Assessment of Pattern of Energy Consumption with Varying Building Parameters

by

Gaurav Jain

A Thesis Presented in Partial Fulfillment
of the Requirements for the Degree
Master of Science

Approved November 2016 by the
Graduate Supervisory Committee:

Huei-Ping Huang, Chair
Yi Ren
Jay Oswald

ARIZONA STATE UNIVERSITY

December 2016

ABSTRACT

A large fraction of the total energy consumption in the world comes from heating and cooling of buildings. Improving the energy efficiency of buildings to reduce the needs of seasonal heating and cooling is one of the major challenges in sustainable development. In general, the energy efficiency depends on the geometry and material of the buildings. To explore a framework for accurately assessing this dependence, detailed 3-D thermo-fluid simulations are performed by systematically sweeping the parameter space spanned by four parameters: the size of building, thickness and material of wall, and fractional size of window. The simulations incorporate realistic boundary conditions of diurnally-varying temperatures from observation, and the effect of fluid flow with explicit thermal convection inside the building. The outcome of the numerical simulations is synthesized into a simple map of an index of energy efficiency in the parameter space which can be used by stakeholders to quick look-up the energy efficiency of a proposed design of a building before its construction. Although this study only considers a special prototype of buildings, the framework developed in this work can potentially be used for a wide range of buildings and applications.

DEDICATION

To my parents,
Suresh Kumar and Alka Jain

ACKNOWLEDGMENTS

Foremost, I would like to express my sincere gratitude to my advisor Dr. Huei-Ping Huang for the continuous support and guidance during my research. I could not have imagined having a better advisor for my research study.

Besides my advisor, I would like to thank Dr. Yi Ren and Dr. Jay Oswald for having agreed to be on my thesis committee.

Last but not the least I would like to thank my parents who always believed in me and sent me to graduate school for higher studies.

TABLE OF CONTENTS

Page

CHAPTER

CHAPTER Page

CHAPTER Page

APPENDIX

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

Figure Page

CHAPTER 1

INTRODUCTION AND METHODOLOGY

1.1 Introduction

Energy conservation is one of the important challenges that our society faces today. Energy consumption by buildings contributes a significant percentage to the total energy usage. Therefore, improving energy efficiency for homes and buildings is an important aspect of energy conservation. Heating and cooling of interior of buildings, in turn, is the largest component of the total energy consumption for buildings. A building is considered to have high energy efficiency if the daily temperature range inside the building is sufficiently reduced, compared to the outside temperature, due to the existence of building along. This energy efficiency depends on the geometry and the material of the building. An adequate assessment of the efficiency relies on detailed thermo-fluid simulation taking into account both heat transfer and thermal convection due to fluid flow inside the building. Moreover, such a three dimensional simulation should be subject to a realistic boundary condition with oscillating temperature from observation.

Given the complexity of computational problem in quantifying the energy efficiency of buildings, it is not trivial to define indices of the efficiency as a function of building geometry and material. (For some examples of the construction of such indices, see Deng et al. 2000 [13] and Schlueter et al. 2009 [14]). This generally leads to simplifications of the computation with some loss of accuracy. Given this background, in this study we will attempt to perform realistic 3D simulations with thermal convection for buildings with a wide range of geometrical parameters, using the outcome to more accurately define indices for energy efficiency of buildings. The result of this study will provide a framework for future upgrade of the definition of indices of energy efficiency which could potentially be used by stakeholders.

Due to the diurnal variation of temperature as the boundary condition, instead of seeking the steady state solution, transient 3D thermo-fluid simulations are needed in the aforementioned framework. This is computationally costlier. This study also attempts to assess the computational aspect of the required task for future construction of indices for energy efficiency. This is done by using the numerical simulation to extract the more relevant geometrical parameters that effect the energy efficiency of the building. Therefore, future constructions of indices can focus only on those small number of parameters.

1.2 Conceptual Framework and Methodology

The main tool for performing the 3D thermo-fluid simulation is computational fluid dynamic (CFD) solver that also incorporates the process of heat transfer. In general, many geometric parameters of building can affect energy efficiency. To maintain focus, we consider mainly the size of building, thickness and material of wall, and fractional area of windows. A large number of simulations are performed in the manner of parameter sweeping. Namely, multiple simulations are performed along the axis of each parameter. The outcome of the simulations is then analyzed to help determine the strongest dependence of energy efficiency on particular parameters. In this process, specific indices are defined as the time integrated difference between the envelope the diagonal cycle of inside cycle and threshold value that nominally represents the comfort level for human living inside the building.

Certainly, there are many different types of buildings with different purposes of usage. Although this work only considers numerical simulations for a prototype of buildings, the framework developed in this study can be adopted with minor modifications for other types of buildings and applications. Specifically, stakeholders such as city planners could use the indices predetermined by this framework to quickly assess the energy efficiency of a design of building based on only a set of parameters of the geometry and material of the building. The framework can also be used to pre-assess the design for special-purpose buildings with minimal energy consumption. For example, it is known that in the era before the invention of air conditioners, cities and dwellings exist even in regions with very hot climate. Typically, the buildings from that era share a design of having thick walls with highly thermally insulating material, relatively small interior, and small windows. Those buildings were livable even without air conditioners. It will be interesting to use our framework to reassess the energy efficiency of those buildings which might in turn provide new insights for modern design of sustainable buildings.

In the following, we start by constructing the time varying temperature boundary conditions from meteorological observations and testing them using 1-D and 2-D idealized models for heat transfer in Chapter 2. This allows us to first gain insights into the dependence of inside temperature on some of the geometric parameters of the building without taking into account the effect of fluid flows. In Chapter 3, the buildings with full

3-D geometry and with windows are used for the thermo-fluid simulations by the CFD solver. Buoyancy-driven thermal convection is turned on. The outcome of parameter sweeping numerical experiments are used to quantify the indices for energy efficiency of buildings. The results are further synthesized and future work suggested in Chapter 4.

Chapter 2

TEMPERATURE MODELING, BUILDING MODEL DEVELOPMENT

2.1 Introduction

This chapter summarizes diurnal temperature estimation algorithm for Phoenix, Arizona. Hourly temperature measurements from a weather station were used to develop a diurnal temperature variation model. First two harmonics of the Fourier series for interpolating the temperature T_{0uter} at time t is estimated by

$$T_{0uter} = A_0 + A_1 \cos(wt) + B_1 \sin(wt) + A_2 \cos(2wt) + B_2 \sin(2wt)$$

Where $w = \frac{2\pi t}{24*60*60}$

Coefficient vectors A and B were computed by use of orthogonality relation onto a basis of Sine and Cosine functions.

The chapter also presents the development and solving of numerical equations in case of 1-D and 2-D in Matlab and Ansys respectively. Energy balance equations are solved by applying appropriate assumptions. Subscripts inner and outer are used to indicate the inner and outer spaces of room respectively.

2.2 Temperature Modeling

Our earth receives heat from the sun and at the same time loses heat in the form of infrared radiations continuously. During the day heat gained by earth from sun is dominant as compared to lost by earth while in night heat lost is dominant because there is no sun. Therefore, daily rotation of earth about its axis causes diurnal temperature variation and change of tilt angle of axis causes seasonal temperature variation. Trigonometric functions can be used to model the oscillatory phenomena of diurnal and seasonal temperature variations. Taking it into consideration, Fourier transform is used for deriving ambient temperature variation equations for both summer and winter for location.

For July-

$$T_{0uter}(t) = 90.7 - 3.5\cos(wt) - 8\sin(wt) + 0.7\cos(2wt) + 0.3\sin(2wt) \qquad (2.1)$$

For January-

$$T_{0uter}(t) = 51.8 - 5.6\cos(wt) - 9.4\sin(wt) + 0.9\cos(2wt) + 2.47\sin(2wt) \qquad (2.2)$$

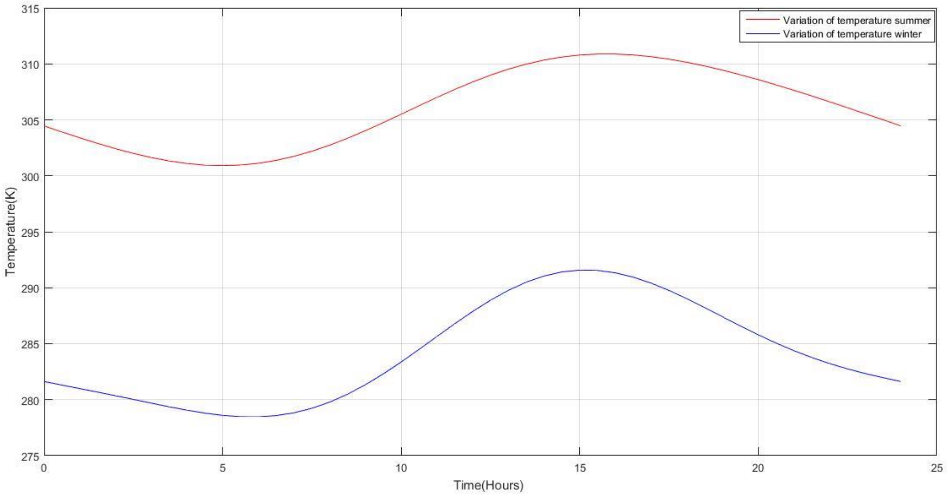


Figure 2.1: Hourly Variation of Temperature for Day Averaged over Month for Phoenix Based on Statistics from Encanto Weather Station

2.3 Building Model Development

2.3.1 One-Dimensional Model

A transient, one-dimensional thermal model for a building is developed to investigate the variation of inside temperature over ambient conditions. The model is constructed by applying the conservation of energy on the whole model. In order to get a smooth transition in the thermal properties at the intersection of wall and air, a hyperbolic tangent function was used that smoothly switches between two values at a defined point. The problem consists of determining the temperature history inside solid wall and in the air in the room.

