loose-fill product that can be blown into walls and ceilings. It can also be installed between wall studs by using a mesh screen across one side of the studs, allowing floor to ceiling filling with a technique virtually the same as with blown-in cellulose. Because of its greater density and water

resistant properties, mineral wool acts as a vapor barrier and, unlike fiberglass, does not need an additional vapor barrier to be effective.

#### **d. Rigid Foam and Foam Boards Insulation**

Foam insulation typically is more expensive than fiber insulation. But it's very effective in buildings with space limitations and where higher resistance is needed. Foam insulation R-values is up to 2 times greater than most other insulating materials of the same thickness. Foam insulation is often made with one of three materials: molded expanded polystyrene (MEPS), extruded expanded polystyrene (XEPS) or polyurethane, polyisocyanurate, or a related chemical mixture.

Although batts are typically used between studs or floor joists, rigid foam boards should be considered as an alternate approach. These boards are lightweight, and provide structural support and acoustical insulation. Rigid boards can also be added to basement walls, exposed foundations, cathedral ceilings, exterior walls, and attic access. Such boards may be faced with a reflective foil that reduces heat flow when next to an air space. Foam insulation can be damaged if they are exposed to direct sunlight; hence it is better to protect them using a rubber or plastic especially in roofs. Foam insulations are toxic when burnt so they are not recommended to use them in residential buildings.

#### **e. Spray Foam Insulation**

Foam insulation can be sprayed into building cavities or directly onto the surfaces. Plastic foams have higher R-values than fiberglass, cellulose or mineral wool. Spray foam is an inert product that resists rot and mildew and, because of the strong bond it makes with structural members, actually adds strength to the building. They can be added into concrete or masonry walls by pouring loose foam beads into masonry blocks or injecting/ pouring liquid foam into the hollow block cores. The same insect infestation warnings apply to sprayed foam as to rigid insulation panels using it within the hollows of cement block foundations and in any other below or near ground level applications can give termites a direct route into the building. In hot climates foam insulation can be used in combination with fiberglass insulation.

#### **f. Radiant Barriers or Reflective Insulations**

Radiant barriers are usually fabricated from aluminum foils with a variety of backings such as Kraft paper, plastic film, polyethylene bubbles, or cardboard. These reflective insulation systems are usually installed directly under the roof rafters to reduce heat gain from the sun. They can also be very effective when used for walls that absorb direct sunlight, especially if an effective roof overhang is not practical (for example walls facing west and east). They are more effective in hot climates than in cool climates where there is intense solar radiation.

All radiant barriers must have a low emittance (0.1 or less) and high reflectance (0.9 or more). Most of them in the market today have about the same emissivity values. Therefore, choice is made by considering other characteristics such as strength, flammability, availability, and cost.

**Table 2. 3** Thermal Properties of Insulation Materials

<b>S.No</b>	<b>Material</b>	<b>Density kg/m<sup>3</sup></b>	<b>Thermal Conductivity W/m K</b>	<b>Specific Heat kJ/kg K</b>
1	Fiber Glass Insulation	32-96	0.036	0.963
2	Cellulose Insulation	36.8 – 51.1	0.0433	1.382
3	Expanded Polystyrene, Extruded	28.8 – 56.1	0.029	1.214
4	Polyurethane Foam	32	0.025	1.12

Source: ASHRAE Handbook Fundamentals, 2001

#### **2.2.4. Floor and Floor Finishing Materials**

Floor has no or little effect on the building cooling load compared to other envelopes like roof, wall and windows. Hence, choice of the materials for these is basically based on cost, strength, durability and aesthetic value of the materials. For each foundation type basement, slab-on-grade, and crawlspace there are several construction systems and products from which to choose. Some of them are Cast-In-Place Concrete, Concrete or Masonry Blocks, Insulating Concrete Forms and Permanent Wood Foundation.

**Floor finishing materials:** Many materials are available in the market, such as hardwood flooring, ceramic tiles, marble and granite, parquet flooring, Cork tiles, terrazzo, PVC tiles, and carpet. Among these materials, the most popular here in Ethiopia are marble, parquet, terrazzo and PVC tiles.

**Table 2. 4** Thermal Properties of Floor and Floor Finishing Materials

S.No	Material	Density kg/m <sup>3</sup>	Thermal Conductivity W/m K	Specific Heat kJ/kg K	Solar Absorpt ance
1	Heavy Weight Concrete	2242.6	1.72	0.83	0.65
2	Light Weight Concrete	640.7	1.72	0.83	0.65
3	Cork Tile	368.4	0.06	1.25	0.8
4	Terrazzo Tile	1922.2	1.79	1.04	0.65
5	Polyvinyl Chloride (PVC) Tiles	1400	0.10	0.96	
6	Marble and Granite	2883.6	2.6	0.795	0.4

Source: EnergyPlus Data Sets

### 2.2.5. Windows and Doors

Commonly clear glass has been the primary material available for window panes in many building in this country. They are low cost and readily available but poor in energy saving. However in recent years, the market for glazing has changed significantly in the developed countries so that several types of special glazing are available that can help control heat gain and condensation. Some of these types of glazing are:

**Low-emissivity (low-e) glass** has a special surface coating to reduce heat transfer back through the window. These coatings reflect from 40% to 70% of the heat that is normally transmitted through clear glass, while allowing the full amount of light to pass through.

**Heat-absorbing glass** contains special tints that allow it to absorb as much as 45% of the incoming solar energy, reducing heat gain. Some of the absorbed heat, however, passes through the window by conduction and reradiation.

**Reflective glass** has been coated with a reflective film and is useful in controlling solar heat gain. It also reduces the passage of light all year round, and, like heat-absorbing glass, it reduces solar transmittance.

**Plastic glazing materials** such as acrylic, polycarbonate, polyester, polyvinyl fluoride, and polyethylene are widely available. Plastics can be stronger, lighter, cheaper, and easier to cut than glass. However, plastics tend to be less durable and more susceptible to the effects of weather than is glass.

**Window frames and dividers** are also important materials that should be addressed in any energy efficient building design. Window frames and dividers can have smaller effect in the total heat gain of the building compared to the glass cover of the window, but can reduce a significant amount of energy by using more efficient window frames. They are available in a variety of materials including steel, aluminum, wood, vinyl, and fiberglass with steel and aluminum frames which are widely used in Ethiopia.

**Table 2.5** Thermal Properties of Glass Material for Window and Glass Door

<b>Name</b>	<b>Ts</b>	<b>Rfs</b>	<b>Rbs</b>	<b>Tv</b>	<b>Rfv</b>	<b>Rbv</b>
Clear 3mm	0.837	0.075	0.075	0.898	0.081	0.081
Clear 6mm	0.775	0.071	0.071	0.881	0.08	0.08
Bronze 3mm	0.645	0.062	0.062	0.685	0.065	0.065
Bronze 6mm	0.482	0.054	0.054	0.534	0.057	0.057
Grey 3mm	0.626	0.061	0.061	0.611	0.061	0.061
Grey 6mm	0.455	0.053	0.053	0.431	0.052	0.052
Green 3mm	0.635	0.063	0.063	0.822	0.075	0.075
Green 6mm	0.487	0.056	0.056	0.749	0.07	0.07
Low Iron 3mm	0.899	0.079	0.079	0.913	0.082	0.082
Low Iron 4mm	0.894	0.079	0.079	0.911	0.082	0.082
Blue 6mm	0.48	0.05	0.05	0.57	0.06	0.06
Ref A Clear Lo 6mm	0.066	0.341	0.493	0.08	0.41	0.37
Ref A Clear Mid 6mm	0.11	0.27	0.43	0.14	0.31	0.35
Ref A Clear Hi 6mm	0.159	0.22	0.37	0.2	0.25	0.32
Ref A Tint Lo 6mm	0.04	0.15	0.47	0.05	0.17	0.37
Ref A Tint Mid 6mm	0.06	0.13	0.42	0.09	0.14	0.35
Ref A Tint Hi 6mm	0.1	0.11	0.38	0.1	0.11	0.32
Ref B Clear Lo 6mm	0.15	0.22	0.38	0.2	0.23	0.33
Ref B Clear Hi 6mm	0.24	0.16	0.32	0.3	0.16	0.29
Ref B Tint Lo 6mm	0.04	0.13	0.42	0.05	0.09	0.28
Ref B Tint Mid 6mm	0.1	0.11	0.41	0.13	0.1	0.32
Ref B Tint Hi 6mm	0.15	0.09	0.33	0.18	0.08	0.28
Ref C Clear Lo 6mm	0.11	0.25	0.49	0.13	0.28	0.42
Ref C Clear Mid 6mm	0.17	0.2	0.42	0.19	0.21	0.38
Ref C Clear Hi 6mm	0.2	0.16	0.39	0.22	0.17	0.35

Table 2.5. Cont'd

Ref C Tint Lo 6mm	0.07	0.13	0.49	0.08	0.13	0.42
Ref C Tint Mid 6mm	0.1	0.1	0.42	0.11	0.1	0.38
Ref C Tint Hi 6mm	0.12	0.09	0.39	0.13	0.09	0.35
Ref D Clear 6mm	0.429	0.308	0.379	0.334	0.453	0.505
Ref D Tint 6mm	0.3	0.14	0.36	0.25	0.18	0.45
LoE Clear 3mm	0.63	0.19	0.22	0.85	0.056	0.079
LoE Clear 3mm Rev	0.63	0.22	0.19	0.85	0.079	0.056
LoE Clear 6mm	0.6	0.17	0.22	0.84	0.055	0.078
LoE Clear 6mm Rev	0.6	0.22	0.17	0.84	0.078	0.055
LoE Tint 6mm	0.36	0.093	0.2	0.5	0.035	0.054
LoE Spec Sel Clear 3mm	0.45	0.34	0.37	0.78	0.07	0.06
LoE Spec Sel Clear 6mm	0.43	0.3	0.42	0.77	0.07	0.06
LoE Spec Sel Clear 6mm Rev	0.43	0.42	0.3	0.77	0.06	0.07
LoE Spec Sel Tint 6mm	0.26	0.14	0.41	0.46	0.06	0.04

Source: EnergyPlus Reference Data Set for Window Glass

Terminology used in the above table:

xmm Glass thickness in mm  
 Clear No impurities added to glass mix  
 Low Iron Clear glass with low iron content, resulting in higher transmittance  
 Tint Tinted with inorganic materials to increase absorption  
 Bronze, Grey, Green, Blue: Tinted the indicated color  
 Ref, Reflective -- metallic coating on one surface to increase solar reflection.  
 Ref A: stainless steel coating; REF B: titanium coating; Ref C: pewter coating; REF D: tin-oxide coating;  
 Lo, Mid, Hi: low, medium and high transmittance coating, respectively.  
 LoE, Low-emissivity metallic coating  
 Spec Sel, Spectrally selective: part of solar spectrum preferentially transmitted  
 Rev, Reversed: Coating is on front side instead of back side

The values after the name are:

Ts: Solar transmittance at normal incidence  
 Rfs: Front solar reflectance at normal incidence  
 Rbs: Back solar reflectance at normal incidence  
 Tv: Visible transmittance at normal incidence  
 Rfv: Front visible reflectance at normal incidence  
 Rbv: Back visible reflectance at normal incidence

where

"Front" is side of glass furthest from zone window is defined in  
 "Back" is side of glass closest to zone window is defined in

All solar and visible transmittance and reflectance values are spectral average

Values and the thermal conductivity of all glass about 0.9 W/m-K.

# **CHAPTER THREE**

## **ELEMENTS OF ENERGY EFFICIENT BUILDINGS**

### **3.1. Introduction**

An energy-efficient building minimizes energy costs, increases occupant comfort, provides a healthier living environment, and reduces negative impact on the environment. Creating an energy-efficient building requires planning, foresight, and follow-up. The end result can be comfort and energy savings for years to come.

The way a building uses energy can best be understood as the interaction of several related energy systems that continually respond to changing climatic conditions and the comfort requirements of the occupant. The building design elements that directly impact the energy efficiency of a building are:

- Site
- Landscaping
- Orientation and Layout
- Building Envelope (Windows, Foundation, Wall, Roofs and Ceilings)
- Infiltration and Ventilation
- Air Conditioning
- Lighting and Appliances

### **3.2. Site**

Site selection can be having a significant impact on the design of houses. Although land for affordable projects is usually selected based on price and available free space, the site can preclude several sustainable features. Preplanning of a site should consider constraints of existing surrounding and on site development (such as overshadowing, and overlooking), vegetation (overshadowing), natural factors (such as sun angle, prevailing winds and views), topography (slope) and street shape. Many of these decisions are outside the scope of things that can be influenced by the builder or contractors. However, making the most out of what the site has to offer can be the difference between an energy performer or an energy guzzler. Hence there are some items that one can consider when selecting the building site. Some of these designed developments include the following features:

- Minimal land disturbance so that the existing topography and trees are preserved.
- Minimal solar radiation reaching the building, this will reduce the cooling requirements of the building.
- Knowing the direction of the prevailing wind so that the door and windows and other openings can be placed to reduce the possible infiltration of air from the outside environment.

### **3.3. Landscaping**

The most effective way to keep a building cool is to prevent the heat from entering the building. This can be attained using a proper landscaping. Landscaping is a natural and beautiful way to keep building more comfortable and reduce energy bills. In addition to

adding aesthetic value and environmental quality to a building, a well-placed tree or shrub can deliver effective shades which reduce the overall energy consumption of a building.

Shading and evaporative cooling from trees can reduce the air temperature around a building there by reduce the cooling load of the air conditioner. The American Department of Energy (DOE) has made an investigation on this and put some results. Some of these results are summarized below [20].

A well-planned landscape can reduce an unshaded home's summer air-conditioning costs by 15% to 50%. An average of 25% can be saved from a typical house's energy for cooling and heating with carefully positioned trees. One Pennsylvania study reported air-conditioning savings of as much as 75% for small mobile homes. Computer models from DOE (American Department of Energy) predict that just three trees, properly placed around the house, can save an average household between \$100 and \$250 in heating and cooling energy costs annually. Another study conducted by the Lawrence Berkeley National Laboratory found that summer daytime air temperatures to be 2<sup>0</sup>C to 3<sup>0</sup>C cooler in tree-shaded neighborhoods than in treeless areas.

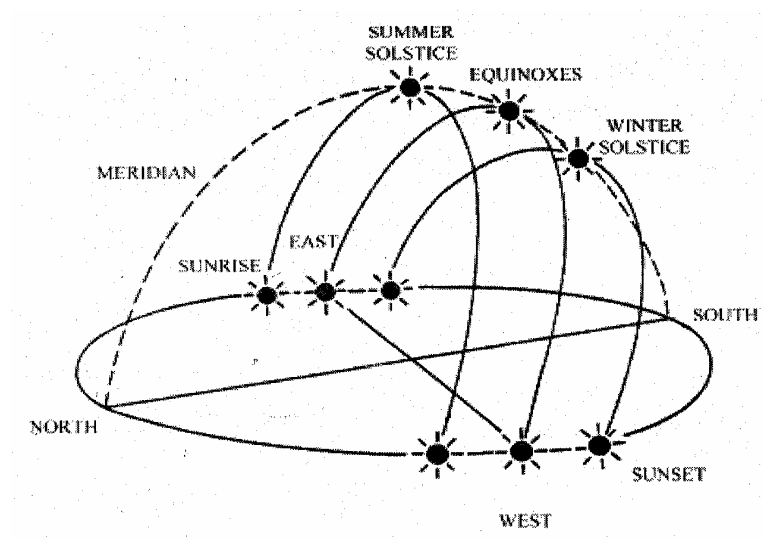
The energy-conserving landscape strategies which one should use for buildings depend on the type of climate the building is located. In the hot areas of Ethiopia the average maximum temperature is greater than 30<sup>0</sup>C throughout the year; hence it is good practice to plant evergreen trees rather than deciduous (leaf-shedding) trees which will able to shade the building a year round.

### 3.4. Building Orientation and Layout

Building orientation determines the buildings relationship with the sun's path. This in turn determines solar gain characteristics of the building. Therefore the sun's apparent path should be carefully observed to decide an efficient orientation of the given building in a given area or site.

#### 3.4.1. Apparent path of the sun

The sun rises in the east and sets in the west. At noon the sun is toward the south in the northern hemisphere. During summer the midday sun might be in the opposite direction between the tropical circles ( $23.5^\circ$ ). A solar diagram is a simple, useful tool to study solar angles in a more detailed way. It allows one to define the position of the sun at all times of the day, every day of the year.



**Figure 3.1** Apparent path of the sun in the northern hemisphere

### **3.4.2. Orientation in Northern Hemisphere**

From the apparent motion of the sun in the northern hemispheres, it is clear that the amount of daily solar radiation incident per unit area on north and south facing walls is much less as compared to that on the walls facing other directions. Hence, for minimum solar heat gain by the building envelope, it is desired that the longer axis of building should lie along East-West direction i.e. the wall with larger surface area should face either north or south.

The northern facade is least exposed to the sun. In fact, exposure occurs only in the early and late hours of summer days when the angle of altitude is low and the angle of declination is such that the sun's rays are almost tangential to the surface of the wall. An advantage to rooms opening on this facade is that their illumination is always evenly distributed, making them ideal for hospital operating rooms and for school classrooms.

The southern facade is highly exposed to the sun and care should be taken. Windows should be minimized or careful external shading like overhangs can be used. With regard to the sun factor, external shadings like overhangs have an advantage for the southern facades in the Tropics and Subtropics as the sun is high over the horizon in summer and can be shaded using a relatively small overhang.

East- and west-facing facades receive direct solar radiation for more hours during the day than a south and north facades and the radiation is at lower angle which makes it difficult to prevent from reaching the building envelop. Thus, these facades are the worst faces with

regard to the sun's radiation, and therefore, the surface area of the building exposed to these facades should be minimized as much as possible and windows on these facades should be minimized or avoided. One advantage of the eastern facade is, it is exposed to the sun's rays only from sunrise to noon. Thus the walls cool down considerably by evening, making this exposure more suitable for bedrooms than the western exposure.

Non-optimal orientation, or aligning the long building axis with the north-south axis, carries two penalties. First is the thermal penalty, i.e. excess solar heat gain from wall and glazing in the east and west facades. Second is the daylighting penalty. When sunlight comes from a low angle (as it does from east and west), exterior shading becomes very difficult and occupants have to use interior shades to reduce glare and localized overheating.

### **3.5. Building Envelopes**

A building envelope is everything about the building that serves to shield the living space from the outdoors. It includes the wall and roof assemblies, insulation, windows, doors, finishes, weather-stripping, and air/vapor retarders. Envelope design is a major and critical component of any facility in determining the amount of energy a building will use in its operation and as it both protects the building occupants and plays a major role in regulating the indoor environment. For the different climatic regions different design strategies are suggested, thus specific designs and materials can take advantage of or provide solutions for the given climate. A second important factor in envelope design is what occurs inside the building. If the activity and equipment inside the building generate a significant amount

of heat, the thermal loads may be primarily internal (from people and equipment) rather than external (from the sun). This affects the rate at which a building gains or loses heat. Building volume and siting also have significant impacts on the efficiency and requirements of the building envelope.

The challenge in designing the windows, foundation, walls, and roof and ceiling is to minimize conductive and radiative heat loss or heat gain, depending on the outside air temperature, while minimizing the uncontrolled movement of air into the building.

### **3.5.1. Windows and Shadings**

Roughly 40% of the unwanted heat that build up in a room comes in through windows [16]. Hence one of the most effective ways of controlling the overheating of a building is to prevent summer sun from reaching windows. In the first instance, this should be achieved by window orientation, use of appropriate shading methods and glazing treatment will also be important. Unshaded glass will typically allow 86% of summer heat into a building, whilst shaded glass will only allow around 25%. [16]. North facing windows should be adopted. Rooms with windows facing east and west can be subjected to overheating because of the low morning and afternoon sun, and should be shaded carefully or if possible such windows should be avoided. A properly designed roof overhang for south facing windows will help prevent over heating.

The installation of high performance windows is an energy efficiency measure. The key design consideration is whether to reduce the shading coefficient of the windows, there by

reducing the solar gain and cooling load, or maximize natural lighting levels. A double-glazed, low-emissivity (low-e) window with an air gap between panels can be used.

### ***Shading***

A very important strategy to stop heat gain and unwanted direct sunlight through windows and glass doors is to use shadings. Shading is the most cost-effective way to reduce solar heat gain and cut air-conditioning costs. Using shade effectively requires one to know the size, shape, and location of the moving shadow that the shading device casts. The most important consideration is the orientation of the aperture which is being shaded. South-facing windows are easy to shade, because the angle of the sun is high. However, east and west facing windows are much more difficult to shade because the sun is much lower in the sky.

Shadings can be of fixed and adjustable or external and internal. Exterior shades are generally more effective than interior shades because they block sunlight before it reaches the window. Exterior shading devices include awnings, louvers, shutters, rolling shutters and shades, and solar screens. Overhangs can also be considered as external shading. Venetian blinds can also be considered as internal or external shadings. To be effective, the reflective surfaces must face the outdoors and some newer blinds are coated with reflective finishes. . Venetian blinds are effective if they are used as exterior shades and are widely used in many buildings as they have good aesthetic value.

### **3.5.2. Roof and Ceiling**

If the outdoor air temperature is higher than the indoor temperature, the outer surface of the roof exposed to the sun is heated as it absorbs solar radiation, and, being in contact with the outside hot air, is also heated by conduction. The roof then transmits this heat to the inner surface, where it raises the temperature of the air in contact with it by conduction. This heat gain constitutes about a third of the unwanted heat that build up in the building [16]. At the same time, it radiates heat that is absorbed by people and objects indoors, thereby affecting thermal comfort. And this is hard to control with traditional roofing materials. There are two common methods to control heat gain through roofs. These are using insulation to retard the heat which conduct and a radiant barrier which reflect the radiation which comes from the sun and other sources. Therefore, the reflectivity of the outer surface of the roof and ceilings and the thermal resistivity of their materials are of primary importance.

Using insulation is most effective way to reduce the heat gain through conduction. A largest saving can be achieved through insulating a roof for buildings where external heat gain dominate and small glazing size like most residential buildings. Another option is to shade the roof by using a double roof with a layer of air between or by covering the roof surface with hollow bricks.

Radiant Barrier is a reflective foil sheet that works differently than insulation but has a similar impact. The effectiveness of a radiant barrier depends on its emissivity, which should be less than 0.1 or they reflect radiant heat back towards its source, reflecting as much as 97%. In general, the shinier is the better. Installed under the roof deck, it cuts the

amount of heat that is radiated from the hot roof to the ceiling below. When installed correctly, a radiant barrier can reduce heat gain through ceiling by about 25% [16].

The shape of the roof is also of considerable importance in a sunny climate. A flat roof receives solar radiation continuously throughout the day, at a rate that increases in the early morning and decreases in the late afternoon due to changes in both solar intensity and angle of the sun. Thus, pitching or arching the roof has several advantages over a flat structure. First, the height of part of the interior is increased, thereby providing a space far above the heads of the inhabitants for warm air that rises or is transmitted through the roof. Second, for most of the day, part of the roof is shaded from the sun, at which time it can act as a radiator, absorbing heat from the sunlit part of the roof and the internal air, and transmitting it to the cooler outside air in the roof's shade.

Venting roofs is also another method to reduce heat gain through roofs. In hot climates, the temperature of the space between the roof and ceiling (attic) is higher than the outside and inside environments; hence making a vent (hole) through the roof or ceiling to the outside will reduce the heat gain through the roof. This hole will help in flowing out the air at higher temperature to the outside.

### **3.5.3. Walls**

The basic factor in selecting wall material with respect to energy consumption is the thermal mass of the wall. For different types of climates different types of walls should be adopted.

Buildings in hot/dry climates with significant diurnal temperature swings have traditionally employed thick walls constructed from envelope materials with high mass, such as adobe and masonry. A building material with high thermal mass and adequate thickness will lessen and delay the impact of temperature variations from the outside wall on the wall's interior. Because the temperature in hot/dry climates tends to fall considerably after sunset, the result is a thermal flywheel effect—the building interior is cooler than the exterior during the day and warmer than the exterior at night.

In hot/moist climates, where nighttime temperatures do not drop considerably below daytime highs, light materials with little thermal capacity are preferred. In some hot/moist climates, materials such as masonry, which functions as a desiccant, are common. Walls should be protected by plants or overhangs. Large openings protected from the summer sun should be located primarily on the north and south sides of the envelope.

#### **3.5.4. Foundations and Floor**

Foundation walls and slabs can be also insulated as walls. Uninsulated foundations have a negative impact on a building energy use and comfort as the soil temperature is different than the room temperature. Using plastic and ceramic floor finishing materials with low thermal conductivity is preferable to reduce the heat loss through the floor.

### 3.5.5. Insulation

Insulation is the building component which controls temperature directly, and indirectly affects the movement of moisture to and from building spaces. Provision of insulation on walls and roof of a building increases their thermal resistance and curtails conductive heat flow through the building envelope. There by reduces the cooling load. It should be noted that insulation can have a negative impact in buildings when the internal heat gain from lights, people and equipment is larger than the heat gain from the external sources such solar and infiltration. In this case the insulation will prevent heat loss from the building which will increase the cooling load.

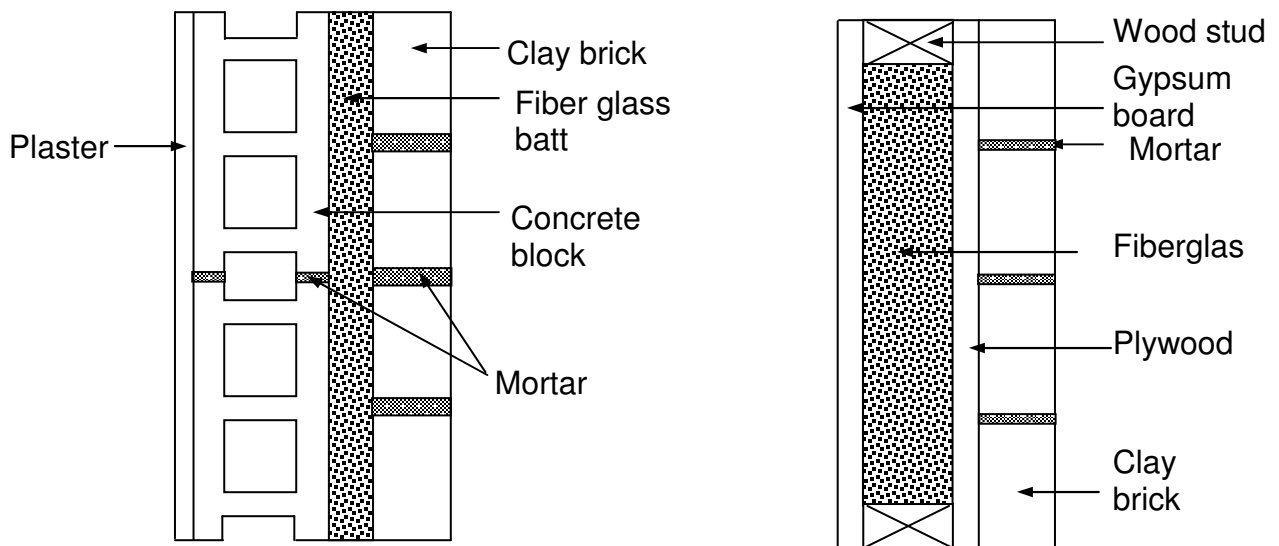
The roof is the most important element to control heat gain/ loss and usually easiest and cheaper place to improve insulation performance of new or existing buildings. Wall insulation is not as important for cooling as attic insulation because outdoor temperatures are not as hot as attic temperatures. Also, floor insulation has little or no effect on cooling.

The Office of Energy (Western Australia) suggests that energy efficient house design can achieve an average internal temperature of 5<sup>0</sup>C warmer in winter and 10<sup>0</sup>C cooler in summer, than poorly designed homes [22]. A combination of insulation techniques (floor, roof, and wall) can reduce fuel bills up to 40% [22].

Introduction of air cavity in a wall also increases its thermal resistance. Studies on estimation of thermal properties of such a wall revealed that the overall heat transmission coefficient U of a 275 mm brick cavity wall (112.5 mm brick + 50 mm air gap + 112.5 mm brick) is 1.63 W/m<sup>2</sup> K while that of a 225 mm solid brick wall with 12.5 mm cement plaster

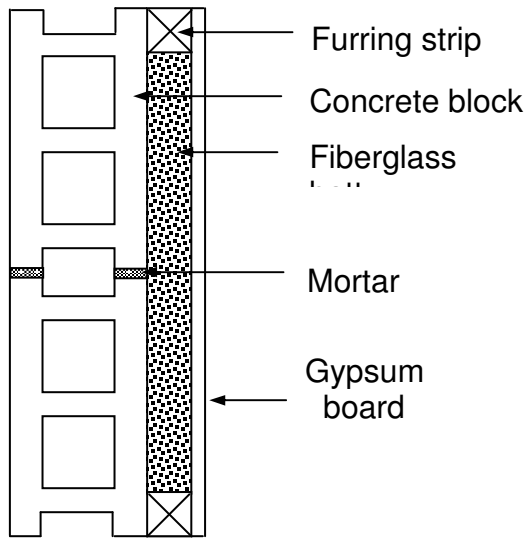
on both the side U value is  $2.26 \text{ W/m}^2 \text{ K}$ . Here, it is worth emphasizing that the thermal performance of the above cavity wall is slightly better than that of a 350mm solid brick wall [7].

Installing insulation at different parts of the building envelope will have a little effect. For example installing fiber glass batt in the exterior side of a wall can worth little saving as it is on the inside side of the wall. And similarly installing the insulation above the ceiling material can have an advantage over installing beneath the roof (figure 3.3). However, these savings are very small and the choice can be made on other factors like installation cost, space for installation and maintenance. To place in position while installing fiberglass insulation a thin plastic or paper is used and is fastened to the wood stud using nail or staple. The figures below show the possible installation for insulation in walls and roofs.

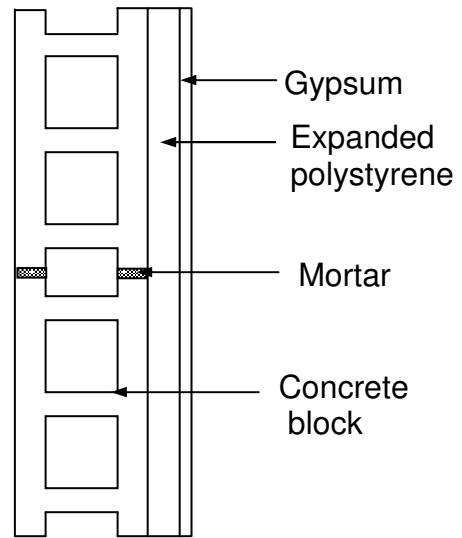


(a) Fiber glass batt can be installed between clay brick and concrete block .

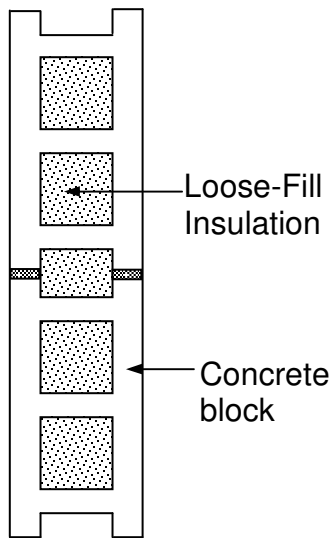
(b) Fiber glass insulation installed in the interior side of the wall with gypsum board as a sheathing material.



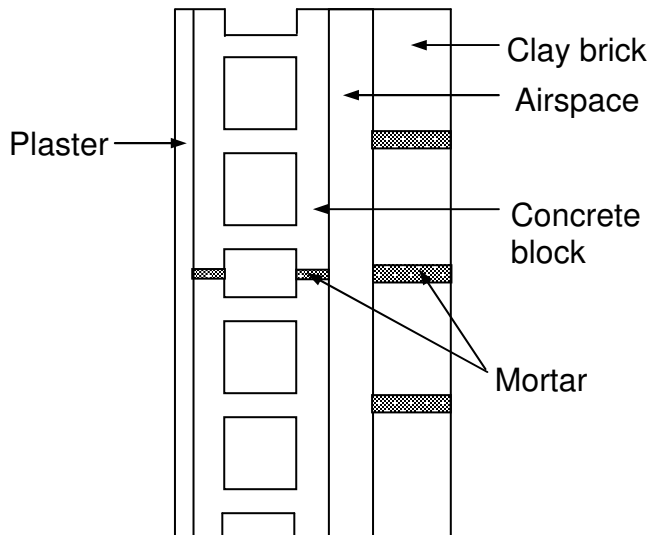
(c) Fiber glass batt installed in the exterior side of the wall with gypsum board as a sheathing material.



(d) Expanded polystyrene insulation can be used instead of fiber glass insulation.

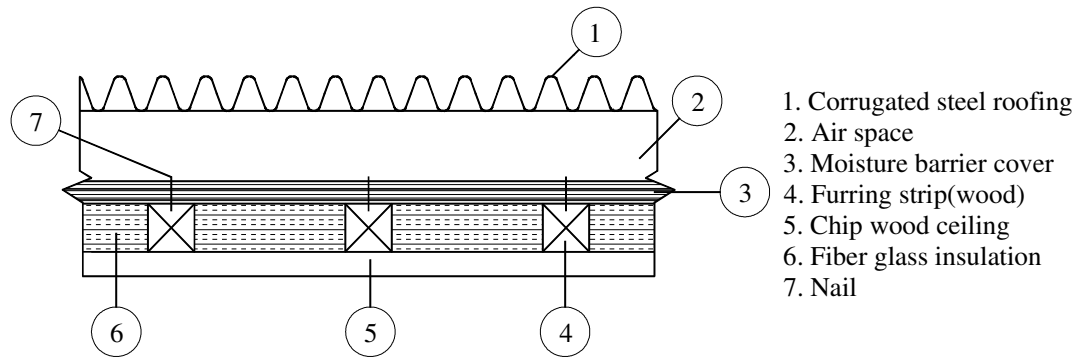


(e) Loose-fill can be applied in holes of hollow concrete block.



(f) Air gap between blocks

**Figure 3. 2** Different possible installation of insulation in walls



**Figure 3. 3** Installation of roof insulation.

### 3.6. Infiltration and Ventilation

Infiltration is the uncontrolled movement of air through unintentional openings such as cracks in the walls and ceilings and through the perimeter gaps of windows and doors driven by wind, temperature difference, and internal induced pressures. The amount of infiltrated air depends on this pressure difference; the number, the size, and the shape of the cracks involved; the number, the length, and the width of the perimeter gaps of windows and doors; and the nature of the flow in the crack of gap. Infiltration of outside air may be a significant contributor to inside temperature and it is a good idea to keep it out. Outside air can infiltrate a building around poorly sealed doors, windows, electrical outlets, and through openings in exterior walls.

The infiltrating air has to be cooled to the desired space temperature and this adds a cooling load to the building. Hence minimizing the infiltrated air will reduce the cooling load of the building. It is possible to minimize infiltration through proper sealing of cracks, closing of

openings like doors and windows. Once the building is sealed to prevent air leaks, it is necessary to provide controlled ventilation. This can be achieved through natural or forced ventilation. Natural ventilation relies only on natural air movement, thereby reducing the need for mechanical ventilations and air conditioning. Ventilation in general helps promote good indoor air quality and prevent the accumulation of moisture in the indoor air.

### **3.7. Air Conditioning Systems**

These systems use more energy, cost more to operate, and are more complex than other energy systems in the building. Reducing the cooling load of the building allows for the installation of a smaller cooling system. But they need to be properly sized; a system that is not properly sized can increase the cost of the cooling system as well as the cost to operate it. Another critical aspect to the efficiency of cooling is the design and installation of ducts. Ducts must be properly insulated and leak off.

### **3.8. Lighting and Appliances**

Lighting equipments are also some sources of load to air conditioning system so that one should consider using energy efficient lighting bulbs. Turning off lights during day time when enough natural light is available should be considered as an advantage. Some results on the efficiency of daylighting control systems, based on simulations run over a year with hourly data for Rio de Janeiro, indicates: the use of a proper daylight control systems can reduce artificial lighting by 60 – 80%, at the same time cutting down the cooling load of the building [18].

Incandescent lighting use only 10% of the energy they consume for lighting and the rest will change to heat energy which constitute to cooling load. Hence take advantage of daylight to illuminate the building and consider switching to compact fluorescent lamps. These use about 75% less energy than incandescent lamps, and emit 90% less heat for the same amount of light [18].

The type of appliances installed in a building such as entertainment systems, stereos, computers, stoves, and any electric driven equipment can have a large impact on energy use and cooling load as they generate a lot of heat.

### **3.9. Color and Surface Texture**

The nature and color of the external surface which alters the solar absorptance of the surface of the building envelop determines the amount of solar radiation absorbed or reflected in the structure. This will increase the heat conducted to the inside building thereby increase the cooling load. A measurement carried out in Israel in summer time on light weight horizontal panel with external colors grey or white washed. It was seen that with a dark exterior the surface temperature was elevated up to 32<sup>0</sup>C above the maximum air temperature, while the corresponding increase for white surface was only about 1<sup>0</sup>C [33].

The color used in a room can make you feel warmer or cooler. Generally, reds, oranges and yellows are considered warm colors. These would be used where the actual room temperature is cooler, such as on the north side of the house where there is no direct

sunlight. The cool greens, blues and violets should be used in rooms with southern or even western exposure.

**Table 3. 1** Absorption coefficient of various colors

No	Surface color type	Absorption coefficient
1	New white washed surfaces	0.1-0.15
2	White oil paint	0.2-.03
3	White marble	0.4-0.5
4	Medium grey	0.6-0.7
6	Brick, concrete	0.7-0.75
7	Glossy black	0.8-0.85
8	Matt black	0.9-0.95

Source: Reference [32]

Therefore, using light colors are proffered for external walls and roofs to minimize the heat absorbed by the surfaces.

## CHAPTER FOUR

### ENERGYPLUS: BUILDING ENERGY SIMULATION SOFTWARE

#### 4.1. Introduction

Nowadays there are a lot of building simulation software developed throughout the world. Among these the most familiar and widely used softwares are: BLAST (Building Loads Analysis and System Thermodynamics), DOE-2, and EnergyPlus. SPARK, Energy-10, and TRNSYS are also sometimes used.

**BLAST** (Building Loads Analysis and System Thermodynamics) which was developed by the U.S. Army Construction Engineering Research Laboratory (USACERL) is a comprehensive set of programs and with a number of user-friendly features for predicting energy consumption and energy system performance and cost of new or retrofit building design options of almost any type and size. In addition to performing peak load (design day) calculations necessary for mechanical equipment design, BLAST also estimates the annual energy performance of the facility, which is essential for the design of solar and total energy (cogeneration) systems and for determining compliance with design energy budgets. The BLAST program contains three major subprograms:

The *Space Load Prediction* subprogram computes hourly space loads in a building based on weather data and user inputs detailing the building construction and operation.

The *Air System Simulation* subprogram uses the computed space loads, weather data, and user inputs describing the building air-handling system to calculate hot water, steam, gas, chilled water, and electric demands of the building and air-handling system.

The *Central Plant Simulation subprogram* uses weather data, results of the air distribution system simulation, and user inputs describing the central plant to simulate boilers, chillers, on-site power generating equipment and solar energy systems; it computes monthly and annual fuel and electrical power consumption.

*DOE-2* which was developed by the Lawrence Berkeley Laboratory with support from the U.S. Department of Energy (DOE) was used for many years in building simulation for the design of energy-efficient buildings. DOE-2 accurately estimates the proposed building's hourly energy consumption, interior environmental conditions and energy operation cost of a commercial or residential building given the information about the building's climate, construction, operation, utility rate schedule, and HVAC equipment. DOE-2 consists of four sequential subprograms: loads, systems, plant, and economics.

The *loads* subprogram calculates hourly heating and cooling loads based on heat gains and losses through the building envelope and internal gains

The *systems* subprogram simulates the operation of secondary HVAC (airside) distribution systems used to control the temperature and humidity within each zone of a building. The subprogram takes into account outside air requirements, operating and control schedules,

and transient building responses. It uses the hourly output from the loads subprogram to calculate the hourly thermal and electrical energy requirements of the HVAC system.

The *plant* subprogram calculates the performance of the primary energy conversion equipment based on hourly operating conditions and part-load performance characteristics.

The *economics* subprogram calculates the cost of consumed energy based on user-defined rates. The subprogram can also be used to compute the present value of the life cycle cost of the building, including fuel and electricity, equipment, operation and maintenance.

Both BLAST and DOE-2 need hourly weather data and detail geometry and property of the building envelop. But the main difference between these programs is the load calculation method: DOE-2 uses a room weighting factor approach while BLAST uses a heat balance approach. The most recent version of DOE-2 is DOE-2.1E.

*EnergyPlus* is a building energy simulation program for modeling building heating, cooling, lighting, ventilating, and other energy flows. It is constructed on the most popular features and capabilities of BLAST and DOE-2 but also includes many innovative simulation capabilities such as time steps of less than an hour, modular systems and plant integrated with heat balance-based zone simulation, multizone air flow, thermal comfort, and photovoltaic systems. It is a stand-alone simulation program without a 'user friendly' graphical interface. EnergyPlus will be discussed in detail in the next section.

**SPARK** (The Simulation Problem Analysis and Research Kernel) is an equation-based, object-oriented simulation environment which allows users to construct models of complex building energy systems by connecting equation modules from a library. The program then uses robust methods to solve the resulting set of differential and algebraic equations at a user-specified time step. Current research includes work on a SPARK-to-EnergyPlus Link, so that SPARK models of HVAC components, systems and controls can be run within EnergyPlus.

**ENERGY-10** is a software tool for designing low-energy buildings. It integrates daylighting, passive solar heating, and low-energy cooling strategies with energy-efficient shell design and mechanical equipment. ENERGY-10 is most suitable for smaller buildings such as schools, libraries, small banks, stores, restaurants, offices, and low-rise residential buildings.

**TRNSYS** is an energy simulation program with a modular system approach which makes it more flexible for modeling a variety of energy systems in differing levels of complexity. TRNSYS (TRaNsient SYstem Simulation Program) includes a graphical interface, a simulation engine, and a library of components that range from various building models to standard HVAC equipment to renewable energy and emerging technologies. TRNSYS also includes a method for creating new components that do not exist in the standard package. This simulation package has been used for many years for HVAC analysis and sizing, multizone airflow analyses, electric power simulation, solar design, building thermal performance, analysis of control schemes, etc. Unlike many other programs, TRNSYS allows users to completely describe and monitor all interactions between system

components. For example, the user determines the connections between the output of the pump and other system components. The modularity of the program allows the user to have as many pumps, chillers, cooling coils and solar panels as necessary, in any desired configuration.

## **4.2. EnergyPlus**

EnergyPlus is a new building performance simulation program that combines the best capabilities and features from BLAST and DOE-2 along with new capabilities which is constructed using Fortran 90 programming language. The use of Fortran 90 as the programming language for EnergyPlus also allows for the creation of a well-organized and modular program structure that facilitates adding new features and links to other programs. Each module is a separate package of source code stored on a separate file. The entire collection of modulus, when compiled and linked, forms the executable code of EnergyPlus.

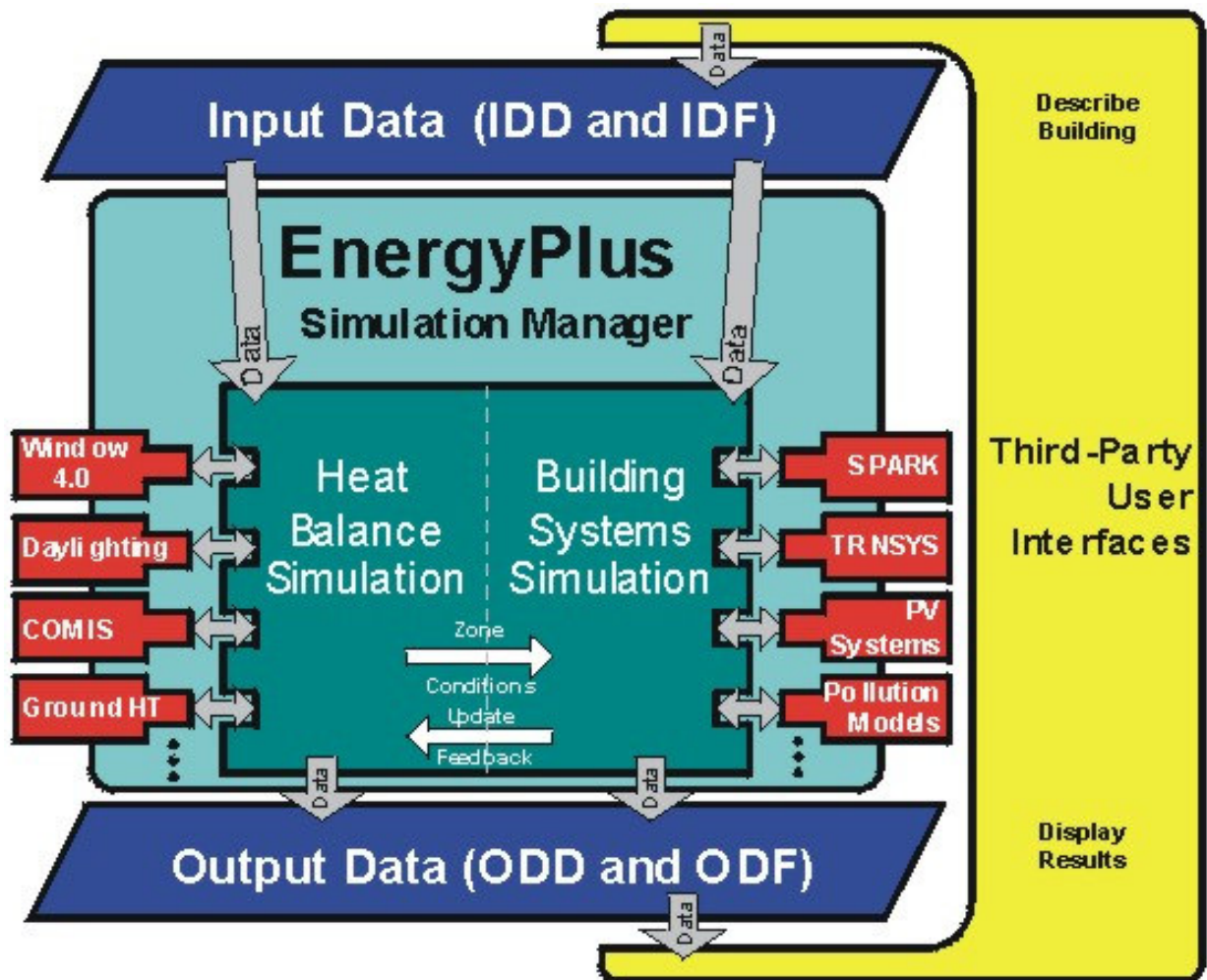
By using an integrated solution technique in EnergyPlus, the most serious deficiency of the BLAST and DOE-2 sequential simulations which leads to inaccurate space temperature predication due to no feedback from the HVAC module to the loads calculations is solved. Accurate prediction of space temperatures is crucial to energy efficient system engineering like system size, plant size, occupant comfort and occupant health all depend on space temperatures. In addition an integrated simulation EnergyPlus allows users to evaluate other processes which the other two programs didn't evaluate well. Some of these are: realistic system controls, moisture adsorption and desorption in building elements, radiant

heating and cooling systems, and inter zone air flow. The integrated simulation concept in EnergyPlus calculates the loads by a heat balance engine at a user-specified time step (15-minute default) are passed to the building systems simulation module at the same time step. The building systems simulation module, with a variable time step (down to seconds), calculates heating and cooling system and plant and electrical system response. Feedback from the building systems simulation module on loads not met is reflected in the next time step of the load calculations in adjusted space temperatures if necessary. Figure 4.1 shows the overall program structure of EnergyPlus which is consisting of three basic components. These are a simulation manager, a heat balance simulation manager, and a building systems simulation manager.

***The simulation manager*** controls the entire simulation process. It controls the interactions between all simulation loops from a sub-hour level up through the user selected time step and simulation period-whether day, month, season, year or several years. Actions of individual simulation modules are directed by the simulation manager, instructing simulation modules to take actions such as initialize, simulate, record keep, and report.

***Heat and Mass Balance Manager:*** As noted earlier, the underlying building thermal zone calculation method in EnergyPlus is a heat balance model. The fundamental assumption of heat balance models is that air in each thermal zone can be modeled as well stirred with uniform temperature throughout. Although this does not reflect physical reality well, the only current alternative is Computational Fluid Dynamics (CFD) a complex and computationally intensive simulation of fluid (in this case, air) movement. The modular structure of EnergyPlus allows these new models to be included in future releases once they

are available. The other major assumption in heat balance models is that room surfaces (walls, windows, ceilings, and floors) have uniform surface temperatures, uniform long and short wave irradiation, diffuse radiating surfaces, and internal heat conduction.