2.3.1.1 Model Assumptions

- The heat transfer in model is one-dimensional and is only through conduction.
- All material thermal properties are constant with temperature.
- Thermal contact resistance is neglected.
- There is no heat loss through convection or radiation.

2.3.1.2 Energy Equation

The schematic of the thermal resistance network of building is shown in Fig. 1. Principle of conservation of energy was applied to obtain the governing equation of temperature. The energy equation is written as:

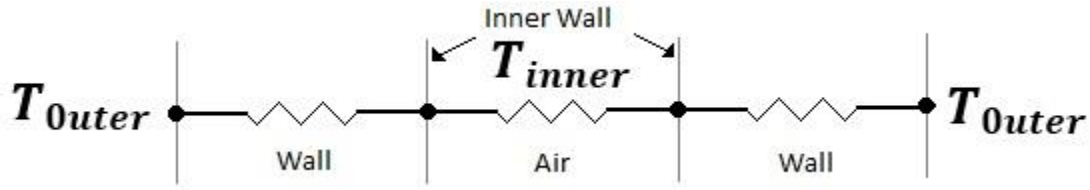


Figure 2.2: Thermal Resistance Model of Building

$$\frac{\partial T}{\partial t} = \frac{1}{\rho(x)c(x)}\frac{\partial(k(x)\frac{\partial T}{\partial x})}{\partial x} \tag{2.3}$$

Where $k(x), p(x) and\ c(x)$ are formulated hyperbolic tangent function as discussed earlier as:

$$k(x) = k_1 + \frac{1}{2}(k_2 - k_1)\big(1 + \tanh(\propto (x - x_1))\big) - \frac{1}{2}(k_2 - k_1)\big(1 + \tanh(\propto (x - x_2))\big) \tag{2.4}$$

Where $\propto$ is coefficient of smoothness of hyperbolic curve

In equation 2.3, The term on the left hand side is the rate of change of temperature, the term on right hand side is the conduction heat transfer. The initial conduction in the model is presumed to be uniform with ambient temperature at that time at all locations in the model. This initial condition was chosen taking into consideration the worst case when there is no heat transfer in the model due to uniform temperature everywhere.

2.3.1.3 Imposed Boundary and Initial Conditions:

Outside the wall, at x=0 and x=L, temperature boundary condition in form of $T_{0uter}(t)$ is applied at all times. For all x, when t=0, the initial temperature is $T_{0uter}(0)$.

2.3.1.4 Design Parameters of Model

Assuming Total Length of room (including walls) (L)= 10m

Thickness of Walls (T)=0.5m

2.3.1.5 Numerical Implementation

This problem is based on transient heat conduction. Further, there is variation of thermal properties along direction. As problem is difficult to be solved analytically so we resort to numerical solution.

Finite difference and finite element method are two methods that are most widely used for numerical solution of partial differential equation of heat and mass transfer. Each method has its own advantages and disadvantages. Finite difference methods are relatively simple to formulate as compared to finite element methods and give satisfied results in case of simple geometries.

The governing equations were discretized using the finite difference method. Explicit technique was used in solving equation involving forward time and central difference displacement derivatives. The general discretized equation for ith point can be written as:

$$T_i^{n+1} = A_i T_{i+1}^n + B_i T_i^n + C_i T_{i-1}^n$$

Where A_i, B_i, C_i are constant and depend on material properties and boundary conditions; $T_{i+1}^n, T_i^n, T_{i-1}^n$ are temperatures of node i and neighborhood nodal points at current time step. And T_i^{n+1} is the temperature at the next time step at node i. This method results in a system of linear algebraic equations in terms of temperature, T. Solving these equations require matrix inversion. But MATLAB has some in built functions which require less efforts to solve these equations. Therefore, hand written system of equations described above was translated into MATLAB for setting up numerical solution.

2.3.1.6 Numerical Stability

Numerical stability is the most important condition for convergence of the solution. Round off errors incurred during calculations may make the solution worse. Barring the amplification of round off errors is necessary for explicit method to give stable solution. This particular explicit method is stable, if and only if

$$\Delta t \leq \frac{\rho c (\Delta x)^2}{2k} \tag{2.5}$$

Where Δt is time step size, ρ is density, c is specific heat capacity, Δx is position step size and k is thermal conductivity of the material.

2.3.1.7 Results and Discussion of 1-D

After successful completion of numerical simulation using MATLAB, results were presented in the form of plot. Two things were of keen interest in the post simulation results: the shape of temperature profile as a function of time; the temperature distribution throughout the domain. The solution profiles of variation of temperature inside building from our well-balanced numerical scheme are depicted by the Figures 2.3-2.6. It is clearly visible that the temperature in the room is an increasing function of time initially till it reaches a stage where variation of temperature is very small and is within some specific range of temperature. And it is actually in line with our observation in our daily life in which it reaches nearly steady temperature after a long period of time.

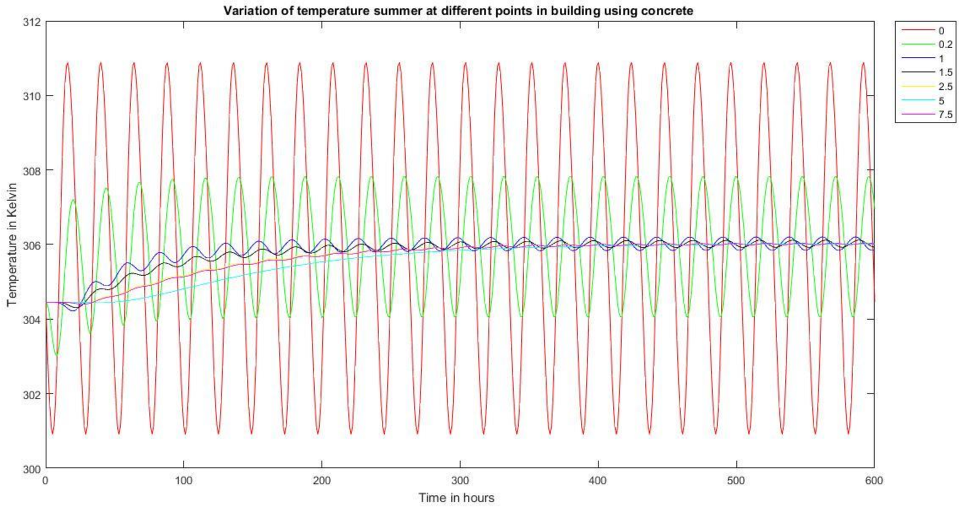


Figure 2.3: Temperature Profile at Different Positions as a Function of Time in Summer