**Figure 4.1** General structure of EnergyPlus

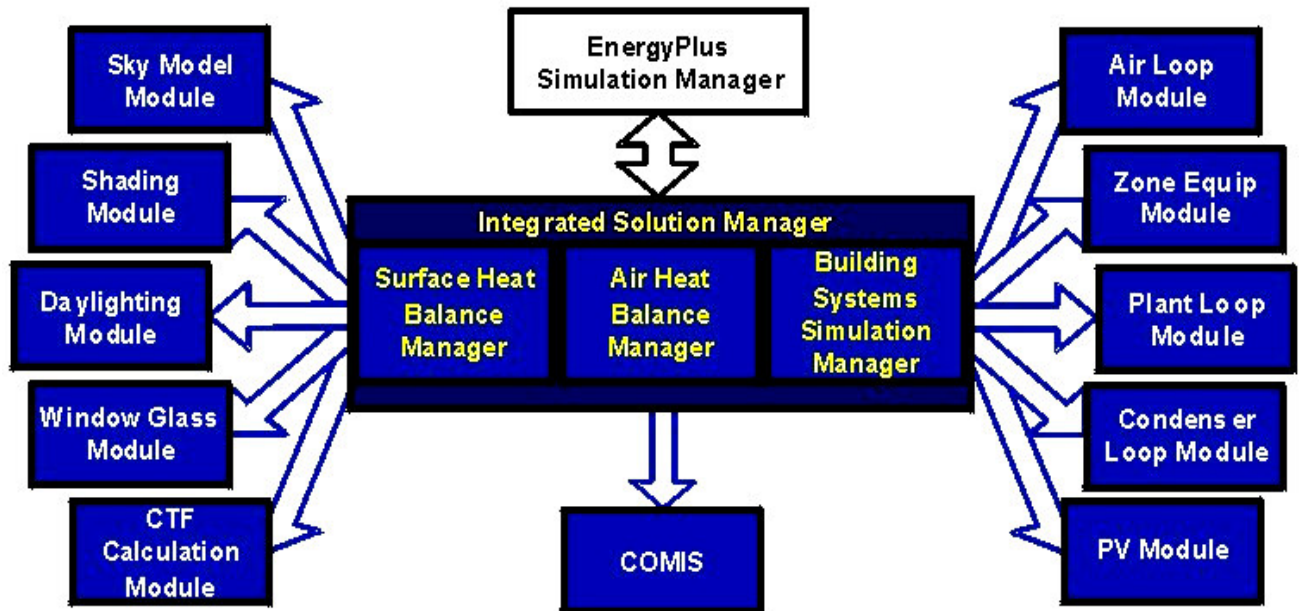
EnergyPlus can accurately calculate solar shading from the given geometry of the building to estimate the direct and diffuse solar radiation. The heat balance engine in EnergyPlus includes mass transfer and radiant heating and cooling. The mass transfer capability allows

fundamental, layer-by-layer solution for mass transfer through surfaces and a mass balance on zone air similar to the air heat balance. The radiant heating and cooling models are an expansion of the conduction transfer function and incorporate thermal comfort calculations. Figure 4.2 shows the structure of the EnergyPlus integrated solution manager that manages the surface and air heat balance modules and acts as an interface between the heat balance and the building systems simulation manager. The Surface Heat Balance Module simulates inside and outside surface heat balance, interconnections between heat balances and boundary conditions, conduction, convection, radiation, and mass transfer (water vapor) effects. The Air Mass Balance Module deals with various mass streams such as ventilation air, exhaust air, and infiltration. It accounts for thermal mass of zone air and evaluates direct convective heat gains. Through this module that we are connecting to COMIS for improved multizone airflow, infiltration, indoor contaminant, and ventilation calculations.

***Building Systems Simulation Manager:*** After the Heat Balance Manager completes its simulation for a time step, it calls the Building Systems Simulation Manager, which controls the simulation of HVAC equipment/components such as coils, boilers, chillers, pumps, and fans and electrical systems which also handles communication between these HVAC modules and loops and the heat balance engine. The building systems simulation manager also updates the zone-air conditions and controls interaction and data exchange between EnergyPlus and other simulation software like SPARK.

EnergyPlus does not use a sequential simulation method (first building loads, then distribution system, and then plant) as found in DOE-2 and BLAST since this imposes rigid boundaries on program structures and limits input flexibility. Instead, the Building

Systems Simulation Manager has been designed with fully integrated and simultaneous simulation of loads, systems, and plant modules.



**Figure 4. 2** EnergyPlus Integrated Simulation Manager

### 4.3. Heat Transfer Modeling of a Building in EnergyPlus

In buildings the transfer of heat between the inside and outside environment is taking place through conduction, convection, and radiation.

**Conduction** heat transfer in buildings occurs thorough building envelops such as walls, roofs, floors, doors and windows.

**Convection** heat transfers that utilize in buildings are of two types: natural and forced. In buildings natural convection is caused by the movement of air due to pressure difference. This pressure difference is caused by wind (speed and direction) and temperature difference

across the building which drives the air to flow from higher to lower pressure in either side of the building. Forced convection is caused due to the movement of air with the help of mechanical systems like ventilation.

**Radiation** is a heat transfer mechanism where heat is transferred by electromagnetic waves. Heat transfers by radiation in buildings through transparent building envelopes and from internal heat sources to the building envelope. The main source of radiant heat in a building is windows and glass doors which transmit solar radiation directly to the building.

### ***The Heat Balance Method***

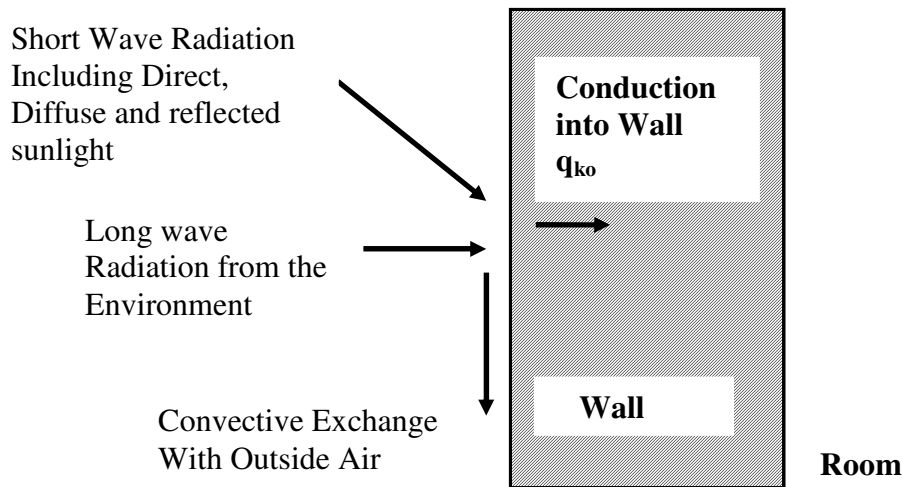
EnergyPlus uses the heat balance method for estimating the cooling load of a given building. The processes that make up the heat balance model consist of four distinct processes. These are:

- a. The outside face heat balance
- b. The wall conduction process
- c. The inside face heat balance
- d. The air heat balance

#### **a. The Outside Face Heat Balance**

On the outside face of a building envelope there are four types of heat exchanges. These are short wave solar radiation including direct, diffuse and reflected, long wave radiation from

the environment, convective heat transfer, and conductive heat transfer into the wall. Figure 4.3 shows these interactions.



**Figure 4. 3** Outside Face Heat Balance Control Volume Diagram

The equation for the outside face heat balance is:

$$\dot{q}_{\text{csol}} + \dot{q}_{\text{LWR}} + \dot{q}_{\text{conv}} - \dot{q}_{\text{ko}} = 0 \text{ -----4.1}$$

where :

$\dot{q}_{\text{csol}}$  = absorbed direct and diffuse solar (short wavelength) radiant heat flux

$\dot{q}_{\text{ko}}$  = conductive heat flux (q/A) into the wall

$\dot{q}_{\text{LWR}}$  = net long wavelength (thermal) radiation flux exchange with the air and surroundings,

$\dot{q}_{\text{conv}}$  = convective flux exchange with outside air,

$\dot{q}_{\text{asol}}$  is the heat gain from both direct and diffuse solar radiation absorbed by the surface. EnergyPlus use the hourly weather data to calculate the hourly values of  $\dot{q}_{\text{asol}}$ . The program has a subroutine which calculates the geometry of any shadow cast on the building envelope from either internal or external shading devices with the help of the building and shading geometry given to the program. For more information on this one can refer the Engineering Document in Reference [6].

$\dot{q}_{LWR}$  is a standard radiation exchange formulation between the surface, the sky, and the ground. The radiation heat flux is calculated from the surface absorptivity, surface temperature, sky and ground temperatures, and sky and ground view factors.

$$\dot{q}_{\text{conv}} = h_{\text{co}} (T_o - T_{\text{so}})$$

where,  $h_{\text{co}}$  is the outside convective coefficient.

$T_o$  = outside air temperature and  $T_{\text{so}}$  = outside face surface temperature.

## **b. Conduction Through the Walls**

There are many ways to formulate the wall conduction process. Among these possible ways to model this process are the numerical finite difference methods, numerical finite element method, transform methods, and the time series methods. Since the heat balance on both sides of the element incorporates both the temperature and heat fluxes, the solution technique must deal with this simultaneous condition. The two possibilities are: either to iterate or to lag some of the quantities in time. From a computational standpoint, the two methods that are reasonable candidates are a finite difference method (FD) procedure or a

conduction transfer function (CTF) procedure. EnergyPlus uses the conduction transfer function (CTF) as it offers much greater computational speed with little loss of generality.

The basic form of a conduction transfer function solution is given by:

$$\dot{q}_{ki} = -Z_o T_{si,t} - \sum_{j=1}^{nz} Z_j T_{si,t-j\delta} + Y_o T_{so,t} + \sum_{j=1}^{nz} Y_j T_{so,t-j\delta} + \sum_{j=1}^{nq} \Phi_j \dot{q}_{ki,t-j\delta} \quad \text{-----4.2}$$

for the inside heat flux and

$$\dot{q}_{ko} = -Y_o T_{si,t} - \sum_{j=1}^{nz} Y_j T_{si,t-j\delta} + X_o T_{so,t} + \sum_{j=1}^{nz} X_j T_{so,t-j\delta} + \sum_{j=1}^{nq} \Phi_j \dot{q}_{ko,t-j\delta} \quad \text{-----4.3}$$

for the outside heat flux ( $\dot{q} = \frac{q}{A}$ )

where:

$X_j$  = Outside CTF coefficient,  $j=0,1,2,\dots,nz$ ,

$Y_j$  = Cross CTF coefficient,  $j = 0,1,2,\dots,nz$ ,

$Z_j$  = Inside CTF coefficient,  $j = 0, 1,2,\dots,nz$ ,

$\Phi_j$  = Flux CTF coefficient,  $j = 0, 1,2,\dots,nq$ ,

$T_{si}$  = inside face temperature,

$T_{so}$  = Outside face temperature,

$\dot{q}_{ko}$  = Conduction heat flux on outside face,

$\dot{q}_{ki}$  = Conduction heat flux on inside face.

The subscript following the comma indicates the time period for the quantity in terms of the time step  $\delta$ . The above equations state that the heat flux at either face of the surface of any generic building element is linearly related to the current and some of the previous temperatures at both the interior and exterior surfaces as well as some of the previous flux

values at the interior surface. The coefficients (CTFs) in the equation are constants that only need to be determined once for each construction type [6].

### c. The Inside Heat Balance

This heat balance is generally modeled with four coupled heat transfer components. These are conduction through the building element, convection to the air, short wave radiation and reflectance, and long wave radiant interchange. The heat balance on the inside face can be written as follows:

$$\dot{q}_{LWX} + \dot{q}_{SW} + \dot{q}_{LWS} + \dot{q}_{ki} + \dot{q}_{sol} + \dot{q}_{conv} = 0 \text{ -----4.4}$$

where:

$\dot{q}_{LWX}$  = net long wave radiant exchange flux between zone surfaces,

$\dot{q}_{SW}$  = net short wave radiation flux to surface from lights,

$\dot{q}_{LWS}$  = long wave radiation flux from equipment into zone,

$\dot{q}_{ki}$  = conduction flux through the wall,

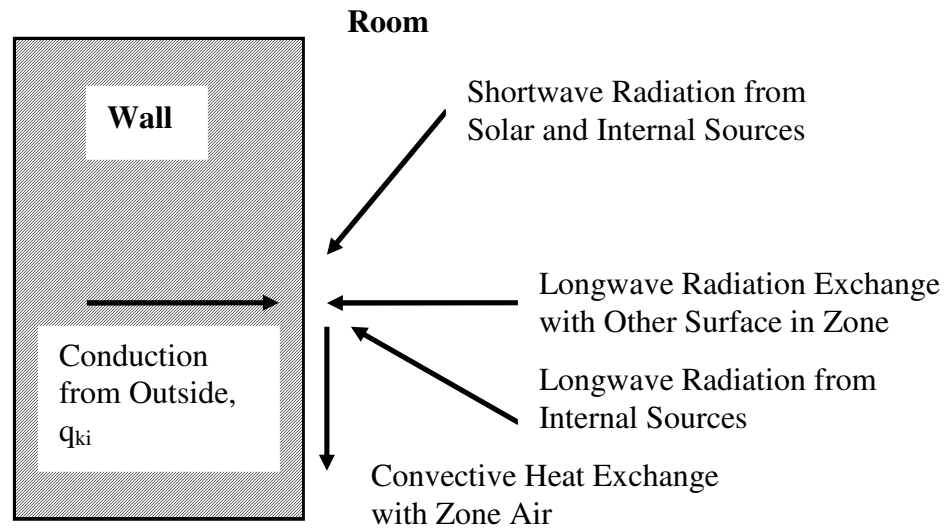
$\dot{q}_{sol}$  = transmitted solar radiation flux absorbed at surface,

$\dot{q}_{conv}$  = convective heat flux to zone air and it is given by:

$$\dot{q}_{conv} = h_{ci} (T_z - T_{si})$$

where:  $T_z$  = zone air temperature,

$h_{ci}$  = convective heat transfer coefficient on the inside.



**Figure 4.4** Inside Face Heat Balance Control Volume Diagram

Generally, the heat balance process for a general thermal zone is formulated for a 24 hours steady periodic condition. The primary variables in the heat balance for the general zone are about 16 inside face temperatures and 16 outside face temperatures at each of the 24 hours. The 16 surfaces of the building that are modeled in the heat transfer process are: four walls, a roof or ceiling, a floor, a thermal mass surface (like furniture and internal partitions), each walls consists a window and door, and a roof can consist a skylight. Assuming that the first subscript,  $i$ , is assigned as the surface index and the second subscript,  $t$ , as the hour index or in the case of conductive transfer function (CTFs) the sequence index. Then the primary variables are:

$$T_{so,i,t} = \text{outside face temperature, } i = 1,2,\dots,16 ; t = 1,2, \dots, 24,$$

$$T_{si,i,t} = \text{inside face temperature, } i = 1,2,\dots,16 ; t = 1,2, \dots, 24,$$

In addition we have the variable  $q_{sys}$  = cooling load,  $t = 1, 2, \dots, 24$ . Now combining equations 4.1 and 4.3 and solving for  $T_{so}$  we obtain,

$$T_{so_{i,t}} = \frac{\sum_{j=1}^{nz} T_{si_{i,t}} Y_{i,j} - \sum_{j=1}^{nz} T_{so_{i,t-j}} X_{i,j} - \sum_{j=1}^{nq} \Phi_{i,j} \dot{q}_{ko_{i,t-j}}}{X_{i,0} + h_{co_{i,t}}} + \frac{\dot{q}_{\alpha sol_{i,t}} + \dot{q}_{LWR_{i,t}} + T_{si_{i,t}} Y_{i,0} + T_o h_{co_{i,t}}}{X_{i,0} + h_{co_{i,t}}} \text{-----4.5}$$

Similarly by combining equations 4.2 and 4.4 and solving for  $T_{si}$  yields;

$$T_{si_{i,t}} = \frac{T_{so_{i,t}} Y_{i,0} - \sum_{j=1}^{nz} T_{so_{i,t-j}} Y_{i,j} - \sum_{j=1}^{nz} T_{si_{i,t-j}} Z_{i,j} + \sum_{j=1}^{nq} \Phi_{i,j} \dot{q}_{ki_{i,t-j}}}{Z_{i,0} + h_{ci_{ij}}} + \frac{T_o h_{ci_{i,t}} + \dot{q}_{LWS} + \dot{q}_{LWX} + \dot{q}_{SW} + \dot{q}_{sol}}{Z_{i,0} + h_{ci_{i,t}}} \text{-----4.6}$$

Now by solving equations 4.5 and 4.6 simultaneously the inside and outside face temperatures can be calculated.

#### d. The Air Heat Balance

In heat balance formulations aimed at determined cooling loads, the capacitance of the air in the zone is neglected and the air heat balance is done as a quasi – steady balance in each time period. There are five contributors to the air heat balance. They are: convection from the zone surfaces, infiltration and ventilation introduced directly into the zone from the outside, interzone air mixing, and the HVAC system air. If the energy stored in zone air is neglected the air heat balance equation is given by:

$$q_{sys} = \sum q_i + \sum_{i=1}^{N_{surface}} h_{ci} A_i (T_{si} - T_z) + \sum_{i=1}^{nz} \dot{m} C_p (T_{zi} - T_z) + \dot{m}_{inf} C_p (T_o - T_z) \text{-----4.7}$$

If the zone capacitance is taken and there is energy stored in the zone air the above equation can be written as:

$$C_z \frac{dT_z}{dt} = q_{sys} + \sum q_i + \sum_{i=1}^{N_{surface}} h_{ci} A_i (T_{si} - T_z) + \sum_{i=1}^{nz} \dot{m} C_p (T_{zi} - T_z) + \dot{m}_{inf} C_p (T_o - T_z) \text{ -----4.8}$$

where:

$$C_z \frac{dT_z}{dt} = \text{energy stored in zone air,}$$

$$\sum q_i = \text{sum of the convective internal loads (people, light and equipments),}$$

$$\sum_{i=1}^{N_{surface}} h_{ci} A_i (T_{si} - T_z) = \text{convective heat transfer from the zone surface,}$$

$$\dot{m}_{inf} C_p (T_o - T_z) = \text{heat transfer due to infiltration of outside air,}$$

$$\sum_{i=1}^{nz} \dot{m} C_p (T_{zi} - T_z) = \text{heat transfer due to interzone air mixing,}$$

$$q_{sys} = \text{heat transfer to/from the HVAC system,}$$

$$C_p = \text{the heat capacity of air,}$$

Air system provides hot or cold air to the zone to meet heating and cooling loads. The system energy provided to the zone,  $q_{sys}$ , can thus be formulated from the difference between the supply air enthalpy and the enthalpy of the air leaving the zone as in equation 4.9.

$$q_{sys} = \dot{m}_{sys} C_p (T_{sup} - T_z) \text{ -----4.9}$$

This equation assumes that the zone supply air mass flow rate is exactly equal to the sum of the air flow rates leaving the zone through the system return air plenum and being

exhausted directly from the zone. Both air streams exit the zone at the zone mean air temperature. Substituting equation (4.9) in (4.8)

$$C_z \frac{dT_z}{dt} = \sum q_i + \sum_{i=1}^{N_{surface}} h_{ci} A_i (T_{si} - T_z) + \sum_{i=1}^{nz} \dot{m} C_p (T_{zi} - T_z) + \dot{m}_{inf} C_p (T_o - T_z) + \dot{m}_{sys} C_p (T_{sup} - T_z) \quad \text{-----4.10}$$

This equation states that the sum of zone loads and system output equals the change in energy stored in the zone. Now in order to calculate the derivative term a finite difference approximation is used, such as:

$$\frac{dT_z}{dt} = (\delta t)^{-1} (T_z^t - T_z^{t-\delta t}) + 0(\delta t) \quad \text{-----4.11}$$

But using such lower order expression in the finite difference approximation will limit the time step in some conditions; hence a higher order expression is used like:

$$\frac{dT_z}{dt} = (\delta t)^{-1} \left( \frac{11}{6} T_z^t - 3T_z^{t-\delta t} + \frac{3}{2} T_z^{t-2\delta t} - \frac{1}{3} T_z^{t-3\delta t} \right) + 0(\delta t^3) \quad \text{-----4.12}$$

Upon substitution of equation 4.12 in equation 4.10 yields:

$$C_z (\delta t)^{-1} \left( \frac{11}{6} T_z^t - 3T_z^{t-\delta t} + \frac{3}{2} T_z^{t-2\delta t} - \frac{1}{3} T_z^{t-3\delta t} \right) = \sum q_i + \sum_{i=1}^{N_{surface}} h_{ci} A_i (T_{si} - T_z) + \sum_{i=1}^{nz} \dot{m} C_p (T_{zi} - T_z) + \dot{m}_{inf} C_p (T_o - T_z) + \dot{m}_{sys} C_p (T_{sup} - T_z) \quad \text{----- 4.13}$$

Then solving for the zone temperature gives:

$$T_z^t = \frac{\sum q_i + \sum_{i=1}^{N_{surface}} h_{ci} A_i T_{si} + \sum_{i=1}^{nz} \dot{m} C_p T_{zi} + \dot{m}_{inf} C_p T_o + \dot{m}_{sys} C_p T_{sup} - \left( \frac{C_z}{\delta t} \right) \left( -3T_z^{t-\delta t} + \frac{3}{2} T_z^{t-2\delta t} - \frac{2}{3} T_z^{t-3\delta t} \right)}{\left( \frac{11}{6} \right) \frac{C_z}{\delta t} + \sum_{i=1}^{N_{surface}} h_{ci} A_i + \sum_{i=1}^{nz} \dot{m} C_p + \dot{m}_{inf} C_p + \dot{m}_{sys} C_p} \quad \text{-----4.14}$$

This is the equation used by EnergyPlus to calculate the zone temperature at any time step t. since the load on the zone drives the entire process, that load is used as a starting point to

give a demand to the system. Then a simulation of the system provides the actual supply capability and the zone temperature is adjusted if necessary. This process is referred to as a predictor/corrector process and is summarized below:

- Using equation 4.7, an estimate is made of the system energy required to balance the equation with the zone temperature equal to the setpoint temperature.
- With that quantity as a demand, the system is simulated to determine its actual supply capability at the time of simulation.
- The actual system capability is used in equation 4.14 to calculate the resulting zone temperature.

#### **4.4. EnergyPlus Input Files**

EnergyPlus needs two different input files for its simulation, namely the input data file (in.idf) and the input weather data file (in.epw). In.idf is an ASCII file containing the data describing the building and HVAC system to be simulated and is kept simple in order to accept simulation input data from other sources such as CADD systems, programs that also do other functions, and preprocessors similar to those written for BLAST and DOE-2. The input file is not intended to be the main interface for typical end-users. To make it easy for current DOE-2 and BLAST users to move to EnergyPlus, utilities have been written that convert BLAST and DOE-2 input to the new EnergyPlus input. Since EnergyPlus is a modular in its structure, each module is responsible for getting its own input. It receives this input from the input processor in the form of alpha (A1, A2, . . .) and numeric field (N1, N2, . . .). EnergyPlus reads Data Dictionary (Energy+.idd) and input data files (In.idf)

prior to doing anything else. This is done by the EnergyPlus input processor which only knows as much as the data dictionary has told it. It knows which field should be alpha and which field should be numeric. The data dictionary (.idd) is an ASCII (text) file containing a list of all possible EnergyPlus objects and specification of the data each object requires. The user is not required to make an .idd file. It is already included in the software, but he/she should understand the detail structure and order of the parameters given in each object of the .idd. This will help the user to write the correct in.idf. EnergyPlus will read in.idf and checks with .idd for the given object. If it finds it doesn't match with .idd file an error will occur and simulation will terminated. Some of the input data that must be entered in the idf file for EnergyPlus simulates the building properly are;

***Version*** - this allows the user to enter the proper version that your idf was created for.

***Time step in hours*** - this specifies the basic time step for the simulation.

***Building*** – these are parameters that control certain elements of the simulation. This contains building name, building north axis, terrain, load convergence, temperature convergence, solar distribution, maximum number of warm up days.

***Air flow model*** – this allows to model air flow in to and through building using either a simplified infiltration model and user specified interzone air flow, or the COMIS (Conjunction of MultiZone Infiltration Specialists) multizone air flow model.

***Inside Convection Algorithm*** – this will model the inside convection heat transfer of the building surfaces. There are four models in EnergyPlus but two of them are available for

any building. The simple natural convection model applies constant heat transfer coefficients depending on the surface orientation. The second model is the detailed natural convection model which correlates the heat transfer coefficient to the temperature difference for various orientations. The third and fourth modes are the mixed and forced convection model for ceiling diffuser configuration, and natural convection model which correlates for trombe wall passive solar applications.

***Outside Convection Algorithm*** – here there are two models. The simple convection model applies constant heat transfer coefficient depending on the roughness and wind speed. And the detailed convection model applies heat transfer coefficients depending on the roughness, wind speed, and terrain of the building location.

***Solution Algorithm Selection*** – this provides a way to select what type of heat in the moisture transfer algorithm will be used across the building construction. There are three values allowed to select from. The CTF selection is sensible heat only solution and does not take in to account moisture storage or diffusion in the construction element. The MTF selection is a simultaneous heat and mass transfer solution with vapor adsorption taking place in the building construction. And the EMPD is a sensible heat diffusion and an inside surface moisture storage algorithm that also needs additional moisture material property information. Currently it is difficult to use MTF and EMPD in the program hence CTF is the only option to use.

***Zone Volume Capacitance Multiplier*** – is the capacitance of the air in the volume of the specified zone.

***Run Control*** – this allows the user to specify what kind of calculation a given EnergyPlus simulation will perform. There are five yes/no inputs to use here and these are; Do the zone sizing calculation, Do the system sizing calculations, Do the plant sizing calculations, Do the design day simulation, and Do the weather file simulation. One can select more than one calculation so that EnergyPlus can perform simultaneous simulation.

***Location*** – this describes the parameters for the building location. This includes location name, latitude, longitude, time zone and elevation. Weather data file location, if it exists will override any location data in the idf.

***Run period*** – this describes the element necessary to create a weather simulation. If it will allow users to specify for what period does the program perform simulation? EnergyPlus can perform simulation for a day, fraction of day, days, year and even for more than a year.

***Design day*** – this input describes the parameters to effect a design day simulation, often used for load calculation or sizing equipment. At least two design day (summer design day and Winter design day) should be specified for EnergyPlus to perform simulation.

***Material*** – this allows users to enter the materials used in the construction of the building. It consist the thermal property of the material. There are three material types which can be used to describe layers with opaque construction elements. These are; Material:Regular, Material:Regular:R, and Material:Air. Material:Regular is the preferred one. It requires the knowledge of many of the thermal properties of the material, but it allows EnergyPlus to

take into account the thermal mass of the material and thus allows the evaluation of transient conduction effect. Material:Regular:R is similar in nature but only requires the thermal resistance (R - value) rather than thickness, thermal conductivity, density, and specific heat. Using this EnergyPlus assumes steady state heat conduction through the material. Material:Air is used for an air gap between layers in a construction element. Material:Window:Glass allows users to specify the material type used for windows and glass doors. Other material like Material:Window:Shade to specify the shading material used for window and Material:Window:Blind to specify the thermal property of blind shades can also be defined if necessary.

**Construction** – for walls, roofs, floors, windows, and doors constructions are built from the included materials. Each layer of the construction is a material name listed in order from outside to inside of the given zone.

**Zone** – this describes the thermal zone characteristics which sets up the parameters to simulate. It consists zone name, zone north axis (measured relative to building north axis), zone origin, zone multiplier, ceiling height, zone volume.

**Surface geometry** – this allows users to specify the description of the geometric parameters in EnergyPlus to be used. EnergyPlus uses three dimensional (3D) Cartesian coordinate system for surface vertex specification. This contains Surface starting position (upper left corner, lower left corner, upper right corner or lower right corner), vertex entry (clock wise or counter clock wise from the surface starting position), an surface geometry key (absolute/world coordinate or relative coordinate systems).

**Surface** – this allows user to specify surfaces in the building. EnergyPlus allows several surface types to be used in defining the surface in the building. Some of them are; surface:HeatTransfer, Surface:Heattransfer:Sub, Surface:HeatTransfer:InternalMass. Surface:HeatTransfer are used to describe the important elements of the building such as walls, roofs, floors and ceilings. It contains surface name, surface type (wall, floor, ceiling, roof), construction name of the surface, inside face environment, outside face environment, wind exposed (windExposed or nowind), sun exposed (SunExposed or NoSun), view factor to ground, and number of surface vertices and their coordinates. Surface:HeatTransfer:Sub is used for sub surfaces such as windows, doors and glass doors. Windows and glass doors are considered to have one or more glass layers and so transmit solar. Doors are considered to be opaque. Surface:HeatTransfer:InternalMass is used to specify the construction/material parameters and areas of items within the space. Furniture within the space, and internal walls or partitions can be included in this category of material type. Other surfaces like Surface:Shading:Detached:Fixed, Surface:Shading:Attached, and Surface:Shading:Detached:Building can be defined for different types of shadings.

**People** – this statement is used to model the occupant's effect on the space conditions. This contains zone name, number of people, schedule name (that modifies the number of people parameters), fraction radiant, activity schedule name (that modifies the amount of heat gain per person in the zone under design conditions).

**Lights** – this statement allows the user to specify information about a zone’s electric lighting system, including design power level and operation schedule and how the heat from lights is distributed thermally.

**Infiltration** – this allows users to enter the amount of infiltration air to and out of the building. It contains zone name, schedule name (that modifies the maximum design volume flow rate parameters), and design volume flow rate.

The above inputs are few of the program need to run properly. The detail discussion and types of input parameters can be found in the input-output reference of reference [6].

In.epw is an ASCII file containing the hourly or sub-hourly weather data needed by the simulation program. The first eight lines or header within this weather file defines basic location information such as longitude, latitude, time zone, elevation, annual design conditions, monthly average ground temperature, typical and extreme periods, holyday/daylight savings periods, and data periods included. The data follows then by hourly weather data for the year. The specific data elements of in.epw format include:

- Location (city, State Province Region, Country, Data Source, Latitude, Longitude, Time Zone, Elevation)
- Typical/Extreme Periods (Number of Typical/Extreme Periods (up to 8), Description of each Typical/Extreme Period, Start Month/Day, End Month/Day)

- Ground Temperature (Number of Ground temperature Depths, Depth of each Ground Temperature set, Soil Conductivity, soil Density, Soil Specific Heat, Monthly Average Ground Temperatures)
- Leap Year Indicator, Daylight Saving Periods, Holidays
- Comments
- Time Step Data Periods, number of Interval in an hour, Description, (Start Day of Week, Start Month/Day, End Month/Day)
- Time Step Data (Year, Month, Day, Hour, Minute), Data source and Uncertainty Flags
- Time Step Data(Dry Bulb Temperature, Dew Point Temperature, Relative Humidity, Atmospheric Station Pressure, Radiation (Extraterrestrial Horizontal, Extraterrestrial Direct Normal, Horizontal Infrared Radiation from Sky, Global Horizontal, Direct Normal, Diffuse Horizontal ), Illuminance(Global Horizontal, Direct Normal, Diffuse Horizontal, zenith Luminance), Wind (Direction, Speed), Sky Cover (Total, Visible, Ceiling Height), Present Weather (Observation, Codes), Precipitable Water, Aerosol Optical Depth, Snow (Depth, Days Since Last Snowfall)). The above data are entered in the order given in the weather file.

#### **4.5. EnergyPlus Output Data**

During a simulation, EnergyPlus saves results for each time step in an output data structure. The Heat Balance time step is user-specified with a default of 15 minutes. HVAC results may proceed at the Heat Balance time step or at smaller time steps in order to reach stability. The EnergyPlus output processor provides these results in a simple variable-based

format (comma separated text file) that can easily be read by post-processing programs or even spreadsheets like excel. EnergyPlus reports many out put variables hence the user can control the number of variable that EnergyPlus should report according to the user's desire. The Program can again report the variables at any time of interval; time step, hourly, daily, monthly, and yearly. The user can specify the variable to be reported and the frequency of report in the report object in the idf file.

## **CHAPTER FIVE**

### **A CASE STUDY OF ENERGY SAVING OF BUILDINGS IN GODE**

#### **5.1. Building Description**

One residential building and one office building are simulated and their energy performances are evaluated for the different design parameters.

##### **5.1.1. Residential building**

This building, which was constructed by the Ministry of Agriculture for its employee, is a single story building. It consists of one bed room, a store, kitchen, and a rest room. It has a 31.5m<sup>2</sup> floor area (5m x 6.3m) and 2.8m floor to ceiling height. The external walls are made up of 200mm hollow concrete blocks and internal walls are made up of 150mm hollow concrete block. Both walls are plastered and painted. The roof is made up of 0.3mm galvanized corrugated steel sheet with 8mm chip wood ceiling with air gap between them. The floor is finished with cement screened. Windows and glass doors are 3mm clear glass with steel frame and divider. Other doors are made of wood. It is assumed that 3 people are living and common 60W incandescent lamps are used in each room. The front side of the building is facing south and one of its sides is adjacent to similar building so that there is no heat transfer along this side as it is kept at fixed temperature. The building is taken as one zone for the simulation. The plan view of this building is attached at the end of this report.

### **5.1.2. Office Building**

This office building is also constructed by the Ministry of agriculture for an office purpose in the town. It has 33 offices which are designed to serve for 52 employees. It is a two story building with  $325.85\text{m}^2$  ( $33.25\text{m} \times 9.8\text{m}$ ) floor area, 6.12m total height, and 3.06m floor to floor height. The external and internal walls are constructed in a similar way as that of the residential building described above. The office floors are finished with PVC (Polyvinyl chloride) tiles while that of the corridor floor is terrazzo tiles. Windows and glass doors are all 3mm clear glass with steel frame and divider. The front side of the building is taken to facing south and it is divided into 8 zones, four in the ground and four in the upper floor. The plan view of this building is attached at the end of this report.

## **5.2. Weather Data for Gode**

### **5.2.1. Climatic Classification**

Classification of climate with respect of building design means zoning the country into regions in such a way that the difference of climate from region to region is reflected in the building design, warranting some special provision for each region. Based on this criteria, there are five major climatic zones, hot-dry; warm-humid, cold, temperate, composite.

**Table 5.1** Climatic zones of area

Climatic Zone	Mean Monthly Maximum Temperature, °C	Mean Monthly Relative Humidity, %
Hot-Dry	above 30	below 55
Warm-Humid	above 30 above 25	above 55 above 75
Temperate	25-30	below 75
Cold	below 25	all values

\*\* Composite are areas with a combination of two or more of the above conditions.

According to table 5.1 most hot areas of Ethiopia are classified as hot and dry. For example for Gode the average mean monthly maximum temperature for all months of the year is greater than 32<sup>0</sup>C and the mean monthly relative humidity is less than 52%.

### 5.2.2. Temperatures and Relative Humidity

EnergyPlus needs hourly dry bulb temperatures, dew point temperature, and relative humidity in its weather file; however in Ethiopia it is difficult to get hourly data for most cities. Hence estimation of hourly dry-bulb temperature from the daily mean maximum and daily mean minimum temperatures will give a reasonable result. It is then good assumption to take a sinusoidal variation of the dry-bulb temperature through the day. Here it is assumed that the maximum temperature occurs at 15:00 h sun time.

If we take the outside temperature is T(t) at any time t, then [29]:

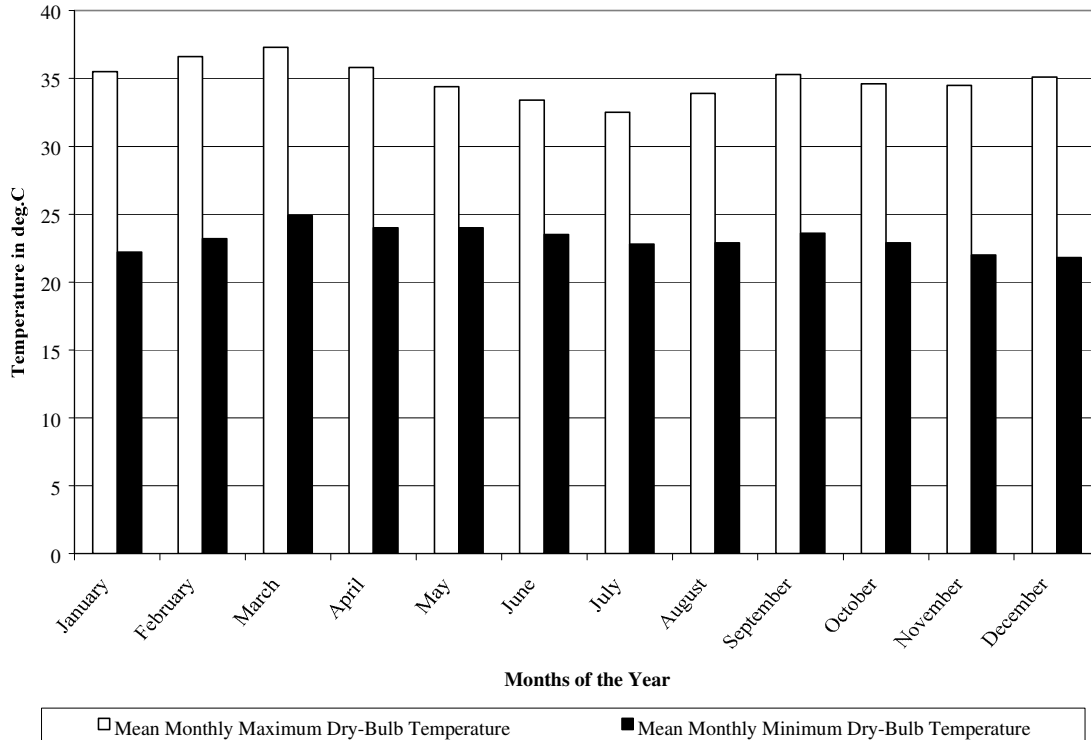
$$T(t) = T(15) - \frac{T_{\max} - T_{\min}}{2} \left[ 1 - \sin \frac{(t\pi - 9\pi)}{12} \right] \text{-----5.1}$$

where,  $T(15)$  = maximum temperature at 15:00 h sun time

$T_{\max}$  = mean daily maximum temperature

$T_{\min}$  = men daily minimum temperature

$t$  = sun time in hours



**Figure 5. 1** Monthly Mean Maximum and Minimum Dry-Bulb Temperature for Gode

The relative humidity is also assumed to vary sinusoidal with time where its minimum value is assumed to be at 15:00h and maximum value at 06:00h. By rearranging equation 5.1 in the form of equation 5.2 it can be used to estimate the hourly relative humidity of any place. Figures 5.2 and 5.3 shows the daily variation of dry-bulb temperature and relative humidity for Gode for the months of March and July which are assumed to be the hottest

and coldest months. Figure 5.1 shows the mean monthly maximum and minimum temperatures for Gode.

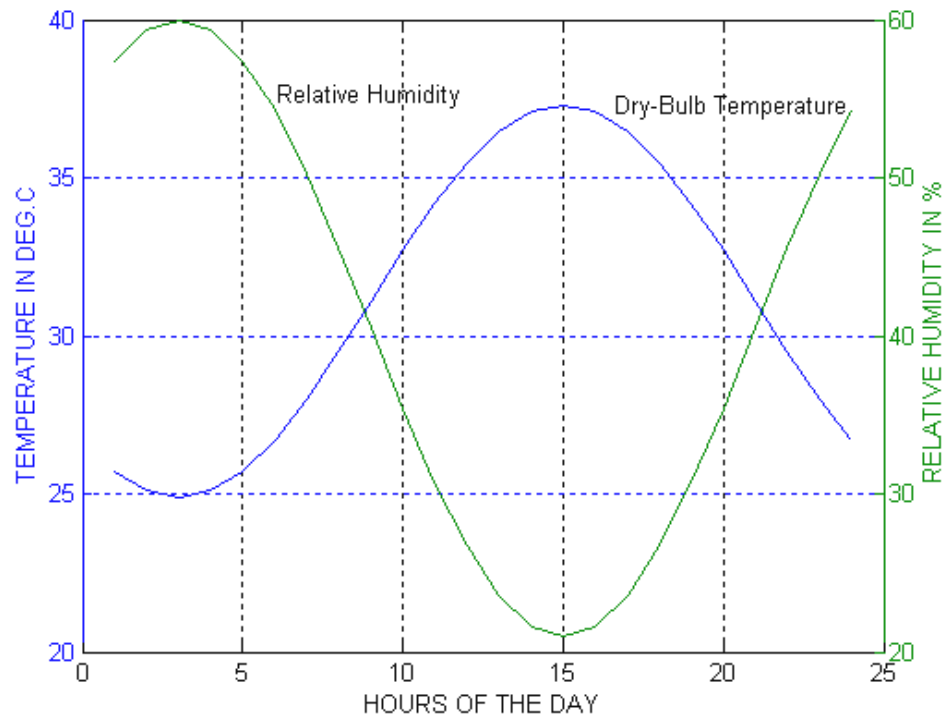
$$RH(t) = RH(15) + \frac{RH(6) - RH(15)}{2} \left( 1 - \sin\left(\frac{\pi t - 9\pi}{12}\right) \right) \text{-----5.2}$$

where: RH(t) = relative humidity at any time t,

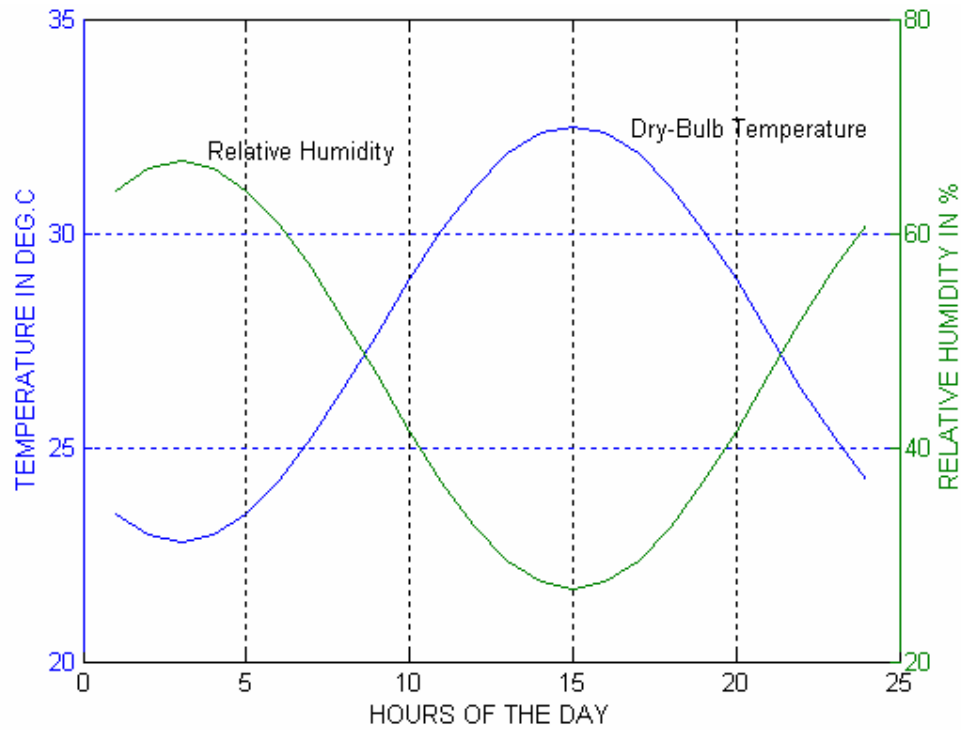
RH(15) = relative humidity at 15:00 hrs,

RH(6) = relative humidity at 06:00 hrs,

t = time in hours.



**Figure 5. 2** Daily Temperature and Relative Humidity profile for the hottest month, March



**Figure 5.3** Daily Temperature and Relative Humidity Profile for the Month, July

**Dew Point Temperature** is defined as the temperature for which air would need to be cooled at constant pressure and constant moisture content in order for the vapor pressure and saturation vapor pressure of the air to be equal. In other words, it is the temperature at which air would be saturated (i.e., 100% relative humidity). As there are no measured data for dew point temperature the following empirical equation which is a function of temperature and relative humidity has been used [10]:

$$T_d = \frac{b - \sqrt{b^2 - C_3}}{C_4} \quad \text{where } b = C_{15} - \ln(e) \text{ and } e = RH * e_s$$

and

$$e_s = \exp\left(C_{15} - C_1 T - \frac{C_2}{T}\right)$$

----- 5.3

and  $T_d$  = dew-point temperature [K],  $T$  = dry-bulb temperature [K]

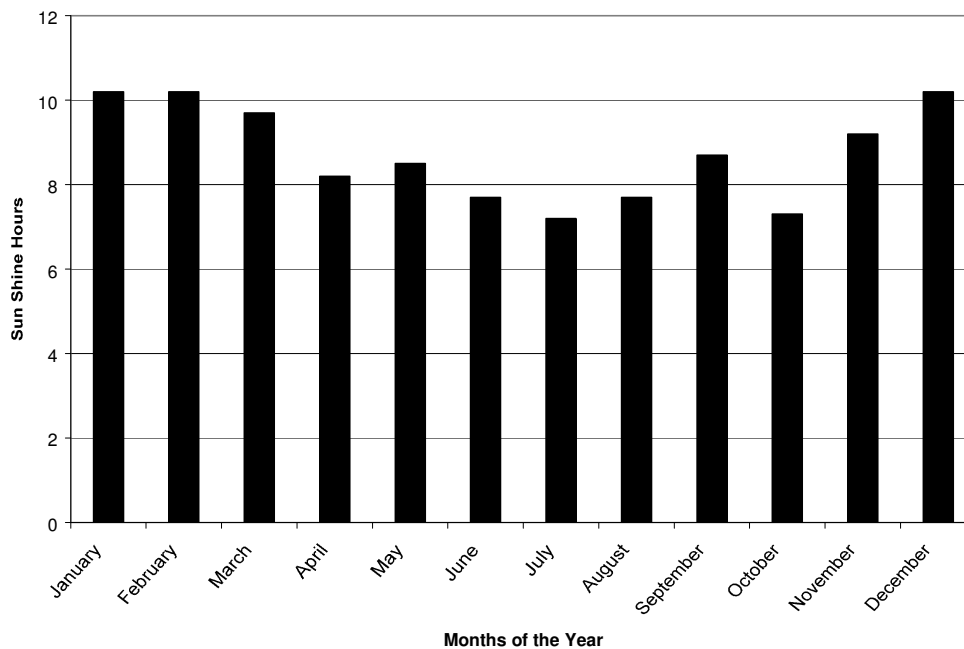
RH = relative humidity (ratio)

$C_{15} = 26.66082$ ,  $C_1 = 0.0091379024$

$C_2 = 6106.396$ ,  $C_3 = 223.1986$ , and  $C_4 = 0.0182758048$

### 5.2.3. Solar Radiation

The Ethiopian Meteorological Service collects only the average sunshine hours as solar radiation data for some cities of the country. Hence the solar radiations used in EnergyPlus are estimated from the average monthly sunshine hours available. The average monthly sunshine hours for Gode are given in figure 5.4.



**Figure 5.4** Monthly Average Sun Shine Hours for Gode

**Extraterrestrial Radiation**

The extraterrestrial radiation which is the radiation value on a plane normal to the radiation on the n<sup>th</sup> day of the year is given by [5]:

$$G_{on} = G_{sc} \left[ 1 + 0.033 \cos \left( \frac{360n}{365} \right) \right] \text{-----5.4}$$

where  $G_{on}$  = Extraterrestrials radiation normal to the radiation

$G_{sc}$  = solar constant, given by  $G_{sc} = 1367 \text{ W/m}^2$

n = day of the year, 1 for 1<sup>st</sup> January, 2 for 2<sup>nd</sup> January, etc.

The extraterrestrial radiation incident on a horizontal plane outside the atmosphere is given by [5]:

$$G_{on} = G_{sc} \left[ 1 + 0.033 \cos \left( \frac{360n}{365} \right) \right] \cos \theta_z \text{-----5.5}$$

where  $\theta_z$  is the zenith angle and is given by :

$$\cos \theta_z = \cos \phi \cos \delta \cos \omega + \sin \phi \sin \delta \text{-----5.6}$$

where  $\Phi$ , **latitude**, is the angular location of the area north or south of the equator, north positive.

$\delta$ , **declination**, is the angular position of the sun at solar noon given by:

$$\delta = 23.45 \sin \left( 360 \frac{284 + n}{365} \right)$$

$\omega$ , **hour angle**, the angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis at 15<sup>0</sup> per hour, morning negative, afternoon positive. It is given by:

$$\omega = (h - 12) * 15^0, \quad h \text{ is the sun time in hours}$$

By integrating equation 5.5 from sunrise to sunset we can obtain the daily extraterrestrial radiation on a horizontal surface,  $H_0$ , [5]:

$$H_0 = \frac{24 * 3600 G_{sc}}{\pi} \left[ 1 + 0.033 \cos \frac{360n}{365} \right] \left( \cos \phi \cos \delta \sin \omega_s + \frac{\pi \omega_s}{180} \sin \phi \sin \delta \right) \text{-----5.7}$$

where  $\omega_s$  is the sunset hour angle given by:

$$\omega_s = \cos^{-1}(-\tan \phi \tan \delta)$$

The monthly mean daily extraterrestrial radiation,  $\bar{H}_0$ , can be calculated using equation 5.7 with  $n$  and  $\delta$  for the mean day of the month.

Integrating equation 5.7 for an hour period between hour angles  $\omega_1$  and  $\omega_2$  will give the hourly extraterrestrial radiation incident on a horizontal surface,  $I_0$ , which is given by [5]:

$$I_0 = \frac{12 * 3600}{\pi} G_{sc} \left( 1 + 0.033 \cos \frac{360n}{365} \right) \left[ \begin{array}{l} \cos \phi \cos \delta (\sin \omega_2 - \sin \omega_1) + \\ \frac{\pi (\omega_2 - \omega_1)}{180} \sin \phi \sin \delta \end{array} \right] \text{-----5.8}$$

The above equation is in MJ/m<sup>2</sup>, and dividing by 3600secnds/hour will give in Wh/m<sup>2</sup>. The hourly extraterrestrial radiation can be easily estimated using equation 5.5 by writing in terms of  $I$ , evaluating  $\omega$  at the midpoint of the hour with a negligible error with equation 5.8.