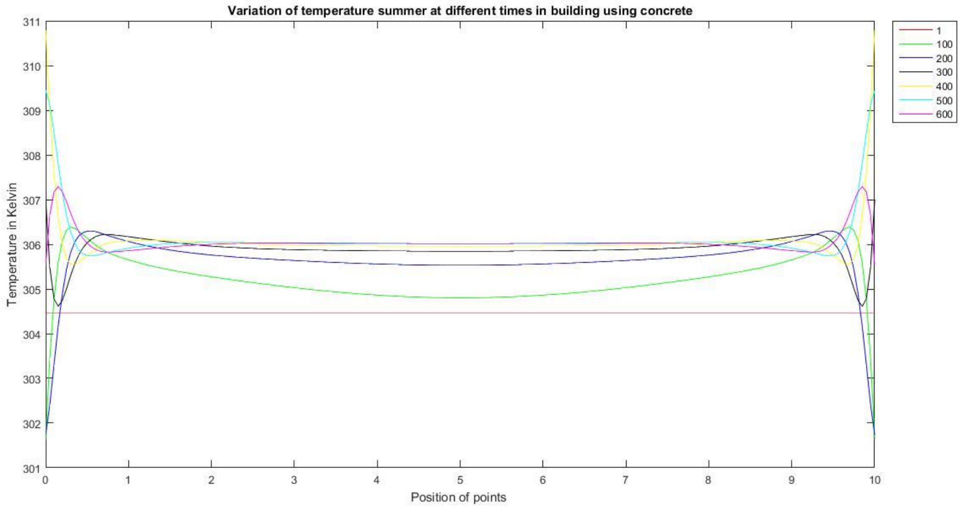


Figure 2.4: Temperature Distribution During Different Times in Summer

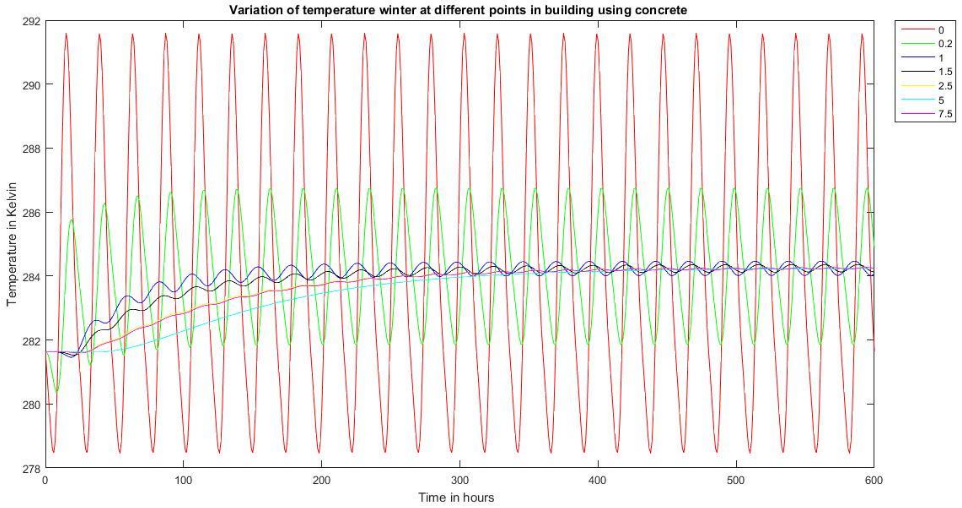


Figure 2.5: Temperature Profile at Different Positions as a Function of Time in Winter

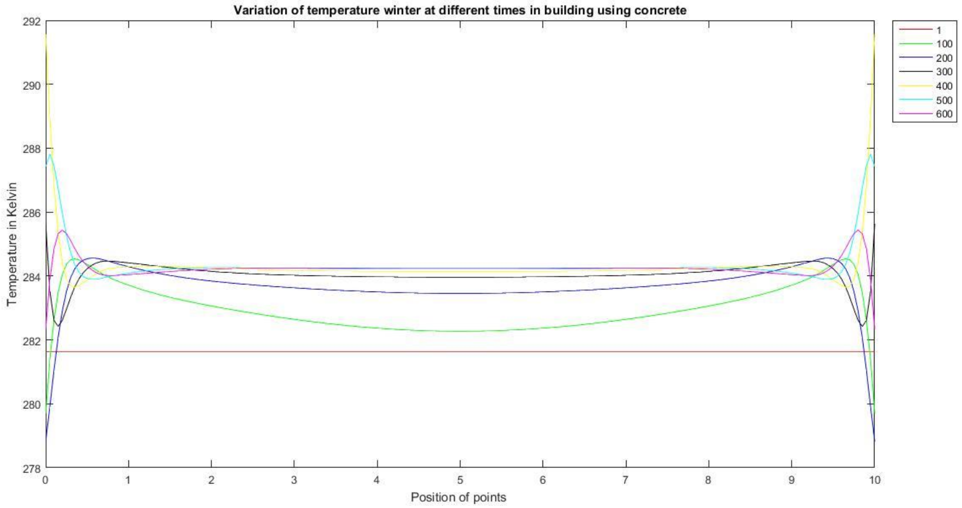


Figure 2.6: Temperature Distribution During Different Times in Winter

Further from the plots it is visible that the points which are nearer from the outside part of wall has more temperature variation as compared to points within the room. This is because of the fact that information regarding variation of temperature outside the room takes more time to reach to the center of the room as compared to points near the wall of the room.

2.3.1.8 Limitations

The study of 1-Dimensional case although provided good idea of inside temperature as compared to ambient diurnal temperature variation but still results are limited by some assumptions. One assumption is that heat transfer through the building is 1-Dimensional which is obviously not true in reality. Also there couldn’t be any real building which doesn’t has windows in it. But a solution to overcome second assumption could be to solve the problem in 2D planar model in which we could introduce glass also in the system using glass and heat will also be transferred laterally also in the cylinder. But this creates multiple complex, time dependent heat- transfer partial differential equations which are difficult to solve using MATLAB coding.

2.3.2 Two-Dimensional Planar Model

As discussed in the last section, one Dimensional case is the most ideal process of heat transfer in a building. Because, in modeling 1-D heat transfer problem it is assumed that heat transfer is only in one direction. Further in actual rooms you would find glass also in addition to wall enclosing the room. To bypass the second assumption, I introduced the 2-Dimensional planar model.

Tremendous progress of Computational Fluid Dynamics (CFD) today has given us the privilege to use fast and reliable software packages to solve complex system of equations rather than developing MATLAB code for them. In this section, I will first discuss how the glass effects in a building are modeled in my simulation. The system is modeled using Ansys design modeler to create needed geometry and Ansys fluent was used to implement boundary conditions and carry out simulations.

In this section, the heat transfer in a building is modeled. The heat flow is assumed to be two dimensional therefore cylinder can be represented as a circle. A domain surrounding the air enclosure in the form of hollow cylinder is created and meshed. Boundary conditions and initial conditions are applied to the simulation to obtain plots of static temperature at center-point and average.

2.3.2.1 Purpose

To achieve more realistic results, when investigating the variation of temperature inside a building with respect to outside, the 1-Dimensional model need to be upgraded to 2-Dimensional to include the effect of glass in the building. The purpose of this section is also to investigate how a building can be modeled in 3D in Ansys Fluent, which extra parameters could be added to the model to get more realistic results and to find out how closely the results of 2-D matches to 3-D models so as 2-D models could be used in future for rest of the simulations to save computational time.

2.3.2.2 Assumptions

- The heat transfer in model is two-dimensional and is only through conduction.
- All material thermal properties are constant over the temperature range considered.
- Thermal contact resistance is neglected.
- There is no heat loss through convection or radiation.
- It is assumed that temperature at all zones in the model is same as outside temperature as initial condition of the simulations.

2.3.2.3 Design Parameters of Model (Gothe et al. 2015, [8] pp 18-19)

Dimensions in m

Assuming Outer Diameter of room (D)= 10m

Thickness of Wall (T)=0.5m

Thickness of Glass (t)=0.05m

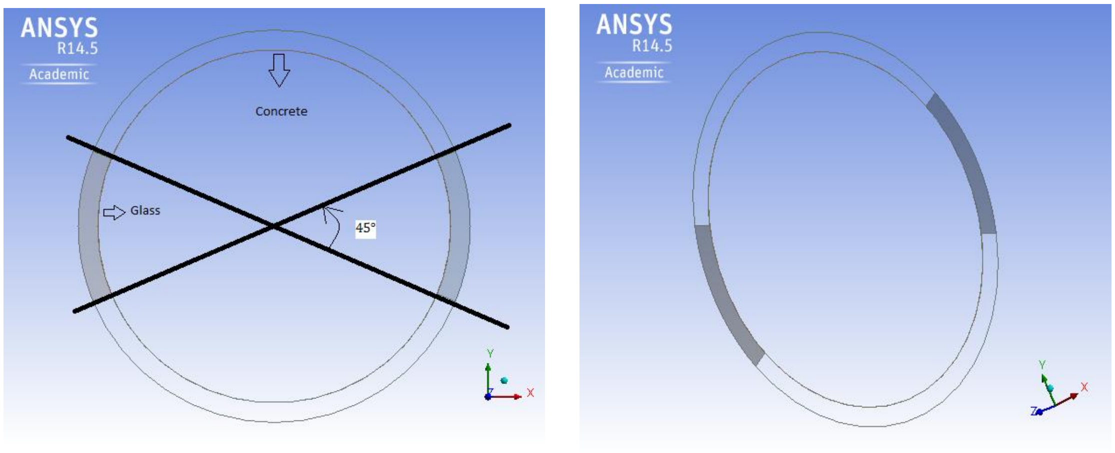


Fig2.7 Two-Dimensional Model of Building

Table 2.1 Element Types

SL NO	TYPE OF ANALYSIS	ELEMENT TYPE
1	2-DIMENSIONAL	2D PLANAR

Table 2.2 Material Properties

MATERIAL	PROPERTY	VALUE
AIR	DENSITY (Kg/m^3)	1.1777
	SPECIFIC HEAT (J/Kg-K)	1005
	THERMAL CONDUCTIVITY (W/m-K)	0.02619
	Viscosity	1.85E-05
GLASS	DENSITY (Kg/m^3)	2500
	SPECIFIC HEAT (J/Kg-K)	800
	THERMAL CONDUCTIVITY (W/m-K)	80
CONCRETE	DENSITY (Kg/m^3)	2307
	SPECIFIC HEAT (J/Kg-K)	658
	THERMAL CONDUCTIVITY (W/m-K)	1.3699

Table 2.3 Boundary Conditions

Location	Value
Outer side of building	User-Defined Function

Table 2.4 Initial Conditions

Location	Value
All zones	Initial temperature of UDF

2.3.2.4 Meshing

In order to analyze internal temperature variation, the domain is split into small control volumes, also called cells, which together form a mesh. For 2-Dimensional simulations, mesh can be built with quadrilaterals or triangles. During simulation in ANSYS FLUENT, the governing equations in the below section are discretized and solved over each cell by the finite volume method working behind software.