### ***Solar Radiation on a Horizontal Surface***

The original Angstrom regression equation related monthly average daily radiation to clear day radiation at the location in question and average fraction of possible sunshine hours [5]:

$$\frac{\bar{H}}{\bar{H}_c} = a' + b' \frac{\bar{n}}{N} \text{-----5.9}$$

where  $\bar{H}$  = monthly average daily radiation on a horizontal surface

$\bar{H}_c$  = average clear sky daily radiation for the location and month on question.

$a'$  ,  $b'$  = empirical constants

$\bar{n}$  = monthly average daily sunshine hours

$N$  = monthly average of the maximum possible daily hours of bright  
sunshine (i.e. the day length of the average day of the month)

The difficulty in using equation 5.9 is in defining a clear sky; hence it is modified by the method to base it on extraterrestrial radiation on a horizontal surface rather than on clear day radiation.

$$\frac{\bar{H}}{\bar{H}_0} = a + b \frac{\bar{n}}{N} \text{-----5.10}$$

where  $\bar{H}_0$  is the extraterrestrial radiation for the location, averaged over the time period in question, and  $a$  and  $b$  are constants depending on location. Reference [5] gives different values of these constants in a general classification of areas. The values  $a = 0.54$  and  $b = 0.20$  are given for a place with arid climate and an average sum shine hour of 84%. This climatic zone is the best one which suites for Gode among the other climatic zones given in the table of reference [5] page 70 and these values are selected for the estimation of hourly solar radiation.

The monthly average of the maximum possible daily hours of bright sunshine, N, can be

calculated as; 
$$N = \frac{2}{5} \cos^{-1}(-\tan \phi \tan \delta) \text{-----} 5.11$$

But for most tropical countries it can be taken an average value of N=12.

By assuming the monthly daily average sunshine hours to be the same for all days of the month we can rewrite equation 5.10 in terms of the daily total radiation.

$$\frac{H}{H_0} = a + b \frac{\bar{n}}{N} \text{-----} 5.12$$

The hourly solar radiation can be estimated now from the daily solar radiation given by equation 5.12 but the method best estimates for clear days, as there is no way to estimate from the daily total the effect of circumstances such as intermittent heavy clouds, continuous light clouds, or heavy cloud cover for part of the day. Statistical studies of the time distribution of total radiation on a horizontal surface through the day, using monthly average data for a number of stations, have lead to generalized chart of  $r_t$ , the ratio of hourly total to daily total radiation as a function of day length and the hours in question.

$$r_t = \frac{I}{H} \text{-----} 5.13$$

The hours are designed by the time for the midpoint of the hour, and days are assumed to be symmetrical about solar noon.  $r_t$  can be estimated as [5]:

$$r_t = \frac{\pi}{24} (C + D \cos \omega) \frac{\cos \omega - \cos \omega_s}{\sin \omega_s - \frac{\pi \omega_s}{180} \cos \omega_s} \text{-----} 5.14$$

The coefficients C and D are given by:

$$C = 0.409 + 0.5016 \sin(\omega_s - 60)$$

$$D = 0.6609 - 0.4767 \sin(\omega_s - 60)$$

### ***Beam and Diffuse Components***

The beam and diffuse radiation components can now be calculated from the hourly clearness index,  $k_T = I/I_0$ .

The diffuse solar radiation on a horizontal surface is then given as [5]:

$$\frac{I_d}{I_0} = \begin{cases} 1 - 0.249k_T & \text{for } k_T \leq 0.35 \\ 1.557 - 1.84k_T & \text{for } 0.35 < k_T < 0.75 \\ 0.177 & \text{for } k_T \geq 0.75 \end{cases} \text{----- 5.15}$$

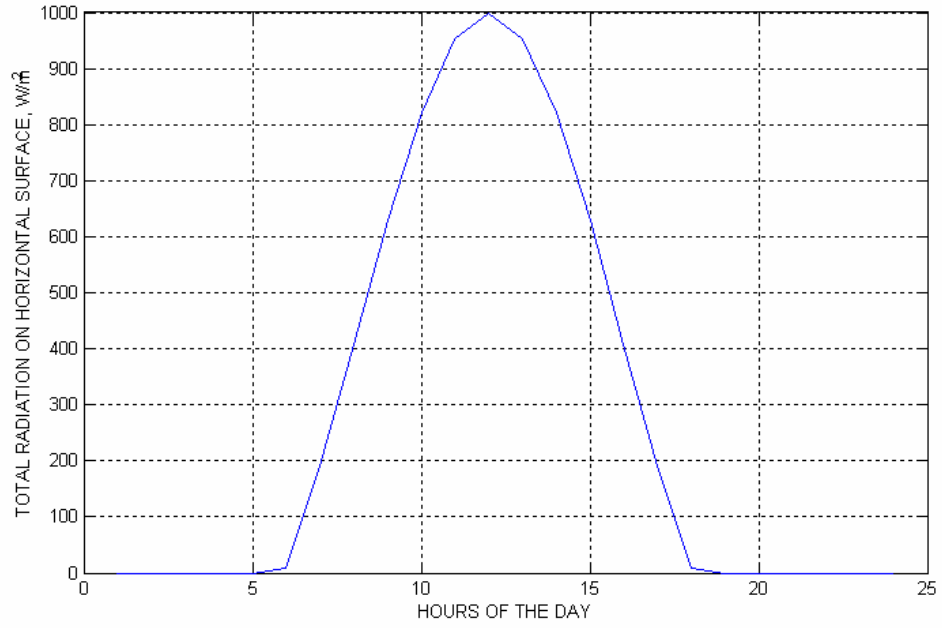
Hence, the beam or direct radiation on a horizontal surface is given by:

$$I_b = I - I_d \text{----- 5.16}$$

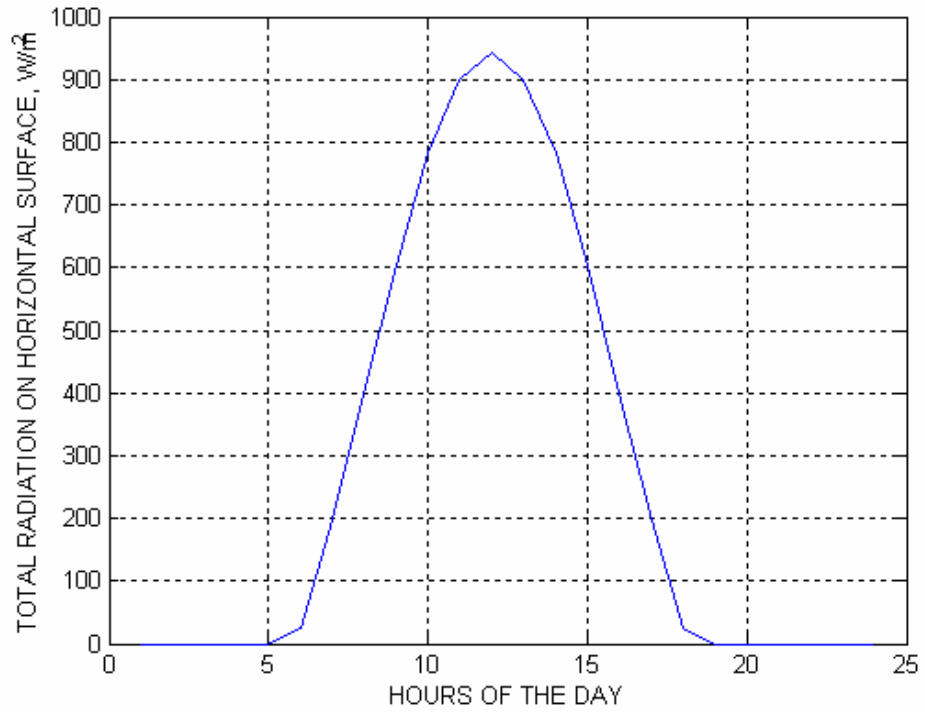
The beam radiation normal to the solar rays can be calculated as:

$$I_{bn} = \frac{I_b}{\cos \theta_z} \text{----- 5.17}$$

The daily profile of solar radiation on a horizontal surface for Gode is shown in figures 5.5 and 5.6 for the months May and July.



**Figure 5.5** Daily Total (Beam Plus Diffuse) Solar Radiation Profile for May



**Figure 5.6** Daily Total (Beam Plus Diffuse) Solar Radiation Profile for July

### **5.3. Calculation of Heat Gains**

#### **5.3.1. Heat Gain from Solar Radiation**

EnergyPlus calculates heat gain from solar radiation through the building envelope from the given weather data and geometry of the building. The solar distribution field in the building object of the IDF determines how EnergyPlus will treat solar radiation entering a zone through exterior windows. There are three choices: MinimalShadowing, FullExterior, and FullInteriorExterior. When the user selects MinimalShadowing EnergyPlus assumes there is no exterior shadowing except from window and door reveals. All beam solar radiation entering the zone is assumed to fall on the floor, where it is absorbed according to the floor's absorptance. Any reflected by the floor is added to the transmitted diffuse radiation, which is assumed to be uniformly distributed on all interior surfaces. In the case of FullExterior the shadow patterns on exterior surfaces caused by detached shadings, wings, overhangs, and exterior surfaces of all zones are computed. Beam solar radiation entering the zone is treated as for MinimalShadowing. FullInteriorExterior is the same as FullExterior except that instead of assuming all transmitted beam solar radiation falls on the floor the program calculates the amount of beam radiation falling on each surface in the zone, including floor, walls, and windows, by projecting the sun's rays through the exterior windows, taking into account the effect of exterior shadowing surfaces and window shading devices. Here, for both buildings, the FullInteriorExterior has been used.

### 5.3.2. Heat Gain through Infiltration

Heat gains through infiltration is entered in to EnergyPlus as the maximum volume flow rate of air and a schedule name that modifies the maximum volume flow rate in hourly volume flow rate according to the user. The volume air infiltrated to the building is caused by the stack pressure and wind pressure. The flow of air due to wind can be calculated from equation [1]:

$$Q = C_v A U \text{ ----- 5.18}$$

where Q = air flow rate, m<sup>3</sup>/s

C<sub>v</sub> = effectiveness of openings (C<sub>v</sub> is assumed to be 0.5 to 0.6 for perpendicular winds and 0.25 to 0.35 for diagonal winds)

A = free area of inlet openings, m<sup>2</sup>

U = wind speed, m/s

If building internal resistance is not significant, the flow caused by stack effect can be expressed by [1]:

$$Q = C_D A \sqrt{2g\Delta H_{NPL} \frac{(T_o - T_i)}{T_o}}, \text{ for } T_i < T_o \text{ ----- 5.19}$$

where Q = air flow rate, m<sup>3</sup>/s

C<sub>D</sub> = discharge coefficient for the opening

ΔH<sub>NPL</sub> = height from mid point of the lower opening to the neutral point, m

The discharge coefficient C<sub>D</sub> accounts for all viscous effect such as surface drag and interfacial mixing. Interfacial mixing occurs across the counter flow interface, and the orifice coefficient can be calculated according to the following equation:

$$C_D = 0.4 + 0.0045|T_i - T_o| \text{ ----- 5.20}$$

If enough other openings are available, the air flow through the opening will be unidirectional, and mixing can not occur. A discharge coefficient of  $C_D = 0.65$  should be used.

Estimation of  $\Delta H_{NPL}$  is difficult for naturally ventilated buildings. If one window or door represents a large fraction of the actual opening area in the envelope, then the neutral point (NPL) is at the mid height of that aperture and  $\Delta H_{NPL}$  equals one half the height of the aperture. For this condition, flow through the opening is bidirectional.

The volume flow rate due to infiltration can be easily estimated by the air change method. Air Change per hour (ACH) is the amount of air that enters the building in an hour. The volume flow rate can be calculated using equation [1]:

$$Q = \text{ACH} * (\text{zone volume}) / 3600 \text{ ----- 5.21}$$

where ACH can be read from Table 5.2

**Table 5. 2** Air Exchange rates (ACH) as a function of airtightness

Class	Outdoor Design Temperature, °C					
	29	32	35	38	41	43
Tight	0.33	0.34	0.35	0.36	0.37	0.38
Medium	0.46	0.48	0.50	0.52	0.54	0.56
Loose	0.68	0.70	0.72	0.74	0.76	0.78

Source: ASHRAE Handbook Fundamentals, 2001.

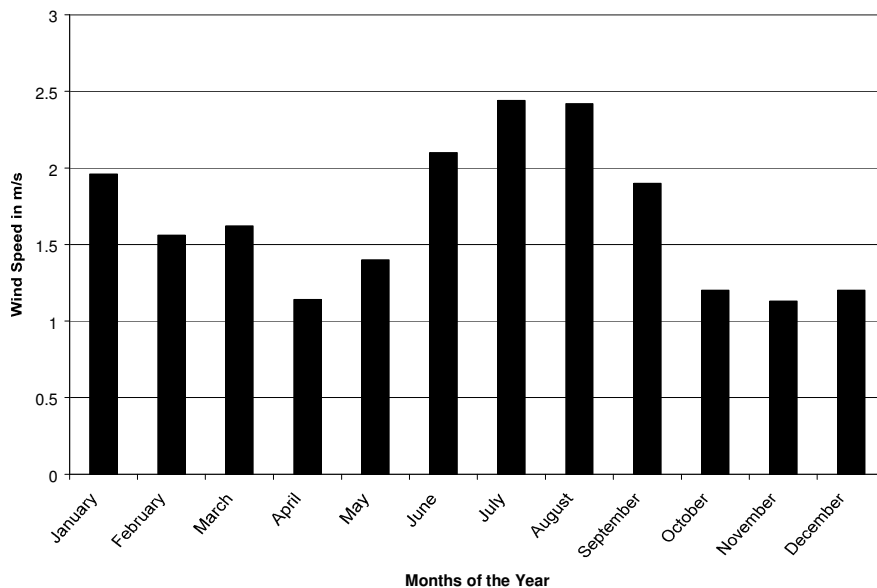
**Tight** are good constructions with close-fitting doors, windows and framing.

**Medium** are structures include new, two story frame houses or one story houses with average fit windows and doors and floor area of greater than 140m<sup>2</sup>.

**Loose** are poorly constructed structures with poorly fitted windows and doors.

The ACH can be ranging from 0.1 for a very tight building with out external window and door to 2 for an entrance hall and open doors for many hours [1].

For both buildings an air change of 0.5 is taken assuming that medium type of construction and the outdoor design temperature is 35<sup>0</sup>C. Using equation 5.21 the design volume flow rate of the zone can be estimated.



**Figure 5.7** Average Monthly Wind speed for Gode

### 5.3.3. Heat Gain from People

The heat gain from people is specified in the people object of EnergyPlus input file. EnergyPlus needs the total number of people and the activity schedule name. This schedule specifies the total heat gain per person for each hour of the day. Table 5.3 shows the total heat gain by a person for different activity levels. EnergyPlus then uses its internal algorithm to determine what fraction of the total is sensible and what fraction is latent. Then the sensible portion is divided into radiant and convective portion according to the value specified in the fraction radiant field. In this thesis a moderately active office work with total heat gain of 140W is selected.

**Table 5.3** Heat gain from people at different activity level

No	Degree of Activity	Total Heat Gain [W]
1	Seated at theater	115
2	Seated, very light work (office, hotel, apartment)	130
3	Moderately active office work (office, hotel, apartment)	140
4	Standing, Light work; walking (Department store, retail store, bank)	160
5	Sedentary work (Restaurant)	145
6	Light bench work (factory)	235
7	Moderate dancing (dancing hall)	265
8	Walking 4.8Km/h; light machine work (factory)	295
9	Heavy work (factory)	440
10	Heavy machine work; lifting (factory)	470
11	Athletics (Gymnasium)	585

ASHRAE Handbook Fundamentals, 2001

Note: Tabulated values are based on 24<sup>0</sup>C room dry-bulb temperature.

### 5.3.4 Heat Gain from Light

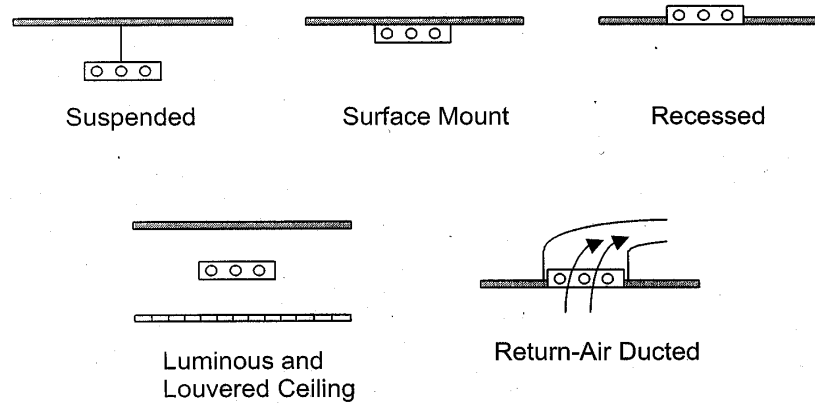
EnergyPlus accepts the input for the heat gain from lighting equipments in the light statement in the input file. This input contains the total power input to the electric lights in the zone and the schedule name that modifies the design level to the hours in the day. In EnergyPlus this heat is divided into four different fractions where three of them are given in the input field as return air fraction, fraction radiant, and fraction visible. The fourth, defined as the fraction of the heat from light convected to the zone air, is calculated by the program as;

$$f_{\text{convected}} = 1 - (\text{Return Air fraction} + \text{Fraction Radiant} + \text{Fraction Visible})$$

**Table 5. 4** Approximate values of Return Air Fraction, Fraction Radiant, and fraction visible for overhead fluorescent lighting for different luminaire configurations.

Field Name	Luminaire Configuration, Fluorescent Lighting				
	Suspended	Surface Mount	Recessed	Luminous and louvered ceiling	Return-air duct
Return Air Fraction	0.0	0.0	0.0	0.0	0.54
Fraction Radiant	0.42	0.72	0.37	0.37	0.18
Fraction Visible	0.18	0.18	0.18	0.18	0.18
$f_{\text{convected}}$	0.4	0.10	0.45	0.45	0.10

Source EnergyPlus documentation: Input-Output reference



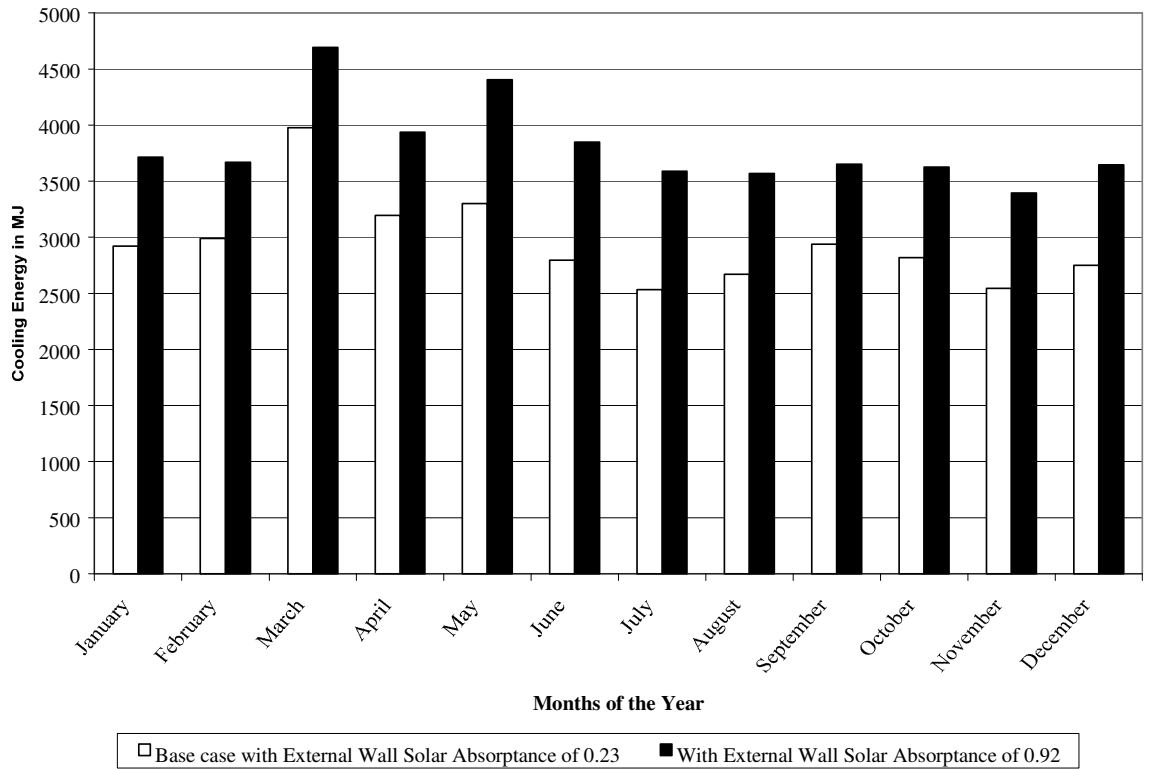
**Figure 5.8** Overhead fluorescent luminaire configurations

#### **5.4. Simulation Result and Discussion of the Residential Building**

The building is taken as one zone. The building is first simulated for the base case and the annual cooling load is taken. It is then simulated for different design improvements and the cooling load saving with respect to the base case is calculated. The design parameters which are included here are: solar absorptance of external walls, wall insulation, roof insulation, window and glass door glazing and shading, widow external overhang shading, and orientation. The insulation used in both walls and roof is fiber glass insulation. A 25mm and 50mm thickness of insulation are studied for walls and for roofs 25mm, 50mm, 75mm, 90mm, 100mm, and 155mm thickness of insulation are used separately. The external overhang shading used is 1m depth from the wall to the outside and the same width as the window. The materials and construction (layer) of the building envelope used in both buildings are given in appendix A and B.

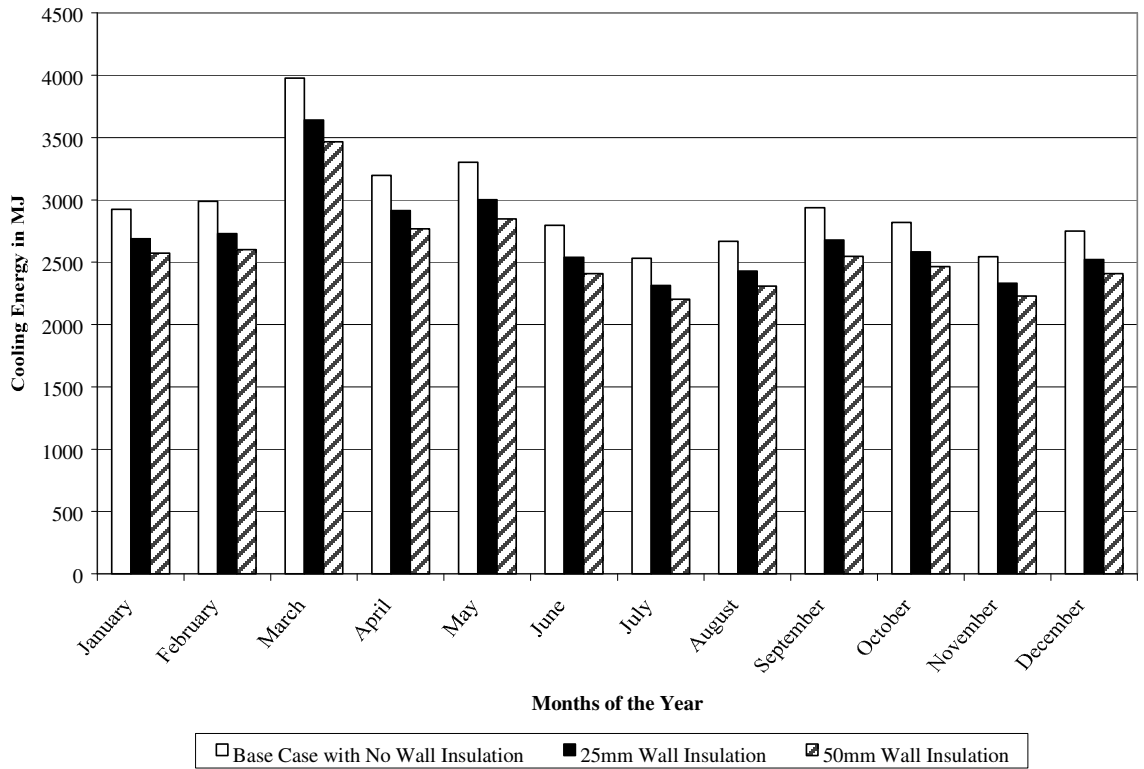
Monthly cooling energy for the different design parameters of the residential building are summarized in figures 5.9 to 5.13 and the daily cooling rate for two months is given in figures 5.14 and 5.15.

The maximum cooling load appears in March which coincides with the hottest month of the year while the minimum cooling load is in July which is the month with lower temperature. Figure 5.9 shows solar absorptance of external walls has great influence on the cooling load of a building. For the same surface texture solar absorptance of 0.23 is nearly white while solar absorptance of 0.92 is nearly black. Therefore, the above figure shows light colored surface can save a considerable amount of energy with respect to air conditioning load. The annual cooling energy increases by about 29% with 0.92 solar absorptance of external walls from that of 0.23. Changing colors for walls may earn little or no cost, hence color is one of a cost effective way of saving energy in buildings.



**Figure 5.9** Cooling Load Variation with Solar Absorptance of External Walls for Residential Building.

Figure 5.10 below shows the cooling load that could be reduced due to insulation on the walls. Wall insulation has little effect on cooling energy as compared to roof insulation. Table 5.5 shows up to 13% of the total annual cooling energy can be saved with wall insulation of 50mm thick. Figure 5.10 shows that a greater saving can be attained with increase in insulation thickness. However, a detail economic analysis should be done before deciding the thickness of insulation needed for a particular building.



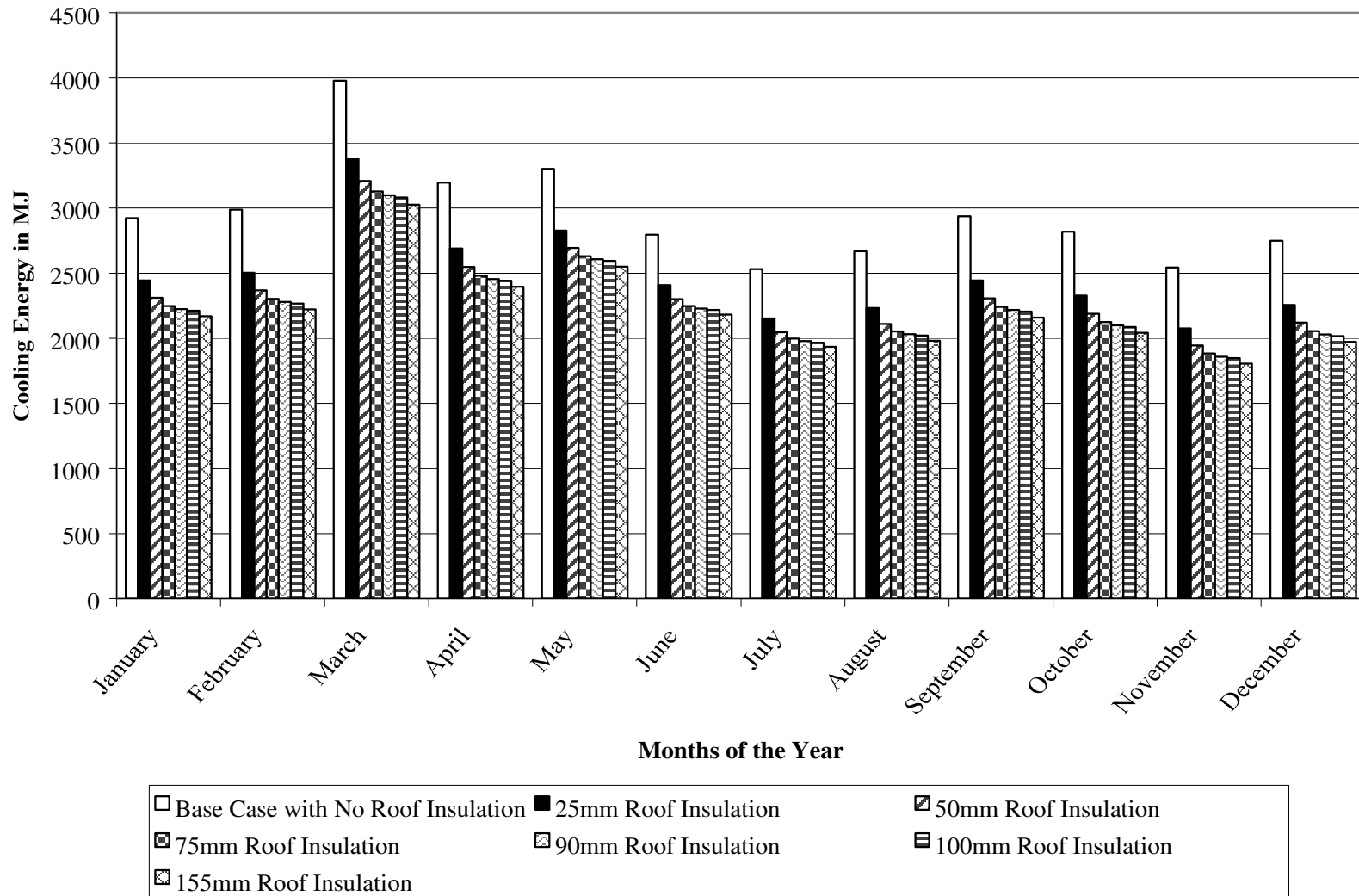
**Figure 5. 10** Cooling Load Variation with Wall Insulation for Residential Building.

Figure 5.11 shows variation of cooling load due to roof insulation. This result shows using roof insulation can give better saving than using in walls. This is due to the reason that roofs are exposed to the sun for more hours than walls and the solar radiation rays are perpendicular to the roof for many hours. Roof insulation is easier to install and maintain which will add an advantage to that of wall insulation by reducing installation and maintenance costs. It is clear that with increasing insulation thickness the saving increases and also the cost of insulation increases. Hence, the optimum thickness is selected after a detail economic analysis for all thicknesses is done. The economic analysis of different thicknesses of roof insulation for both residential and office building has been discussed under the economic analysis section. Table 5.5 shows that using 50mm roof insulation can

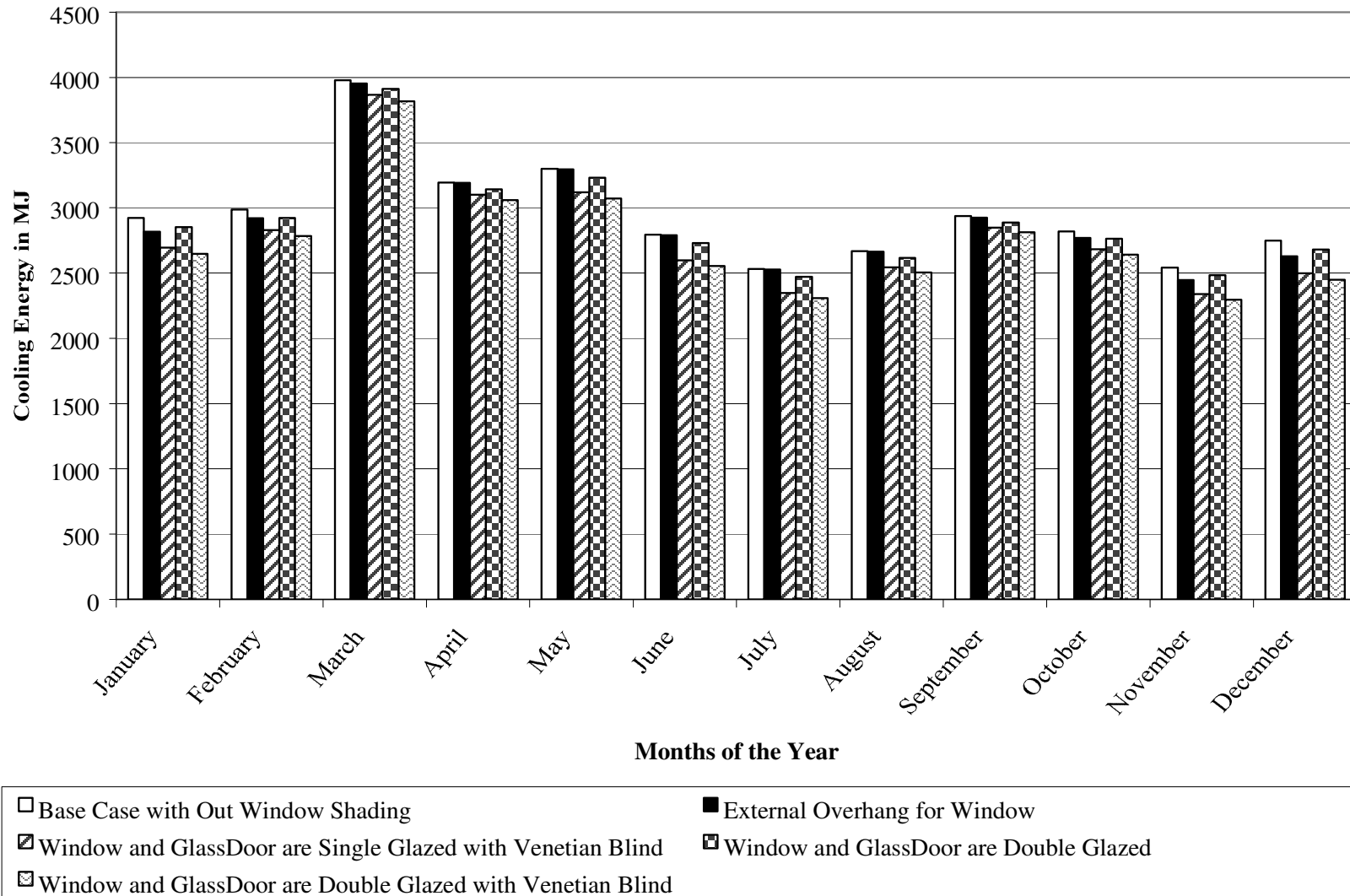
save about 20.5% of the annual cooling energy of the building which is about 7% higher than the saving of the same insulation when using in walls.

Figure 5.12 shows saving due to window shadings. A 1m external overhang and venetian Blind are used. The figure shows using venetian Blind is better than external overhang and double glazed. Table 5.5 shows using venetian blind can save around 5.5% while use of only double glazing can save only 1%. Venetian blinds are more effective when installed on the external side than in the inside of the glazing and on this thesis in all buildings they are installed externally. In addition to their importance to reduce the cooling load of a building venetian blind will help to block direct sun ray from entering the building which will increase comfort of the people inside.

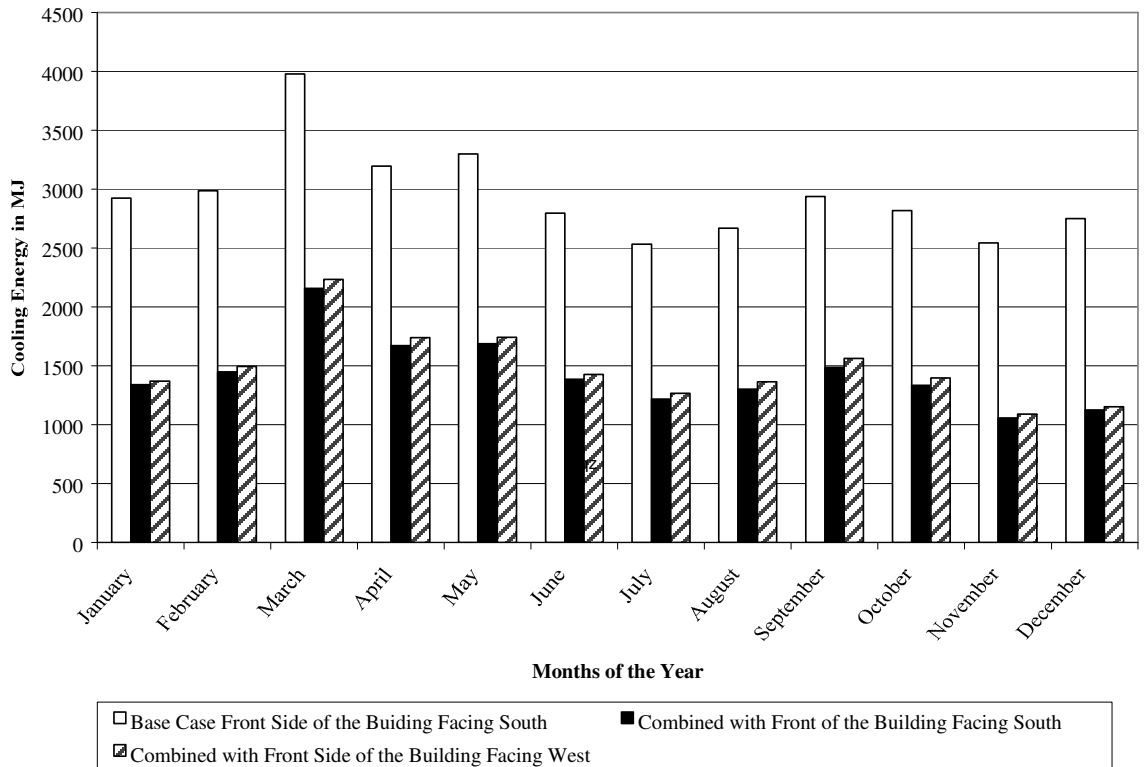
Proper orientation of the building is also a good practice for energy saving. Figure 5.1 shows the effect of the combined parameters and orientation of the building. Only the rotation of the building by 90 degrees can influence the cooling load significantly. In the base case the front side of the building is facing south. This orientation results: in window facing south and the glass door facing north. And this orientation saves more than 2% of the annual cooling energy than facing the front side of the building west see table 5.5.



**Figure 5. 11** Cooling Load Variation with Roof Insulation



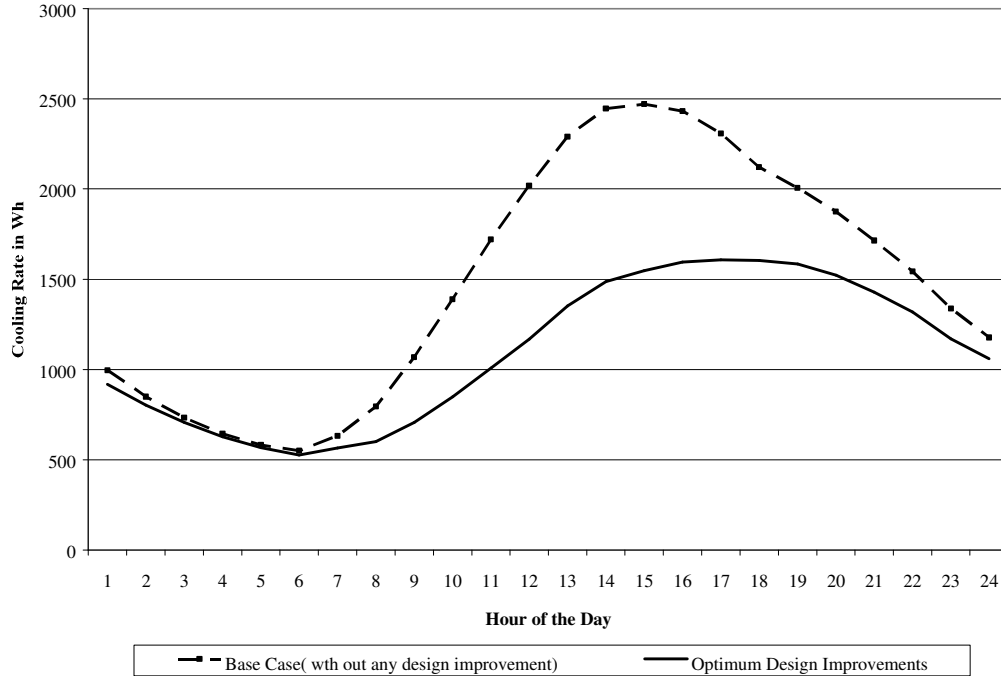
**Figure 5.12** Cooling Load Variation with Window Shading



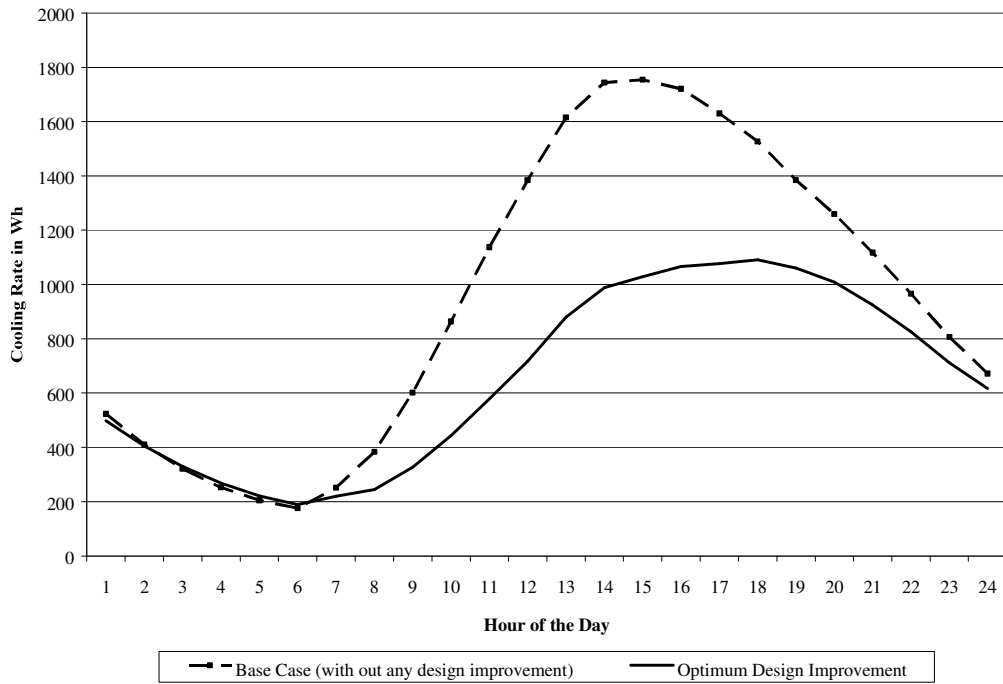
**Figure 5. 13** Combined Effects of the Parameters and Orientation on Cooling Load Variation

Note: Combined means all the design improvements discussed above are applied together. This includes external wall have 0.23 solar absorptance, 50mm wall insulation, 155mm roof insulation, window has external overhang, and window and glass door are double glazed with venetian blind.

The two figures below show the daily cooling load variation for two months. From both figures the minimum cooling load appears at 06:00h and that of maximum cooling load is at 15:00h. This is due to the occurrence of minimum and maximum temperatures of the day at 06:00h and 15:00h respectively.



**Figure 5. 14** Daily Total Cooling Rate Variation of the Residential Building for the Month March.



**Figure 5. 15** Daily Total Cooling Rate Variation of the Residential Building for the Month July

**Table 5.5** Summary for the residential building in Gode

<b>No</b>	<b>Building Case</b>	<b>Annual Energy Consumption of the Building [MJ]</b>	<b>Annual Energy Saving [MJ]</b>	<b>Annual Saving [%]</b>
1	Base Case (With External Walls Solar Absorptance of 0.23) Wall-01	35429.74	-----	-----
2	Base Case But With External Walls Solar Absorptance Of 0.92	45739.73	-10309.98	-29.10
3	Base Case and Walls Have 50mm Insulation (WALL-02)	30817.29	4612.45	13.02
4	Base Case and Walls Have 25mm Insulation (WALL-03)	32366.66	3063.09	8.65
5	Base Case and 25mm Roof Insulation Only	29739.84	5689.90	16.06
6	Base Case and 50mm Roof Insulation Only	28145.89	7283.86	20.56
7	Base Case and 75mm Roof Insulation Only	27394.39	8035.35	22.68
8	Base Case and 90mm Roof Insulation Only	27108.02	8321.73	23.49
9	Base Case and 100mm Roof Insulation Only	26957.02	8472.73	23.91
10	Base Case and 155mm Roof Insulation Only	26435.62	8994.12	25.39
11	Base Case and Window Have External Overhang Shading	34935.17	494.57	1.40

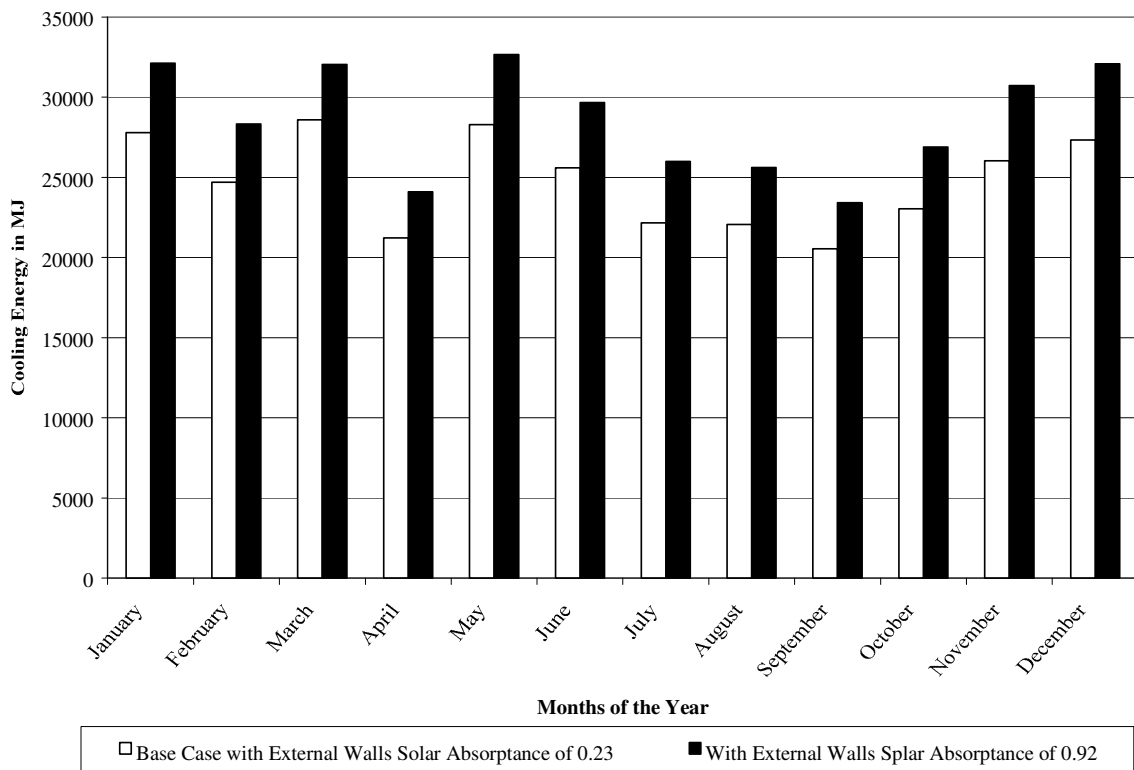
*Table 5.5 Cont'd*

12	Base Case and Window and Glass Door are Single Glazed with Venetian Blind	33474.79	1954.96	5.52
13	Base Case and with Only Window Double Glazed	35073.08	356.67	1.01
14	Base Case and with Only Window Double Glazed and Venetian Blind	34142.65	1287.10	3.63
15	Base Case and with Window And Glass door Double Glazed	34695.28	734.47	2.07
16	Base Case and With Window and Glass door Double Glazed and Venetian Blind	32953.17	2476.58	6.99
17	COMBINED (155mm Roof Insulation, 50mm Wall Insulation, External overhang, and Window and Glass Door are Double Glazed with Venetian Blind)	17216.77	18212.98	51.41
18	Combined and East-West Orientation (Front of The Building Faces West)	17838.57	17591.18	49.65
19	Optimum Design Option	25073.15	10356.60	29.23

**Note:** Optimum Design of the residential building results in 75mm Roof Insulation, Window and Glassdoor are Single Glazed with Venetian Blind, Window External Overhang and Front Side of the Building is Facing South.