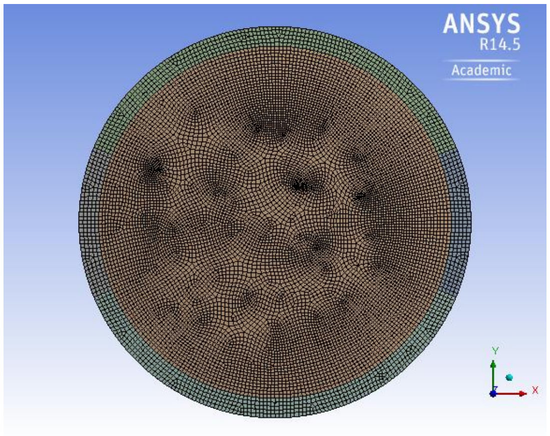


Fig2.8 Meshing of Model

2.3.2.5 Governing Equations

As there is no movement of air in the system. So, only energy equation was used for solving the system. And energy equation is written as:

$$\frac{\partial(\rho h)}{\partial t} = \nabla.(k\nabla T) \qquad (2.6)$$

Where ρ is density, k is conductivity, T is temperature and h is sensitive enthalpy $(c_p dT)$

2.3.2.6 User-Defined Function

Ambient temperature boundary condition was introduced in the model by translating the sinusoidal temperature variation equation as described in section 2.2 in the form of user-defined function which could be compiled in Ansys Fluent. Ansys Fluent has provided with the privilege of writing UDF in C programming language with the specialized syntaxes of Ansys which are given in its user guide.

The customized settings are defined with DEFINE macros. In the UDF, DEFINE_PROFILE macro is used to define profile of temperature variation outside the building. The UDF for 2D and 3D simulations are similar. The UDF used in 2D and 3D simulations are attached in Appendix B.

2.3.2.7 Numerical Settings in Ansys Fluent

The transient simulation was first carried out for a week but no significant change in temperature variation of temperature in building was find out. This was due to the fact that as heat transfer is based completely on conduction in the model which results in the slow rate of transfer. Therefore, then simulation was carried out for a period of a month with time step size of 2000secs and number of steps as 1296.

In order to activate the calculation of heat transfer, the **Energy Equation** option in the **Energy** dialog box was enabled. The material in the cell zone was declared.

2.3.2.7.1 Boundary Conditions

Thermal boundary conditions at the outside part of wall was defined by user-defined function described before. Since the problem was involving three different regions of concrete, glass and air, therefore, separate properties were established by selecting different material for each zone. As problem involves, solid-fluid boundary, therefore, fluent uses the coupled thermal boundary condition since there are cells on both sides of the wall.

2.3.2.7.2 Monitors

For the simulation all residuals had default value of 10^{-3}. Except it surface and volume monitors were set up to collect the values of center-point and average temperature respectively.

2.3.2.8 Results and Discussion of 2-D

Once optimized the 2-D CFD model unsteady simulation was carried out on the model. As described earlier, 2-D model is more helpful and realistic in understanding heat transfer in a room. The results of this model are based on center-point and average temperature approach. The calculated temperature histories are shown in figure 2.9

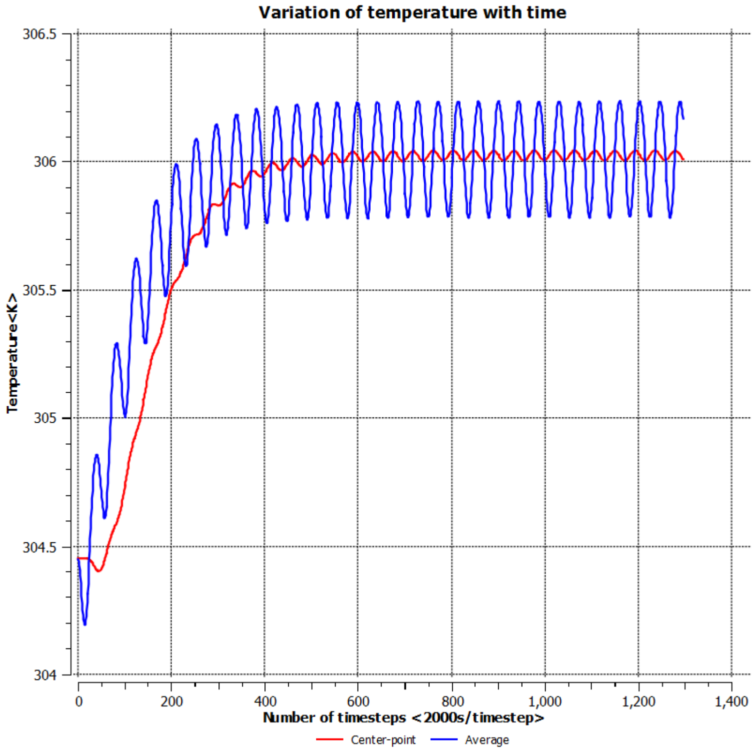


Fig 2.9 Two-Dimensional Results

The results are quite similar to one-dimensional case because here also variation in temperature comes in stable range roughly after 400 time steps which is (222hrs).

2.3.2.9 Limitations

Although 2-Dimensional case gave the effect of introducing a glass in the building but still it is far off the realistic situation because in actual world this variation is actually too large. This is due to limits of 2D model that doesn’t take into account 3D effects. Taking into account this thing a better methodology was used to develop a 3D CFD model with additional parameters which is explained in next chapter.

Chapter 3

THREE-DIMENSIONAL MODEL AND ENERGY CONSUMPTION INDEX

3.1 Introduction

As discussed earlier, although 2-D case gave predictive results but still the temperature variation inside room was too slow as compared to realistic situation. One reason could be that in real buildings the information of change in temperature outside the building reaches to center-point very fast. This thing is possible if there is movement of air due to convection in the room. This brought me with the idea of introducing concept of natural convection into the picture. The air near the glass will be hotter and will be lighter and will try to replace itself with the colder air nearby in the building and this will tend to movement of air in the building. But this thing was not possible in 2-Dimensional. So, 3-Dimensional model came into picture.

A simplified design of building model for purpose of analysis is shown in figure 3.1, in which glass is also included in the building. Details of general numerical algorithm used to deal with heat transfer due to only conduction due to walls in form of one-dimensional equation were documented in previous chapter in which we introduced finite difference based on governing equation from principle of energy conservation. Then we dealt the effect of introducing glass in two dimensional case in which we introduced finite volume method for solving equation using Ansys fluent. The main intent of this chapter is to extend the 1-D and 2-D algorithm to the 3-Dimensional implementation of the finite volume numerical scheme for buildings so as to include the effect of natural convection also inside building.

This study uses the ANSYS Fluent, for the modeling and simulation of the energy consumption of building models. Numerical models used for the analysis and boundary conditions are introduced. The computational results are then validated against 2-Dimensional results. For the calculations, sinusoidal equation of temperature variation in summer and winter modeled using Encanto, Phoenix weather station data (as described in previous chapter) and a model of the building was used. A parametric study is followed to study the influence of various measures on the energy consumption of a building. The measures examined are thickness of wall, window-wall ratio, ventilation, material of walls and enclosure space of building.

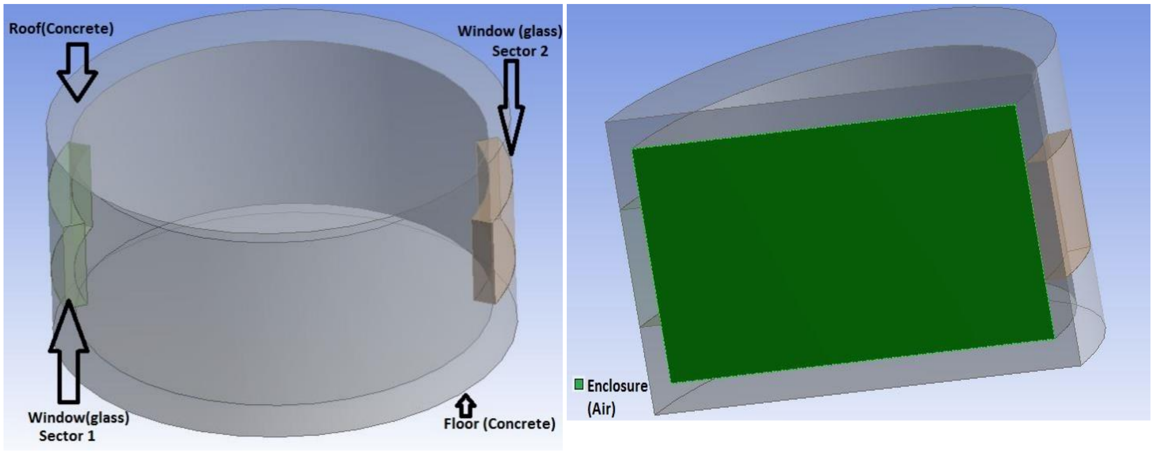


Fig 3.1 Schematic of Typical Building

3.2 Shape of Building

This section reviews my approach to the analysis of energy consumption as function of different parameters. The building form is a perfect cylinder, each surface of which is of homogenous material with a given density, specific heat capacity and thermal conductivity values. The walls, roof and floor are made of concrete. Only two sectors of windows oppositely facing each other are considered instead of number of windows in the wall. The model house is further divided into four identical zones. These simplifications proved to be important in saving the computational time.