## 5.5. Simulation Result and Discussion of Office Building

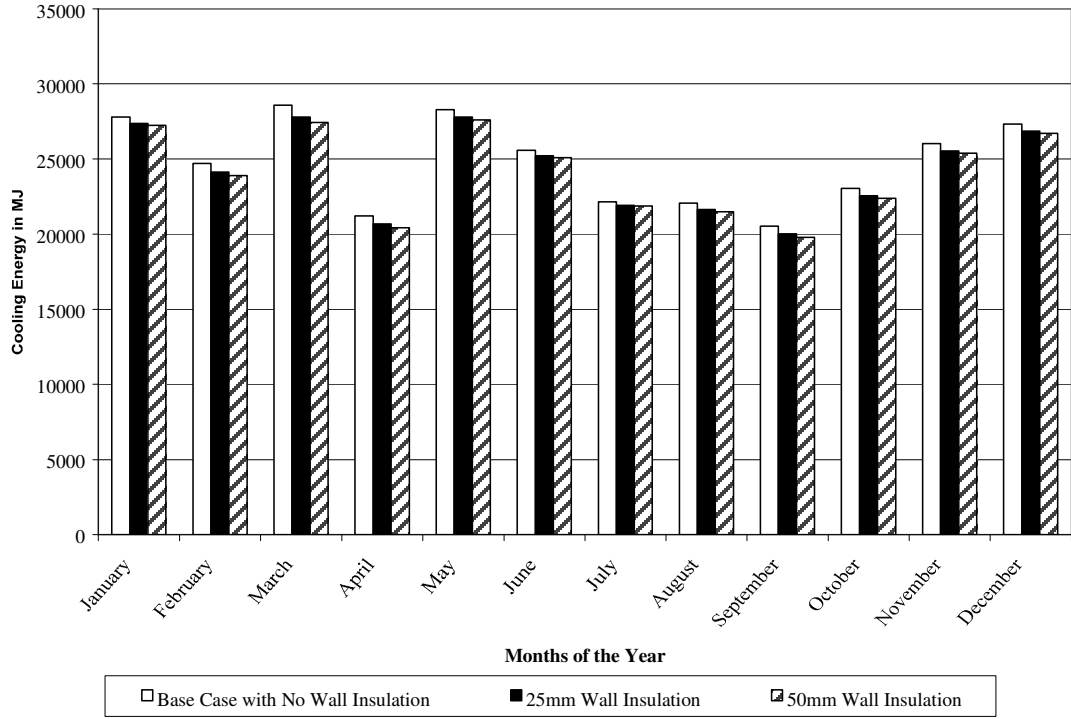
The monthly cooling energy for different cases of the office building is summarized in figures 5.16 – 5.20 and the annual value is given in table 5.6. Figures 5.21 and 5.22 show the daily cooling load variation for two arbitrary months.



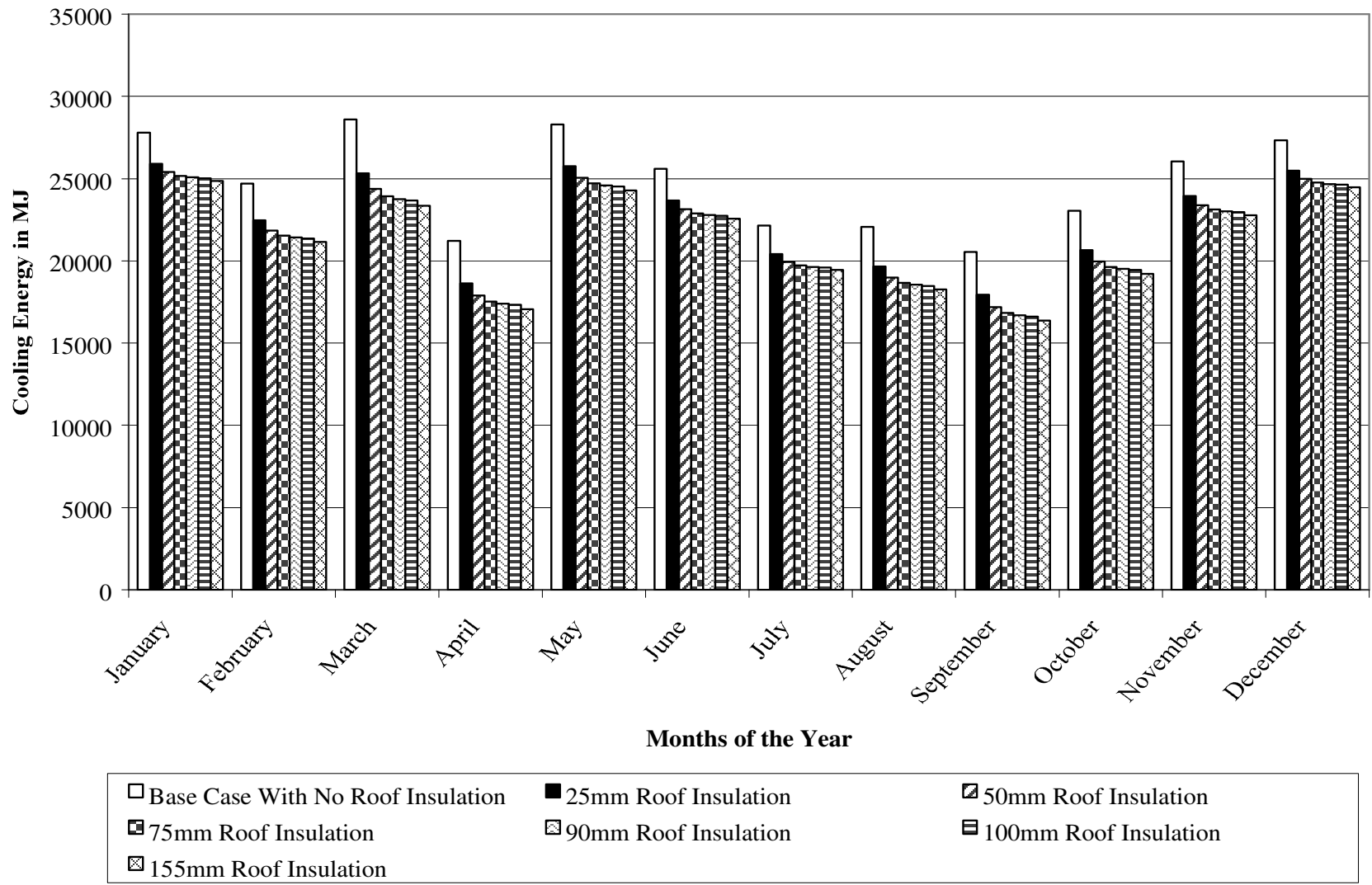
**Figure 5. 16** Cooling Load Variation due to color of External Walls for the Office Building

The effect of color in this building is the same as the residential building discussed above. The magnitude of energy saving may vary according to the size of the walls. The percentage saving of insulation in walls is very small compared to the residential building. Table 5.6 shows only 2.7% of the annual cooling energy can be saved using 50mm wall

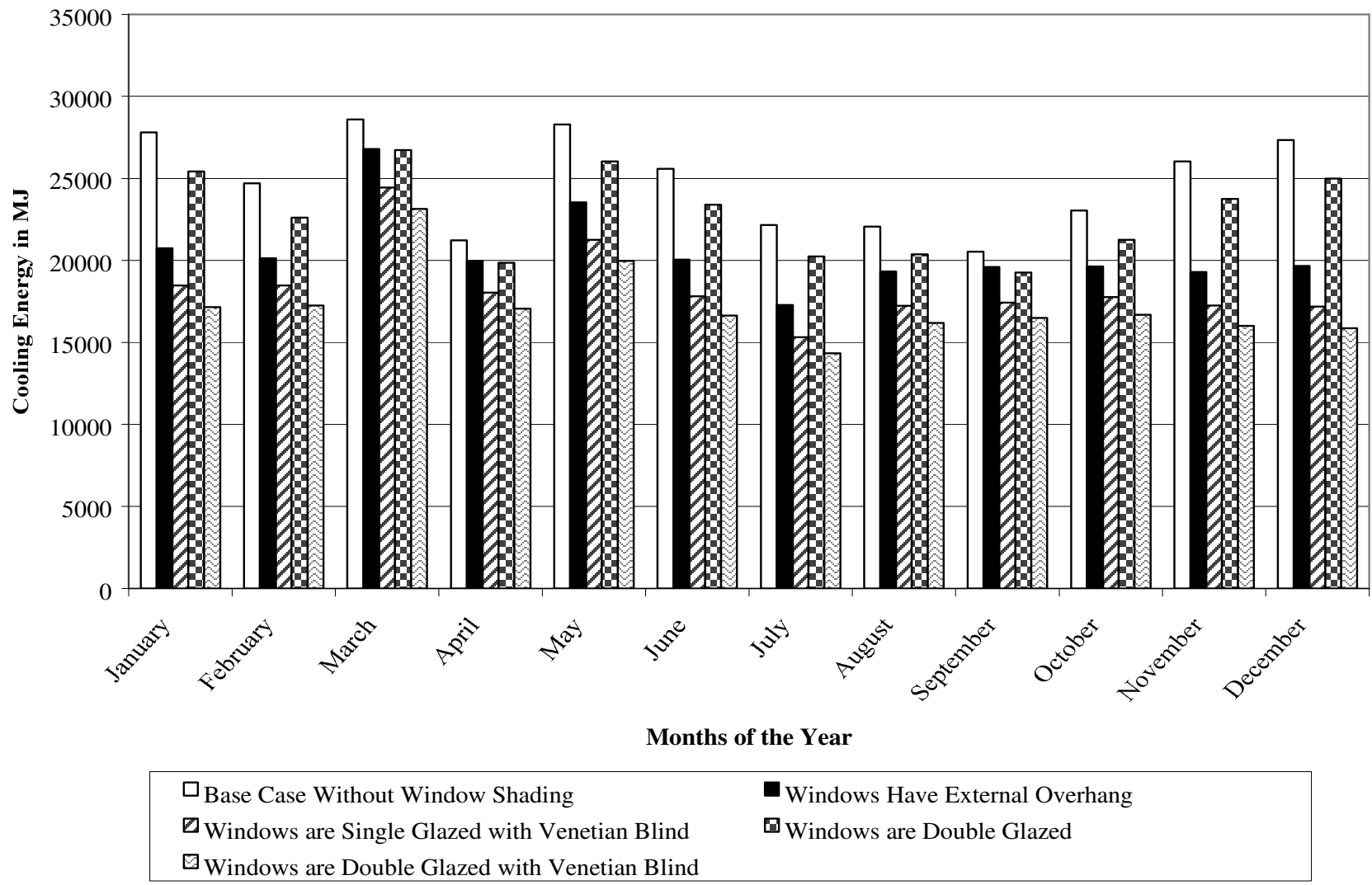
insulation. The effect of roof insulation decreases as compared to the residential building but still it has great impact on the annual cooling energy of the building. Table 5.6 shows that more than 9% of the annual cooling energy can be saved by using only 25mm roof insulation and this increase to 12% by doubling the insulation thickness. But window shadings saves large amount of energy as is shown from table 5.6 window blind can save up to 25.8% of the annual cooling energy while using 1m external overhang for window saves around 17% of the annual energy. These results reflect the effect of window size on cooling load. Since the building has large window size as compared to the walls, most of the heat gain will be the solar heat gain through windows. Hence shading windows gives the highest saving in such buildings rather than roof insulation. But in some cases where internal heat gain and heat gain through window dominates, using insulation can have a negative impact. This mean with increasing insulation the cooling load increases. This effect is discussed in the next section.



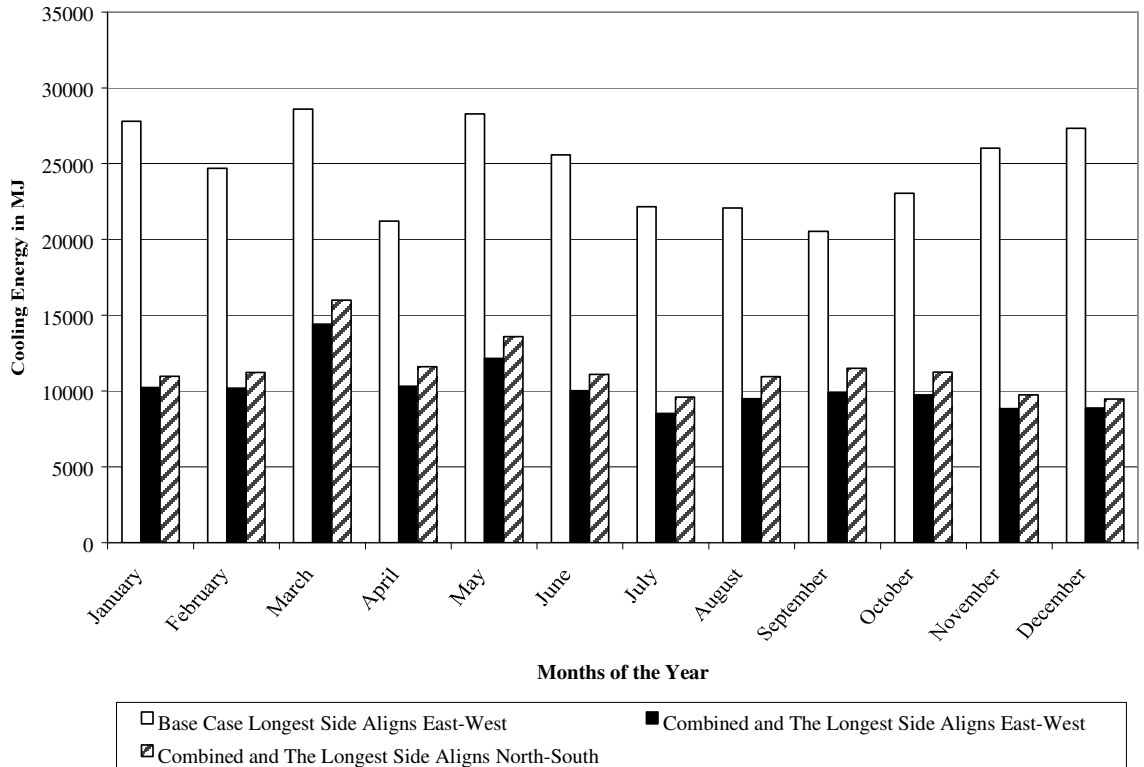
**Figure 5.17** Cooling Load Variation due to Wall insulation for the Office Building



**Figure 5. 18** Cooling Load Variation Due to Roof Insulation for the Office Building



**Figure 5. 19** Cooling Load Variation Due to Window Glazing and shading for Office Building

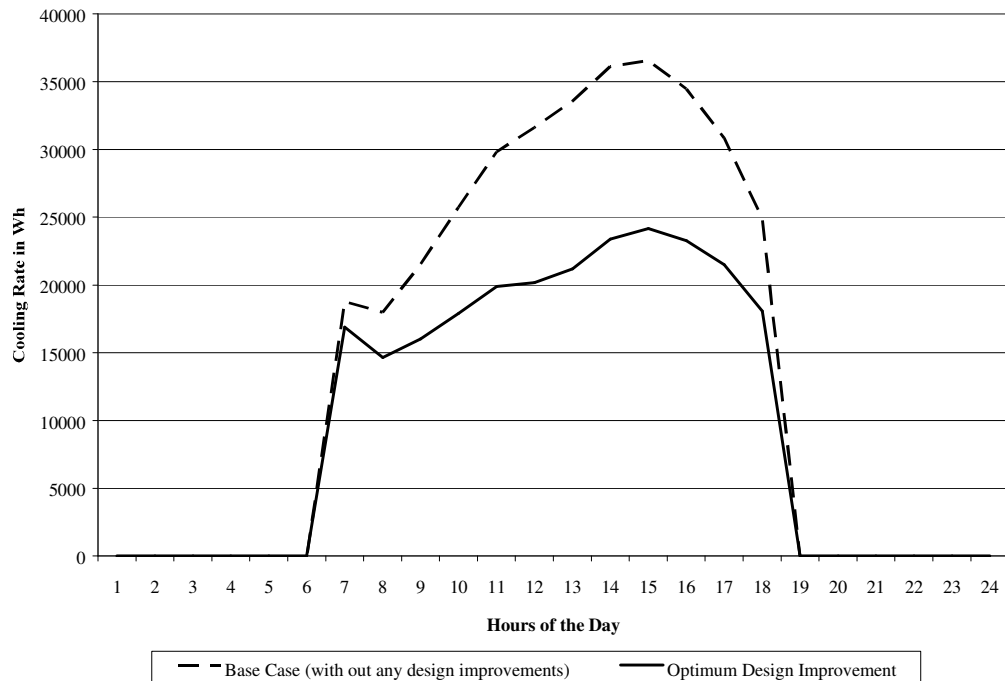


**Figure 5. 20** Cooling Load Variation Due to Orientation and Combined effect of the Parameters for the Office Building

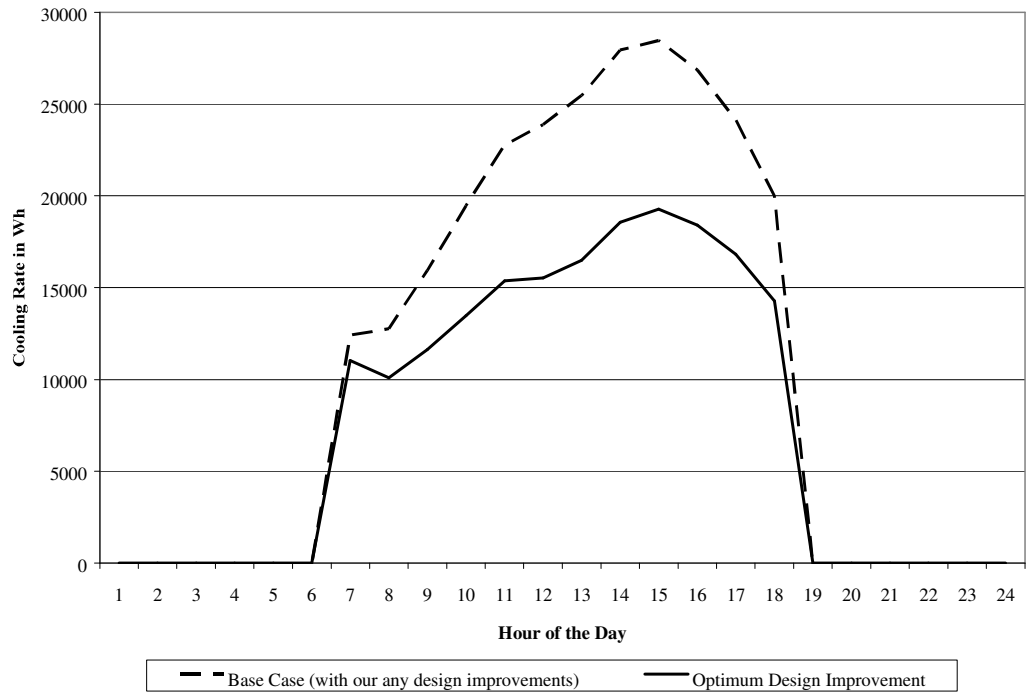
**Note:** combined means the building is modeled with external wall solar absorptance of 0.23, 50mm wall insulation, 155mm roof insulation, and windows are double glazed with Venetian blind and external over hang.

Figure 5.20 shows that facing the longest side or large size of windows to north or south is beneficial than facing to west or east. Table 5.6 shows that an increase in 5% of the annual cooling energy of the building is observed when the longest side of the building is aligning to north-south from the orientation such that the longest side is aligning with east-west.

The two figures below show the daily cooling load variation for two days of the indicated months. The abrupt change in the hours 06:00h and 18:00h is, the system is controlled to work only in the office hours i.e. from 06:00 to 18:00. The discontinuity between the hours 06:00 and 07:00 is, the system is off during the night so that there is a heat gain during this time which is not extracted and when the system is turned on at 06:00 it will work to extract the heat gain which was accumulated throughout the night and perhaps increase the cooling energy. After this the cooling load decreases at 07:00 and the system continue to remove the instantaneous loads. The discontinuity at 12:00 is due to the decrease of cooling energy because of launch time so that there are no occupants.



**Figure 5. 21** Daily Cooling Rate of Office Building for the Month March



**Figure 5. 22** Daily Cooling Rate of Office Building for the Month September

**Table 5. 6** Summary of the results of office building in Gode

<b>No</b>	<b>Type of construction</b>	<b>Annual Cooling Energy Consumption [MJ]</b>	<b>Annual Saving [MJ]</b>	<b>Annual Saving in [%]</b>
1	Base Case (with External Walls Solar Absorptance of 0.23) (WALL-01)	297363.65	-----	-----
2	Base Case (with External Walls Solar Absorptance of 0.92) (WALL-01)	343651.36	-46287.71	-15.57
3	Base Case and With 50mm Wall Insulation (WALL-02)	289322.39	8041.26	2.70
4	Base Case and with 25mm Wall Insulation Only (WALL-03)	91564.10	5799.55	1.95
5	Base Case and 25mm Roof Insulation Only	269865.57	27498.075	9.25
6	Base Case and 50mm Roof Insulation Only	262158.94	35204.71	11.84
7	Base Case and 75mm Roof Insulation Only	258511.44	38852.21	13.07
8	Base Case and 90mm Roof Insulation Only	257113.92	40249.73	13.54
9	Base Case and 100mm Roof Insulation Only	256374.10	40989.55	13.78
10	Base Case and 155mm Roof Insulation Only	253795.16	43568.49	14.65

*Table 5.6 Cont'd*

11	Base Case and External Overhang Shading for Windows Only	246035.98	51327.67	17.26
12	Base Case and Single Glazed Windows with Venetian Blinds	220656.23	76707.42	25.80
13	Base Case and Double Glazed Windows	273903.43	23460.22	7.89
14	Base Case and Double Glazed Windows with Venetian Blinds	206775.63	90588.02	30.46
15	Combined	122697.10	174666.55	58.74
16	Combined And East-West Orientation (Front Of The Building Faces West)	137001.56	160362.09	53.93
17	25mm Roof Insulation & Windows are Single Glazed with Venetian Blinds	187682.35	109681.31	36.89
18	50mm Roof Insulation, Windows are Single glazed with Venetian Blind and External Overhang Shading	164880.99	132482.66	44.55

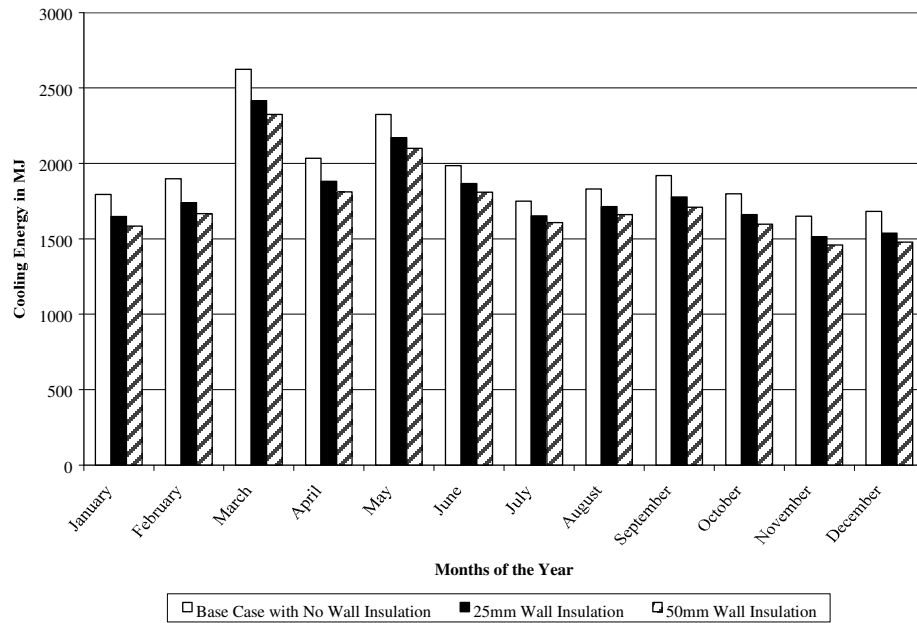
**Note:** Combined means the building is constructed using 50mm wall insulation, 155mm roof insulation, windows have 1m external overhang, windows are double glazed with external Venetian blinds.

## 5.6. Simulation and Result of a Single Room Building

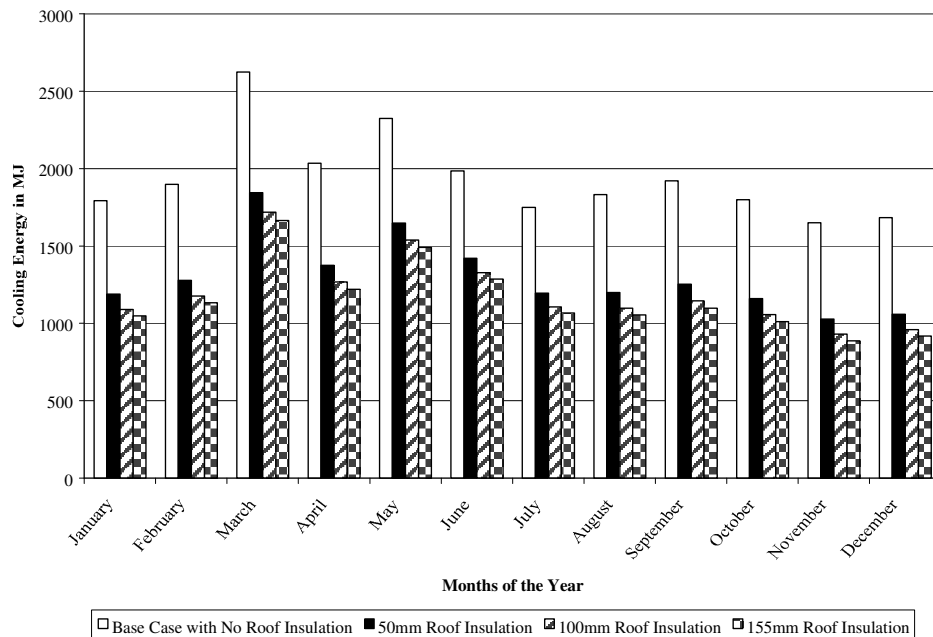
This is a single room building with 6m wide, 8m long and 2.8m floor to ceiling height. The base case is assumed with walls constructed from 200mm hollow concrete block with mortar plastering on both sides (Wall-01 Appendix A). The roof is corrugated steel sheet of 0.3mm thick with 8mm chipwood ceiling. The longest side of the room aligns in the east-west direction. This building is intended to clarify how insulation affects the total cooling load in different cases of internal load and different glazing size. Figures 5.23 - 5.24 and table 5.7 show the simulation results for the building where the glazing size on one of the longest side of the building is taken as small with area of  $3.8\text{m}^2$  (2m x 1.9m) and the number of people present in the room is assumed to be 4 while Figures 5.25 - 5.26 and table 5.8 show the result of simulation with large window size with an area of  $13.3\text{m}^2$  (7m x 1.9m) and the number of people are taken as 40.