Some other assumptions and approximations were also introduced in the model. As the first approximation actual thermal conductivity of glass used in model was normalized according to thickness of wall. It was done so that even if thickness of glass is different from thickness of wall actually but in geometric model we could use thickness of glass as same as thickness of wall and changed thermal conductivity (normalized according to thickness of wall) to simplify the analysis. The new thermal conductivity of glass is given by: $K_{new\ glass} = (\frac{T}{t})^2\ K_{old\ glass}$ where T and t are thickness of wall and glass in actual design respectively. This equation is obtained by non-dimensionalizing the partial differential equation of heat transfer.

It can also be assumed that no heat transfer occurs between building and ground as in actual buildings also floor is almost adiabatic. Even if we consider heat transfer through floor then as all the outer surfaces of building would be at same temperature, therefore, there would be no chance of natural convection in the building.

3.3 Boussinesq Equation (Ansys Fluent user guide [21])

There are two methods to setup natural convection flows. First is setting up fluid density as a function of temperature. Second is using Boussinesq model. The advantage of using second is that it gives fast convergence in case of many flows. The limitation of this model is that it is applicable only when temperature difference in domain are not so large.

To account for natural convection in the building it was used. As air is considered as almost- incompressible fluid, so density variation is very small. Therefore, in inertial term in momentum equation, we may substitute density ρ as constant ρ_o. However, still small density variations are important in buoyancy so we keep the variation of density in buoyancy term in vertical direction.

$$\rho\frac{du}{dt} = -\nabla p - g\rho\hat{z} \tag{3.1}$$

(Here $\hat{z}$ is the upward unit normal.)

Using Boussinesq approximation

$$\frac{du}{dt} = -\nabla\varphi - b\hat{z} \tag{3.2}$$

Where b is buoyancy, which is defined as $b = \frac{g(\rho_{\,o} - \rho)}{\rho_{\,o}}, \varphi = \frac{p}{\rho_{\,o}}$

$$(\rho - \rho_{\,o})g \approx -\rho_{\,o}\beta(T - T_o)g \tag{3.3}$$

Where $\rho_{\,o}$ is constant density of flow, T_o is operating temperature, β is the thermal expansion coefficient.

Steps used in solving Buoyancy driven flows in ansys fluent are given below:

- Turn on gravity in operating conditions panel and set the gravitational acceleration in Cartesian co-ordinates by setting appropriate value in x, y and z.
- Specify the operating temperature in the operating conditions panel which was average temperature of room in our case.
- In the materials panel, set the Boussinesq as the method for density and set appropriate density at operating temperature. Also set the thermal expansion co-efficient.

3.4 Key Parameters

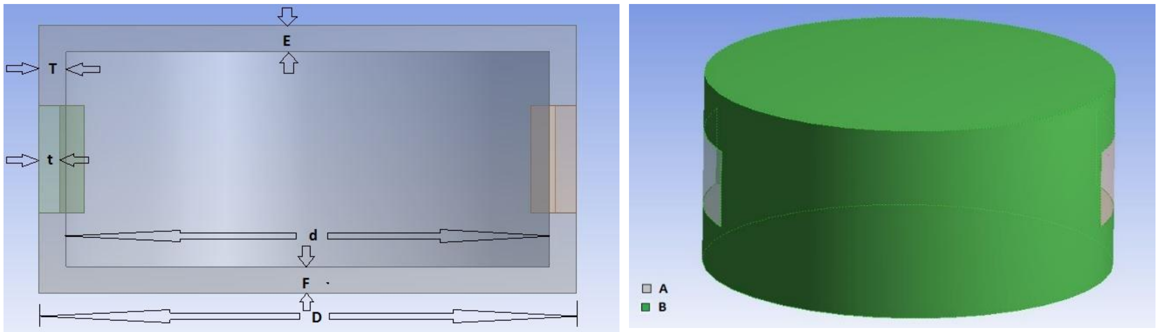


Fig 3.2 Schematic of Model with Key Parameters: Outer Diameter of Cylinder (D), Inner Diameter of Cylinder (d), Thickness of Cylinder Wall (T), Thickness of Roof (E), Thickness of Floor (F), Thickness of Glass (t), Window-Wall Ratio (Surface Area of A/Surface Area of B), Percentage of Glass (Window-Wall Ratio*100)

3.5 Numerical Solution Strategy

A 3D CFD model of the building was generated in the Ansys Workbench. The finite volume method is used to solve the governing equations for this transient system in Ansys Fluent. A workflow chart for whole of this process is given below:

- Generation of 3D CAD simplified model of building with proper assumptions.
- Meshing the domain of the model with right element size and setting the fluent solver with proper boundary conditions and initial condition.
- Post-processing the center-point and average temperature results to assess the energy consumption of the building.

3.5.1 Geometrical Dimensions of the Model

Several simulations have been carried out in Fluent by varying window-wall ratio, thickness of wall, thickness of window (glass), dimensions of room, material of walls, switching off natural convection and introducing air in the room from outside and were used to develop charts with pattern of energy consumption and checking sensitivity of model. Main parameters of very first case (Case I) are given in table below:

Dimensions of Model for Case I

Outer Radius of cylinder (D/2) = 5[m]

Inner Radius of cylinder (d/2) = 4.5[m]

Thickness of cylinder wall (T) = 0.5[m]

Thickness of roof (E) = 0.5[m]

Thickness of glass (t) = 0.05[m]

Thermal Conductivity of glass = 0.8[W/(mK)]

Normalized glass conductivity as thickness of glass same as wall = $0.8*(\frac{0.5}{0.05})^2$ [W/(mK)]

Position of glass = Middle of wall of cylinder in sectors of angle 2ϴ on opposite sides

Sector of glass on both sides (2ϴ) = 45°

3.5.2 Mathematical Modeling (Sun et al. 2009, [9] pp. 5600-5601)

The 3-D heat transfer approach was used to simulate the building, incorporating the effect of both the conduction due to solid material and convection due to fluid in the building. The whole domain is divided into finite control volumes. Ansys fluent uses finite volume method to get discretized equations by integrating the governing equations over each control volume. The governing equations of mass, energy and momentum can be stated as follows:

Continuity equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

Where u, v, w are velocity component in x, y, z direction respectively.

Momentum in x-direction:

$$\frac{\partial u}{\partial \tau}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)$$

Where μ is dynamic viscosity, ρ is density, p is pressure, τ is time co-ordinate

Momentum in y-direction:

$$\frac{\partial v}{\partial \tau}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)$$

Momentum in z-direction:

$$\frac{\partial w}{\partial \tau}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial z}+\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)+\rho\,{}_o\beta(T-T_o)g$$

Where β is volumetric thermal expansion coefficient of air

Energy equation:

$$\frac{\partial T}{\partial \tau}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}=\alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)$$

Where α is thermal diffusivity

3.5.3 Boundary Conditions (Tanaka et al. 1994, [10] pp. 570)

Two types of boundary conditions are considered in this study. Boundary conditions are as follows and shown in fig 3.3. Suppose that whole boundary $\Gamma = \Gamma_1 + \Gamma_2$, then:

1. The temperature boundary condition is $T = \tilde{T}$ on Γ_1
2. The heat flux boundary condition is $\frac{\partial T}{\partial n} = 0$ on Γ_2

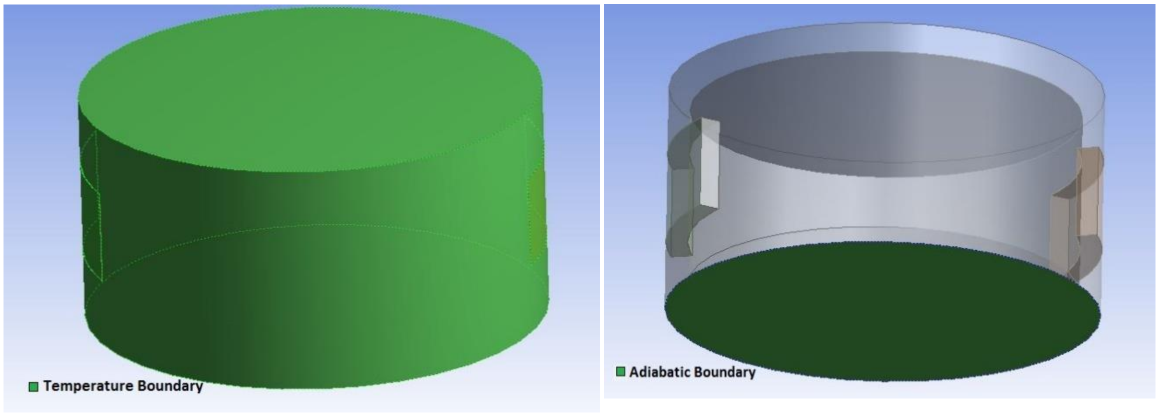


Fig 3.3 Boundary Conditions of the Model

The thermal physical properties employed in the simulation are listed in Table 3.1

Table 3.1 Thermal Physical Properties

MATERIAL	PROPERTY	VALUE	
		SUMMER	WINTER
AIR	DENSITY (kg/m3)	1.1777	1.241344
	SPECIFIC HEAT (J/Kg-K)	1005	1005
	THERMAL CONDUCTIVITY (W/m-K)	0.02619	0.025122
	VISCOSITY (Kg/m s)	1.85E-05	1.85E-05
	VOLUMETRIC EXPANSION COEFFICIENT (1/K)	0.003292	0.003529
GLASS	DENSITY (kg/m3)	2500	
	SPECIFIC HEAT (J/Kg-K)	800	
	THERMAL CONDUCTIVITY (W/m-K)	80	
CONCRETE	DENSITY (kg/m3)	2307	
	SPECIFIC HEAT (J/Kg-K)	658	
	THERMAL CONDUCTIVITY (W/m-K)	1.3699	

3.5.4 Assumptions

The following assumptions were made when modeling the heat transfer characteristics in the building:

- The heat transfer in the model is due to conduction and convection only.

- All fluid properties and material properties are constant except density of fluid which depends on the temperature.
- The flow of air due to natural convection is laminar.
- The initial temperature of all the zones in the model is same as the initial temperature provided by user-defined function.
- The floor of the building is adiabatic.

3.5.5 Generation and Meshing of Computation Domain

While generating computation domain one need to take into account different requirements of analysis as well as speed of computation at the same time. Too small domain gives different results as compared to realistic case and too large increase the computational time tremendously. Taking into account all these requirements and in order to save the computation time, I used a simplified model with two symmetry planes by splitting the full model into 1/4th of model. The computation domain was generated using Ansys Design Modeler. Computational Domain has three subdomains. One as wall of room in the form of cylinder wall, other as window of room in the form of a sector of glass and third as the internal part of hollow cylinder as the air in the room. In order to make the best agreement between accuracy and computation time of the solution, computational domain was solved for different element sizes and time-step size before selecting the most favorable out of them. Boundary conditions were defined in the geometry. The roof and lateral outer surface of cylinder was defined as Outer Temperature type BC; a SYMMETRY type BC was used for the lateral flat planes of the model and bottom surface of cylinder was used for Adiabatic type BC.

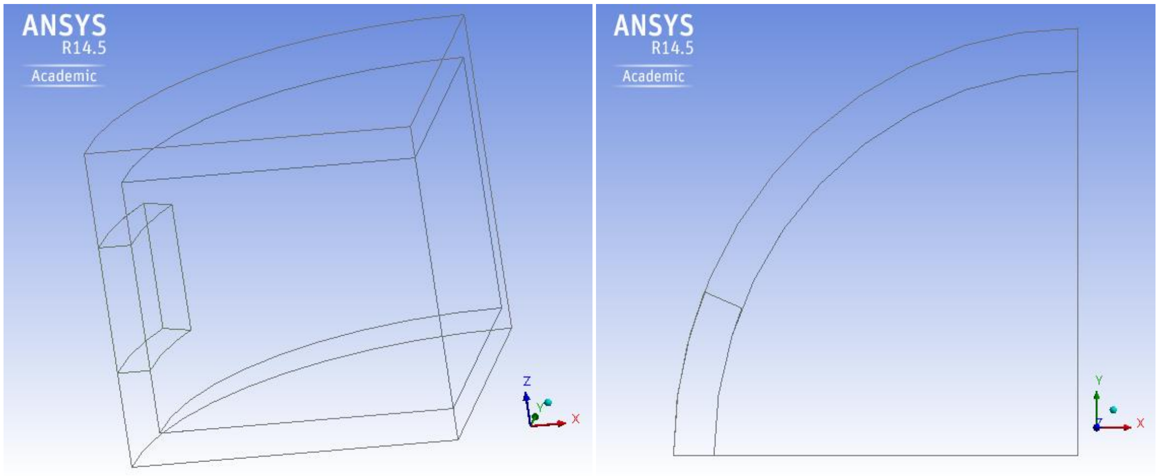


Fig 3.4 CFD Model of Building

3.5.6 Solver Settings

In order to account for unsteady temperature effects, the transient version of Fluent solver was used and a parallel version of solver was used in order to save more computational time.

The solver was set as pressure based and energy equation was set on. The material properties were defined as described in earlier chapter. The BCs at Outer Temperature type BC were defined by User-Defined function as discussed in last chapter whereas Adiabatic type BC was defined as adiabatic. SIMPLE (Semi-Implicit Method for Pressure Linked Equations), PRESTO (Pressure Staggering Option) schemes were selected in solver as other schemes were found to be inefficient in calculating the results.

For control monitors: a default monitor for the residuals of iterative process for the governing equations solved; a monitor for the center-point temperature of the room and a monitor for average temperature were defined. Several simulations were carried out to get an optimized time step size and number of time steps. Optimal time step size was 2000secs and number of time steps were 173 (4 days).

3.5.7 Numerical Simulations and Results

Once optimized the 3D CFD building model several simulations were performed by changing parameters of model and center-point and average temperature variation was calculated. In order to obtain an immediate comparison and demonstration with a building without natural convection inside building, the Boussinesq approximation was switched off.

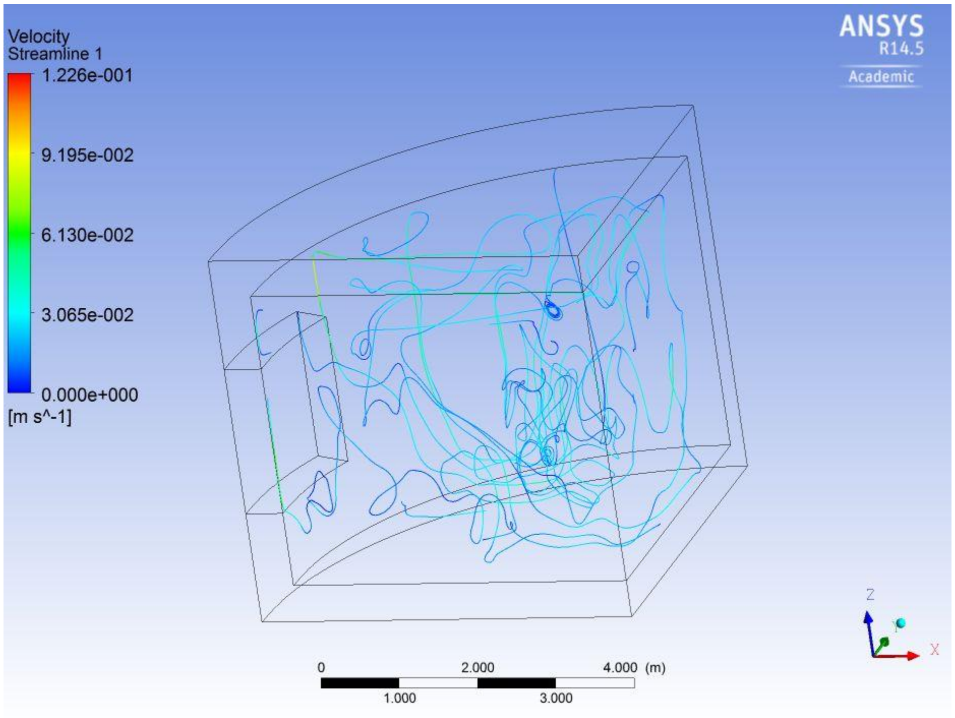


Fig 3.5 Post Processing Velocity Streamline Contour with Boussinesq Approximation

Figure 3.5 shows streamlines of velocity of air for the model in which natural convection was switched on. It is evidence of the good capability of the 3D model to predict movement of air due to buoyancy in the room. The streamlines show the flow conditions of air inside room.

3.5.7.1 Study of Center-Point and Average Point Temperature Profiles

The following figures 3.6 and 3.7 shows the results of numerical simulation in the form of center-point and average temperature data calculated with time. As the results of 3D CFD simulation are more accurate and in good agreement with real world results. Therefore, the methodology of generating and optimizing the 3D model was considered to be a valid and more accurate tool to investigate the energy consumption of a building.