For the first case where the window size is small and the number of people are less we can see from table 5.7 that using 50mm wall insulation can save about 10.6% of the annual cooling load while using 50mm of roof insulation can save about 33% and doubling the insulation thickness in roof rises the saving to 38% of the annual energy. But for the second case where the glazing size and number of peoples are increased, from figure 5.25 shows the cooling energy increases for some months which clarifies the negative impact of insulation table 5.8, using 50mm roof insulation saves only 15% and that of 100mm roof insulation gives a saving of 17% of the annual cooling energy. This result indicates that for such case where there is large glazing size and/or internal loads from people, light and

equipment dominates, using insulation in walls can have a negative impact on cooling load of the building.



**Figure 5. 23** Cooling Load Variation Due to Wall Insulation in Case of Small Window



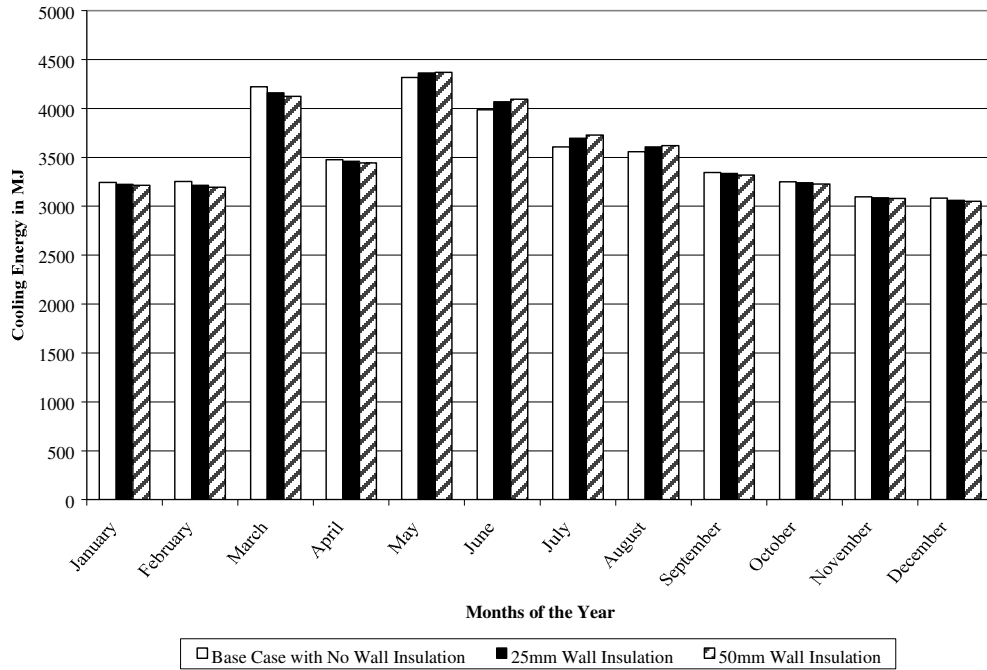
**Figure 5. 24** Cooling Load Variation Due to Roof Insulation in Case of Small Window

**Table 5.7** Summary of simulation results for the one room house with small window size and 4 people.

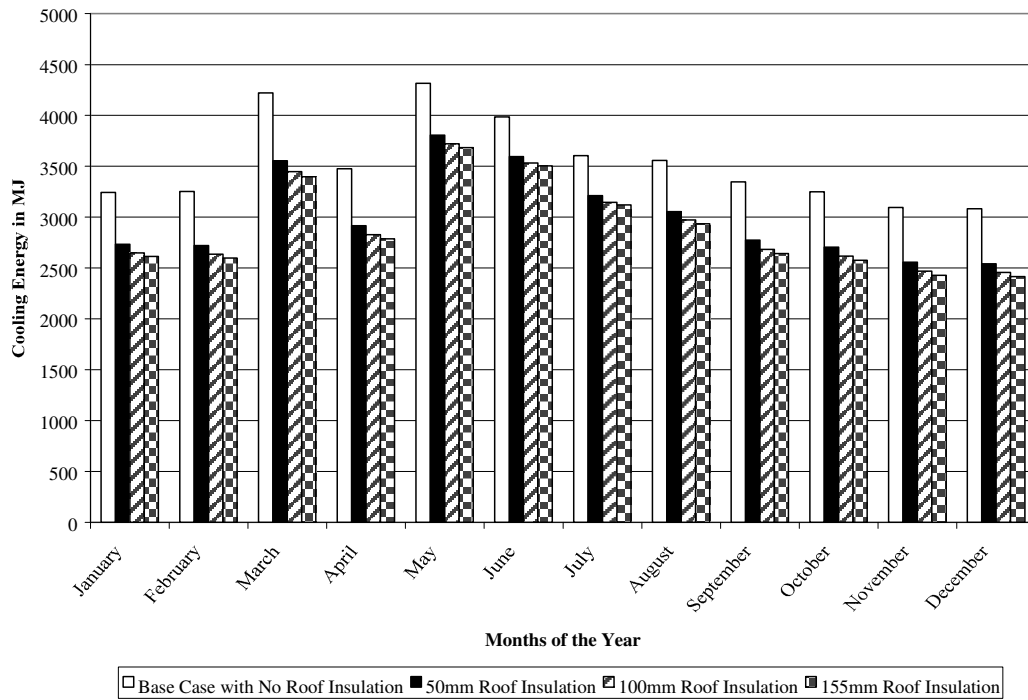
<b>No</b>	<b>Type of construction</b>	<b>Annual Cooling Energy Consumption [MJ]</b>	<b>Annual Energy Saving [MJ]</b>	<b>Annual Saving in [%]</b>
1	Base Case	23291.97	-----	-----
2	Base Case But Walls Have 50mm Insulation(Wall-02)	20809.38	2482.61	10.66
3	Base Case But Walls Have 25mm Insulation (Wall-03)	21575.10	1716.89	7.37
4	Base Case but Only Roof Has 25mm Fiberglass Insulation	17293.60	5998.38	25.75
5	Base Case but Only Roof Has 50mm Fiberglass Insulation	15638.82	7653.17	32.86
6	Base Case but Only Roof Has 75mm Fiberglass Insulation	14863.18	8428.80	36.19
7	Base Case but Only Roof Has 90mm Fiberglass Insulation	14568.16	8723.82	37.45

Table 5.7 Cont'd

8	Base Case but Only Roof Has 100mm Fiberglass Insulation	14412.56	8879.43	38.12
9	Base Case but Only Roof Has 155mm Fiberglass Insulation	13874.08	9417.91	40.43
10	Base Case but Only Windows Have 1m External Overhang Shading	22709.88	582.11	2.50
11	Base Case but Windows are Single Glazed With Venetian Blind	21984.65	1307.33	5.61
12	Base Case but Windows are Double Glazed	22802.44	489.55	2.10
13	Base Case But Windows are Double Glazed With Venetian Blind	21631.94	1660.05	7.13
14	Combined (Wall-02 + 155mm Roof Insulation+ Windows Double Glazed With Venetian Blind and External Overhang)	7504.62	15787.36	67.78
15	Combined But The Longest Side of The Room Lies To The North-South Axis	7790.88	15501.11	66.55



**Figure 5. 25** Cooling Load Variation Due to Wall Insulation in Case of Large Window



**Figure 5. 26** Cooling Load Variation Due to Roof Insulation in Case of Large Window

**Table 5. 8** Summary of Simulation Results for the One Room House with Large Window Size and 40 People.

<b>No</b>	<b>Type of construction</b>	<b>Annual Cooling Energy Consumption [MJ]</b>	<b>Annual Saving [MJ]</b>	<b>Annual Saving [%]</b>
1	Base Case	42425.53	-----	-----
2	Base Case But Walls Have 50mm Insulation(Wall-02)	42448.76	-23.23	-0.055
3	Base Case But Walls Have 25mm Insulation (Wall-03)	42503.96	-78.43	-0.19
4	Base Case But Only Roof Has 25mm Fiberglass Insulation	37521.83	4903.70	11.56
5	Base Case But Only Roof Has 50mm Fiberglass Insulation	36163.32	6262.22	14.76
6	Base Case but Only Roof has 75mm Fiberglass Insulation	35521.69	6903.84	16.27
7	Base Case but Only Roof has 90mm Fiberglass Insulation	35276.55	7148.98	16.85

Table 5.8 Cont'd

8	Base Case but Only Roof Has 100mm Fiberglass Insulation	35146.88	7278.66	17.16
9	Base Case but Only Roof Has 155mm Fiberglass Insulation	34695.00	7730.53	18.22
10	Base Case but Only Windows Have 1m External Overhang Shading	39807.99	2617.54	6.17
11	Base Case but Windows are Single Glazed with Venetian Blind	38065.58	4359.95	10.28
12	Base Case but Windows are Double glazed	41168.50	1257.03	2.96
13	Base Case but Windows are Double Glazed with Venetian Blind	37073.70	5351.83	12.62
14	Combined (Wall-02 + 155mm Roof Insulation+ Windows Double Glazed with Venetian Blind and External Overhang)	25588.17	16837.36	39.69
15	Combined but the Longest Side of the Room Lies to the North-South Axis	26584.92	15840.62	37.34

## 5.7. Economic Analysis

Energy price increases over a long period in this country. Most of the building materials like fiberglass insulation are imported from abroad. Thus, when installing insulation its economic analysis should be done and the optimum thickness should be determined. Thicker insulations can reduce the heat gain much but result in high investment cost while thin insulation result in higher heat gain and less investment cost. Hence a compromise between these should be done and this is done by calculating the total cost of the insulation. If it is assumed that the energy price increases linearly with annual rate of  $i_e$ , then the unit price of energy after  $j$  years from the present year is given by  $p_e(1 + i_e)^j$ . where  $p_e$  is the unit price of electrical energy in Birr/kWh. Since cash flows are spread over entire life of equipment, it is necessary to find their present values. Cash flows in the future are discounted by  $\frac{1}{(1+i)^j}$  or discount factor, where  $i$  is the interest rate and  $j$  is the number of years from the present when the cash flow is expected. The present value of the annual cost of energy savings after  $j$  years is then [4];

$$C_{E,a} = p_e E_a \left( \frac{1+i_e}{1+i} \right)^j \quad \text{----- 5.21}$$

where:  $E_a$  is the annual electrical energy consumption of the air conditioner in kWh and is

given by:  $E_a = \frac{q_a}{COP}$ ,  $q_a$  is the annual energy saving due to insulation in kWh and COP

is the coefficient of performance of the air conditioning system.

The present value of the energy savings during the pay-back period or useful life is evaluated by summing up the annual costs.

$$C_{E,T} = p_e E_a \sum_{j=1}^n \left( \frac{1+i_e}{1+i} \right)^j \text{-----} 5.22$$

The sum of the geometric progression in the above equation gives

$$C_{E,T} = p_e E_a \frac{1+i}{1-i_e} \left( 1 - \left( \frac{1+i_e}{1+i} \right)^n \right) \text{-----} 5.23$$

Therefore, the present value factor for energy saving is

$$PVF = \frac{1+i}{1-i_e} \left( 1 - \left( \frac{1+i_e}{1+i} \right)^n \right) \text{-----} 5.24$$

The viable investment cost for implementing energy conservation measures can be estimated from the present value of annual savings of energy cost during the useful life.

$$C_I = p_e E_a PVF \text{-----} 5.25$$

And the pay-back period can be calculated from a known investment cost as follows [4];

$$n = \frac{\ln \left( 1 - \frac{C_I}{p_e E_a} \frac{i-i_e}{i+1} \right)}{\ln \left( \frac{1+i_e}{1+i} \right)} \text{-----} 5.26$$

Now the total cost of insulation can be determined as the sum of the investment cost and the present value of the cost of heat gain across the insulation during its useful life [4].

$$C_T = C_I + p_e E_a \frac{1+i}{1-i_e} \left( 1 - \left( \frac{1+i_e}{1+i} \right)^n \right) \text{-----} 5.27$$

### ***Economic Analysis of Roof Insulation***

The above equation can be used to calculate the total cost and pay back period of the roof insulations used in both residential and office buildings that are simulated. The current

Ethiopian bank interest rate ‘*i*’ is 7.5%. The average electric power charge per kWh ‘*p<sub>e</sub>*’ is 0.48 Birr. It can be assumed that the price of energy increases linearly at a rate of 1% ‘*i<sub>e</sub>*’. The electrical energy consumption  $E_a$  can be calculated from the energy saving of the air conditioning system as:

$$E_a = \frac{0.277778(\text{Energy saved in MJ})}{COP} \text{-----} 5.28$$

where: 0.277778 is conversion factor from MJ to kWh

COP is the coefficient of performance of the system. It is taken as an average value of 3 [14].

The cost of fiber glass insulation in the foreign market is around \$0.65 per inch per m<sup>2</sup> area. Assuming that 100% of this cost is added for transportation, 50% profit, 50% installation cost, and all taxes including VAT(value added tax) are summed to 40%. Currently the conversion rate is 1\$ = 8.6Birr. Then the approximate total investment cost of insulation in Ethiopia is given by:

$$C_I = (\text{Foreign cost}) \times 2 \times 1.5 \times 1.5 \times 1.4 \times 8.6 \text{-----} 5.29$$

$$\Rightarrow C_I = 35.22 \text{ Birr per inch thickness per m}^2$$

Using equation 5.29 the approximate investment cost for different insulation thicknesses are summarized in table 5.9 below.

**Table 5. 9** Approximate cost for roof insulation in Ethiopia

	Insulation Thickness in mm					
	25	50	75	90	100	155
<b>Cost in Birr per m<sup>2</sup></b>	35.22	70.44	105.66	123.27	132.08	211.32

Using insulation minimizes the cooling load which in turn reduces the size of air-conditioning system (AC). Reducing the AC system size cuts the investment cost of the system. With the current condition in Ethiopian for small AC systems a minimum of 2000 Birr can be reduced for every kW of cooling load reduction and for large AC systems over 30kW capacity a minimum of 4000 Birr can be saved for every kW of cooling load reduction. These figures are minimum values and the actual ones are higher and in some cases it could be doubled. Hence this cost saving from the AC system is an additional profit due to insulation, thus this cost saving should be subtracted from the investment cost of the insulation. The saving from the AC system size reduction and the payback period of the insulation are summarized in tables 5.10 and 5.11 for the residential and office buildings respectively.

**Table 5. 10** Total cost and Payback Period of Roof Insulation of the Residential Building

<b>No</b>	<b>Insulation Thickness [mm]</b>	<b>Investment cost [Birr]</b>	<b>kW saving of AC system</b>	<b>Saving from the cost of AC system [Birr]</b>	<b>Pay back Period [Years]</b>
1	25	1102.2	0.480	960	0.55476
2	50	2204.5	0.618	1236	3.1992
3	75	3306.7	0.681	1362	6.4032
4	90	3857.8	0.705	1410	8.1949
5	100	4225.2	0.717	1434	9.5325
6	155	6613.4	0.762	1524	23.552

**Table 5. 11** Total cost and Payback Period of Roof Insulation of the Office Building

<b>No</b>	<b>Insulation Thickness [mm]</b>	<b>Investment cost [Birr]</b>	<b>kW saving of AC system</b>	<b>Saving from the cost of AC system [Birr]</b>	<b>Pay back Period [Years]</b>
1	25	11402	3.60	14400	1.00
2	50	22804	4.72	18880	2.64
3	75	34206	5.24	20960	10.00
4	90	39907	5.40	21600	15.46
5	100	43708	5.52	22080	20.29
6	155	68412	5.84	23360	-----

The above tables show that at the present cost with the current situation in Ethiopia 75mm thick roof insulation gives a pay back period of its cost in only 6.4 years. Thus, it is more economical for residential buildings and commercial buildings where there is small glazing area and less internal heat gain is present to use 75mm roof insulation. And for building where there is large glazing size and large amount of internal loads using 50mm roof insulation pay its cost in only 3years which makes it more economical than higher thickness if insulation. But with increase in cost of energy and if it is possible to produce fiberglass insulation locally a greater insulation thickness can be used for both residential and commercial buildings.

## **CHAPTER SIX**

### **CONCLUSION AND FUTURE WORK**

#### **6.1. Conclusion**

Design of energy efficient buildings is a burning issue these days throughout the world. The radical increase in cost of energy forces engineers and building designers to research on this area. This research is one of these efforts in our country and it will be a pioneer research for engineers in this country.

From the study it can be concluded that 75mm roof insulation which gives an annual saving of 23% is the most economical in building with small glazing area and less internal heat gain which gives a payback period of 6.4 years while 50mm roof insulation is better to use for buildings with large glazing area and large internal heat gain which offers a payback period of 3 years and an annual saving of 12%. Using external Venetian blinds for windows in large commercial building with large window sizes give a saving around 25% (table 5.6) of the annual cooling load and around 17% of the annual cooling load can be saved using 1m deep external overhang for windows. Using venetian blinds in external side of the glazing is more effective than in internal side. Generally, for buildings with small glazing area the best way to minimize cooling load is by using roof insulation while for buildings with large glazing area the best way to minimize the cooling load is to use either internal or external shadings for glazing.

In any building construction color of external envelopes will have a significant effect on energy consumption of the building. Using lighter color for external walls and roofs rather than dark colors saves a significant amount of cooling energy.

Orientation has also a good method to consider in energy efficient building design. Up to 5% of the annual cooling load can be reduced with proper orientation. If the building has large glazing area, it is better to face this side of the building to north or south. And if the glazing size is not significant align the longest side east-west.

The implementation of design improvements vary greatly from building to building and from place to place. This is because of the difference in the amount of heat gain of the buildings from different sources. The amount of cooling load in a building depends on the number of people present, glazing area, roof area, external color, size of openings, building material and etc. Hence design improvement for energy efficient building should be based on simulation results of the particular building. Then the most economical one can be implemented.

## 6.2. Future Work

As a future work it is recommend that the following to be included in further research.

- Energy saving from daylighting and lighting systems can be investigated in the simulation.
- Heat gain from HVAC systems can be investigated.
- Results from different design options of roofing such as concrete and clay tiles, wood roofing, asphalt roofing, and others can be investigated.
- Result from different design options for walls such as stone wall, bricks, mud and wood, wood, and steel walls can be investigated.
- Additional case studies for other hot areas of Ethiopia can be conducted.
- Ethiopian traditional way of house construction in the hot areas can be analyzed and their good aspect with respect to energy consumption can be included in the modern building designs.

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## APPENDIX

### Appendix A: Wall material properties and constructions used in the simulation

MATERIAL:Regular,C6 - 6 IN LW HOLLOW BLOCK, !- Material Name

MediumRough, !- Roughness

0.1500000 , !- Thickness {m}

0.3700000 , !- Conductivity {w/m-K}

881.0100 , !- Density {kg/m3}

830.0000 , !- Specific Heat {J/kg-K}

0.9000000 , !- Thermal Emittance

0.2000000 , !- Solar Absorptance

0.2000000 ; !- Visible Absorptance

MATERIAL:Regular,C7 - 8 IN LW HOLLOW BLOCK, !- Material Name

MediumRough, !- Roughness

0.2000000 , !- Thickness {m}

0.5700000 , !- Conductivity {w/m-K}

720.8300 , !- Density {kg/m3}

830.0000 , !- Specific Heat {J/kg-K}

0.9000000 , !- Thermal Emittance

0.2000000 , !- Solar Absorptance

0.2000000 ; !- Visible Absorptance

MATERIAL:Regular,E1 - 3 / 4 IN PLASTER OR GYP BOARD, !- Material Name

Rough, !- Roughness

9.9999998E-03, !- Thickness {m}

0.7200000 , !- Conductivity {w/m-K}

1601.840 , !- Density {kg/m3}

830.0000 , !- Specific Heat {J/kg-K}

0.9000000 , !- Thermal Emittance

0.2300000 , !- Solar Absorptance

0.2300000 ; !- Visible Absorptance

MATERIAL:Regular,CONCRETE - 3/4 IN MORTAR, !- Material Name

Smooth, !- Roughness

1.0000000E-02, !- Thickness {m}

0.7200000 , !- Conductivity {w/m-K}

1858.140 , !- Density {kg/m3}

830.0000 , !- Specific Heat {J/kg-K}

0.9000000 , !- Thermal Emittance

0.2300000 , !- Solar Absorptance

0.2300000 ; !- Visible Absorptance

MATERIAL:Regular,B2 - 1 IN INSULATION, !- Material Name  
VeryRough, !- Roughness  
2.0000000E-02, !- Thickness {m}  
3.9999999E-02, !- Conductivity {w/m-K}  
32.03000 , !- Density {kg/m3}  
830.0000 , !- Specific Heat {J/kg-K}  
0.9000000 , !- Thermal Emittance  
0.5000000 , !- Solar Absorptance  
0.5000000 ; !- Visible Absorptance

MATERIAL:Regular,B3 - 2 IN INSULATION, !- Material Name  
VeryRough, !- Roughness  
5.0000001E-02, !- Thickness {m}  
3.9999999E-02, !- Conductivity {w/m-K}  
32.03000 , !- Density {kg/m3}  
830.0000 , !- Specific Heat {J/kg-K}  
0.9000000 , !- Thermal Emittance  
0.5000000 , !- Solar Absorptance  
0.5000000 ; !- Visible Absorptance

!----- WALL TYPE ONE -----

CONSTRUCTION,

EXTWALL01, !- Material layer names follow:  
CONCRETE - 3/4 IN MORTAR, ! – Outside layer  
C7 - 8 IN LW HOLLOW BLOCK,  
CONCRETE - 3/4 IN MORTAR; ! – Inside layer

!-----WALL TYPE TWO-----

CONSTRUCTION,

EXTWALL02, !- Material layer names follow:  
CONCRETE - 3/4 IN MORTAR, ! – Outside layer  
C7 - 8 IN LW HOLLOW BLOCK,  
B3 - 2 IN INSULATION,  
E1 - 3 / 4 IN PLASTER OR GYP BOARD; ! – Inside layer

!-----WALL TYPE THREE -----

CONSTRUCTION,

EXTWALL03, !- Material layer names follow:  
CONCRETE - 3/4 IN MORTAR, ! – Outside layer  
C7 - 8 IN LW HOLLOW BLOCK,  
B2 - 1 IN INSULATION,  
E1 - 3 / 4 IN PLASTER OR GYP BOARD; ! – Inside layer

## Appendix B: Roof and ceiling material properties and constructions used in the simulation

MATERIAL:Regular,METAL - GALVANIZED STEEL , !- Material Name  
Smooth, !- Roughness  
0.3000000E-03, !- Thickness {m}  
45.31000 , !- Conductivity {w/m-K}  
7833.020 , !- Density {kg/m3}  
500.0000 , !- Specific Heat {J/kg-K}  
0.9000000 , !- Thermal Emittance  
0.2300000 , !- Solar Absorptance  
0.2300000 ; !- Visible Absorptance

MATERIAL:Air,E4 - CEILING AIRSPACE, !- Material Name  
0.1700000 ; !- Resistance {m2-K/w}

MATERIAL:Regular,IN02, ! Min.Wool/Fib Batt R-11  
Rough, !- Roughness  
2.500000E-02, !- Thickness {m}  
4.3000001E-02, !- Conductivity {w/m-K}  
32.00000 , !- Density {kg/m3}  
837.0000 , !- Specific Heat {J/kg-K}  
0.9000000 , !- Thermal Emittance  
0.7500000 , !- Solar Absorptance  
0.7500000 ; !- Visible Absorptance

MATERIAL:Regular,WOOD - SOFTWOOD 3 / 4 IN, !- Material Name  
MediumSmooth, !- Roughness  
8.0E-03 , !- Thickness {m}  
0.1100000 , !- Conductivity {w/m-K}  
512.5900 , !- Density {kg/m3}  
1380.000 , !- Specific Heat {J/kg-K}  
0.9000000 , !- Thermal Emittance  
0.7800000 , !- Solar Absorptance  
0.7800000 ; !- Visible Absorptance

!-----ROOF TYPE ONE -----

Construction,  
Roof1, ! – Name  
METAL - GALVANIZED STEEL, !- outside layer  
E4 - CEILING AIRSPACE,  
IN02,  
WOOD - SOFTWOOD 3 / 4 IN; ! - Inside layer