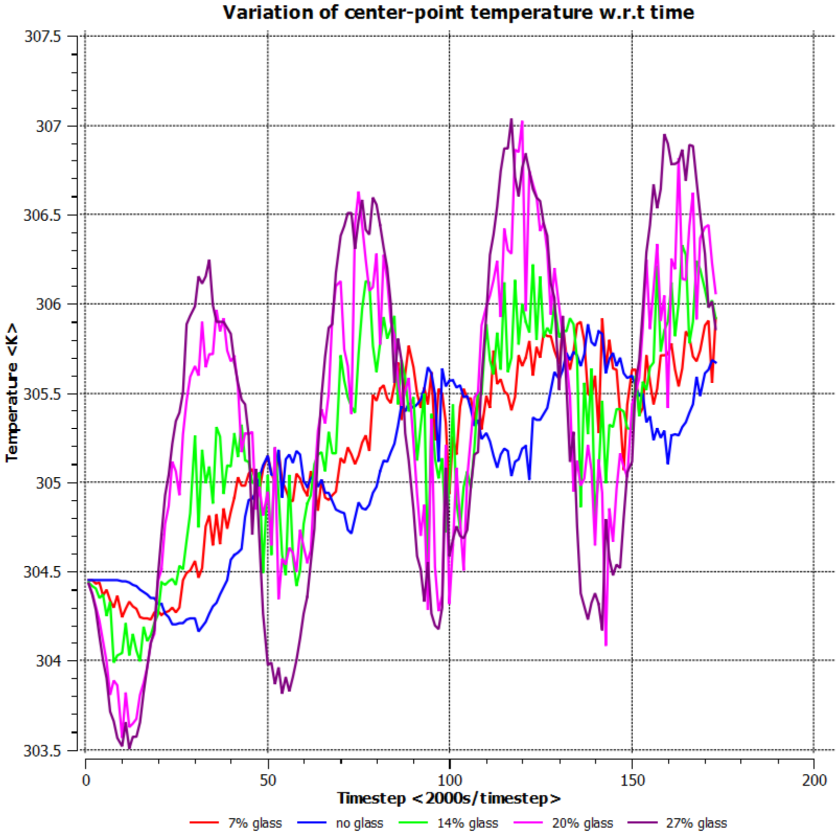


Fig 3.6 Center-Point Temperature Profile

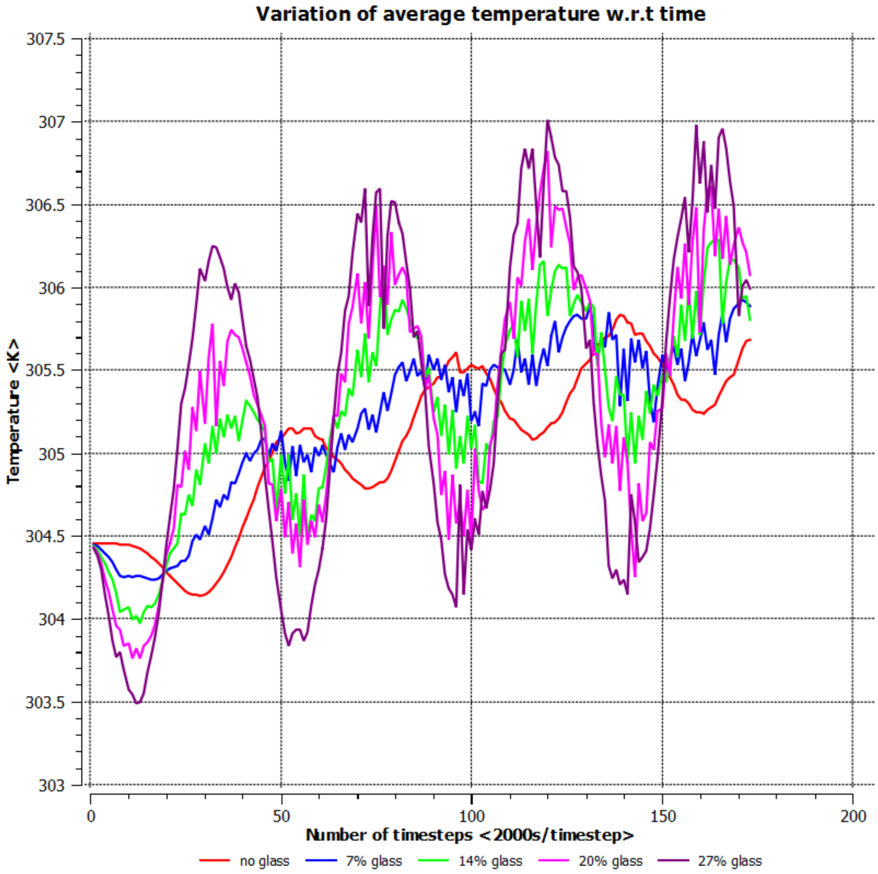
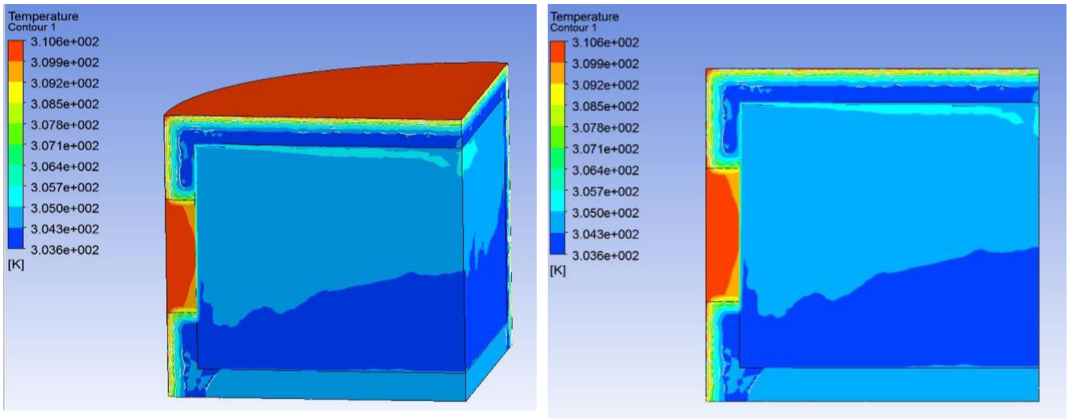


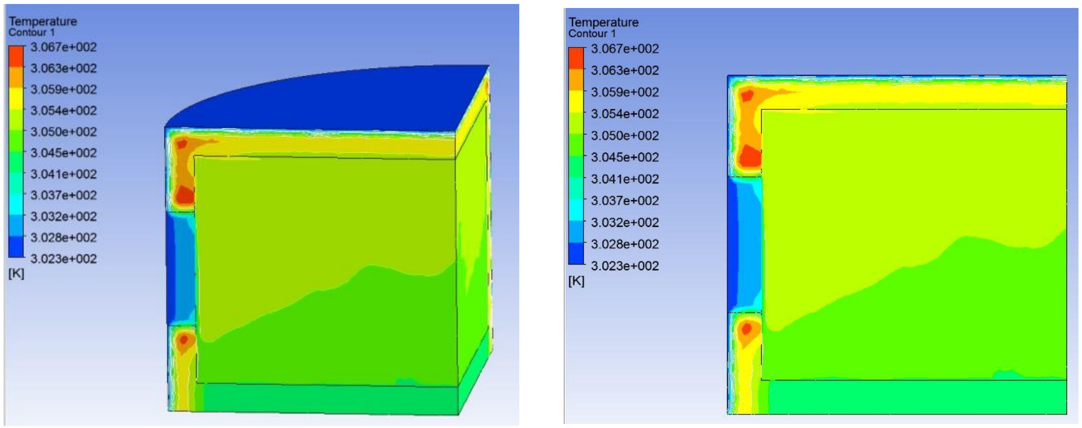
Fig 3.7 Average Temperature Profile

3.5.7.2 Study of Temperature Contour

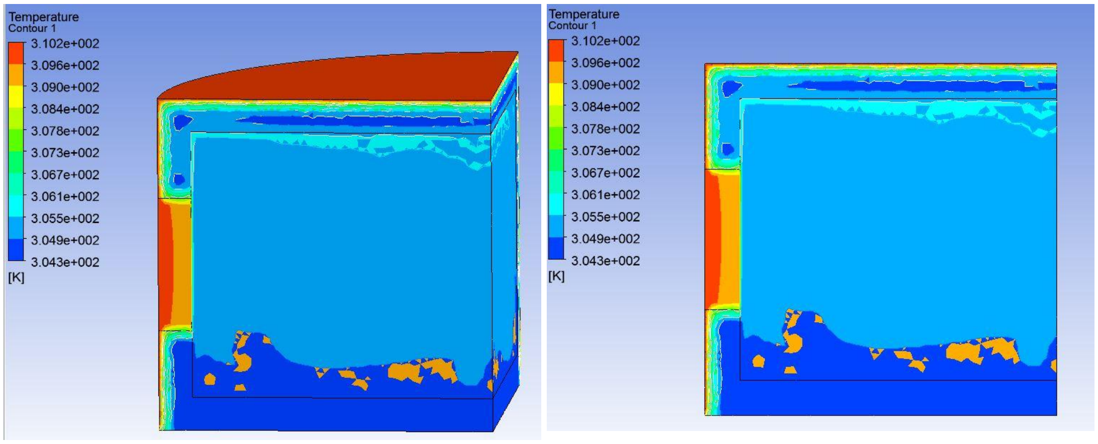
Fig. 3.8 shows the temperature contours in entire and radial section of the models after a time interval of 12 hours until a time period of 4 days. It was observed during each time interval that highest temperature was in the upper part of the model near roof, since the natural convection in the enclosure of the building contributes the highest heat flux in this region. The relatively high temperature of the air enclosure in contact with the windows as compared with the walls causes the circulation of air inside the room. This phenomenon is attributed to the fact that highest temperature in the wall during day time is along the edge of the window.


Temperature
Contour 1
3.106e+002
3.099e+002
3.092e+002
3.085e+002
3.078e+002
3.071e+002
3.064e+002
3.057e+002
3.050e+002
3.043e+002
3.036e+002
[K]
Temperature
Contour 1
3.106e+002
3.099e+002
3.092e+002
3.085e+002
3.078e+002
3.071e+002
3.064e+002
3.057e+002
3.050e+002
3.043e+002
3.036e+002
[K]

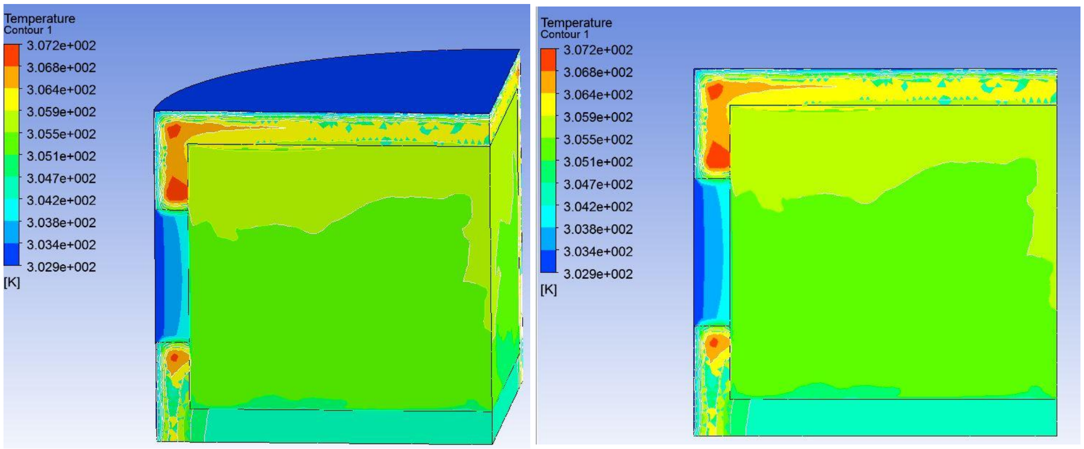
(A)


Temperature
Contour 1
3.067e+002
3.063e+002
3.059e+002
3.054e+002
3.050e+002
3.045e+002
3.041e+002
3.037e+002
3.032e+002
3.028e+002
3.023e+002
[K]
Temperature
Contour 1
3.067e+002
3.063e+002
3.059e+002
3.054e+002
3.050e+002
3.045e+002
3.041e+002
3.037e+002
3.032e+002
3.028e+002
3.023e+002
[K]

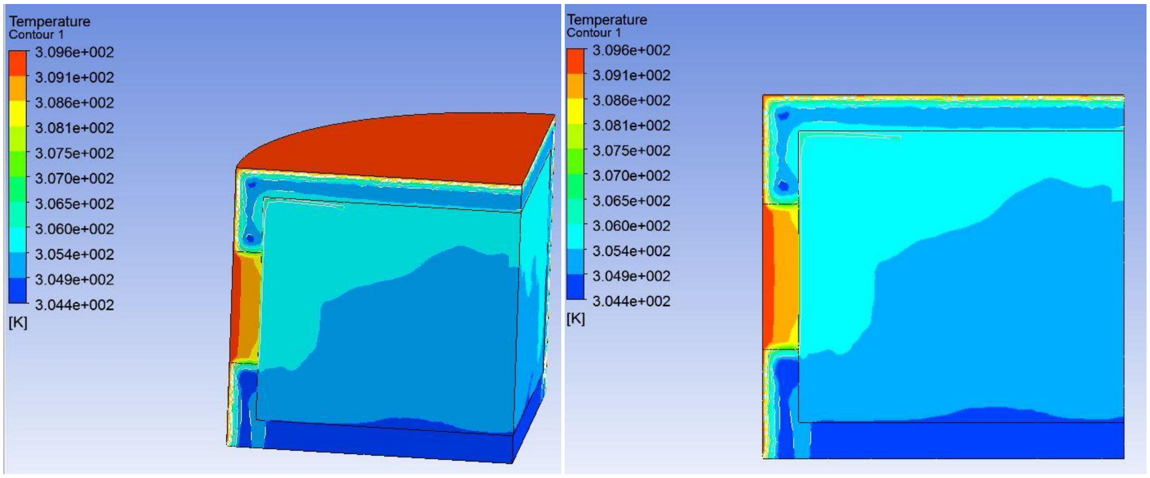
(B)


Temperature
Contour 1
3.102e+002
3.096e+002
3.090e+002
3.084e+002
3.078e+002
3.073e+002
3.067e+002
3.061e+002
3.055e+002
3.049e+002
3.043e+002
[K]
Temperature
Contour 1
3.102e+002
3.096e+002
3.090e+002
3.084e+002
3.078e+002
3.073e+002
3.067e+002
3.061e+002
3.055e+002
3.049e+002
3.043e+002
[K]

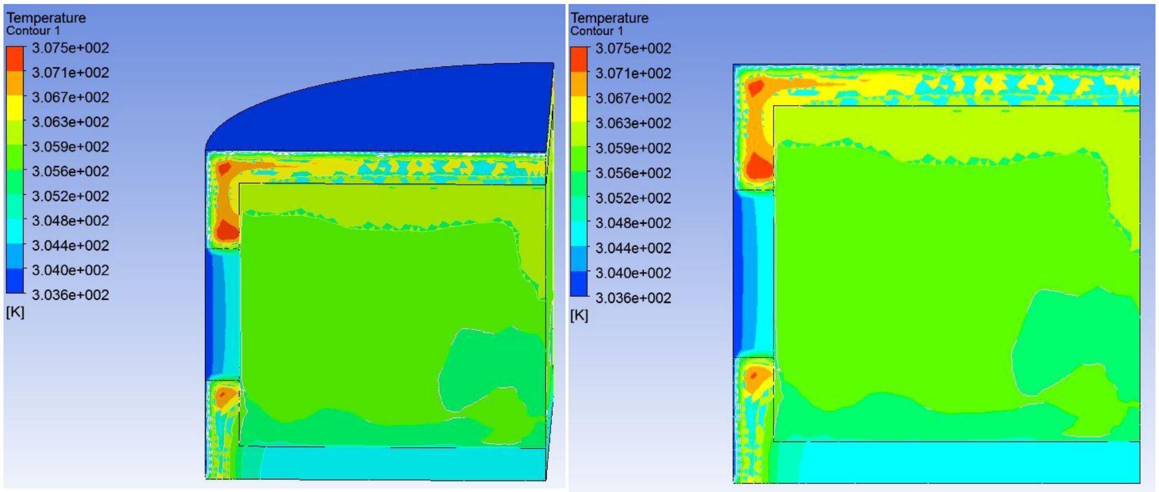
(C)


Temperature
Contour 1
3.072e+002
3.068e+002
3.064e+002
3.059e+002
3.055e+002
3.051e+002
3.047e+002
3.042e+002
3.038e+002
3.034e+002
3.029e+002
[K]
Temperature
Contour 1
3.072e+002
3.068e+002
3.064e+002
3.059e+002
3.055e+002
3.051e+002
3.047e+002
3.042e+002
3.038e+002
3.034e+002
3.029e+002
[K]

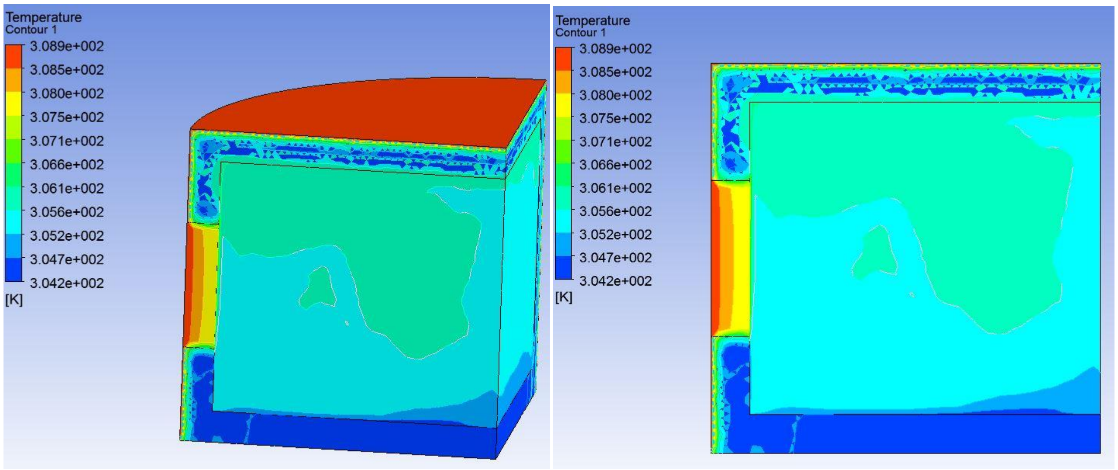
(D)


Temperature
Contour 1
3.096e+002
3.091e+002
3.086e+002
3.081e+002
3.075e+002
3.070e+002
3.065e+002
3.060e+002
3.054e+002
3.049e+002
3.044e+002
[K]
Temperature
Contour 1
3.096e+002
3.091e+002
3.086e+002
3.081e+002
3.075e+002
3.070e+002
3.065e+002
3.060e+002
3.054e+002
3.049e+002
3.044e+002
[K]

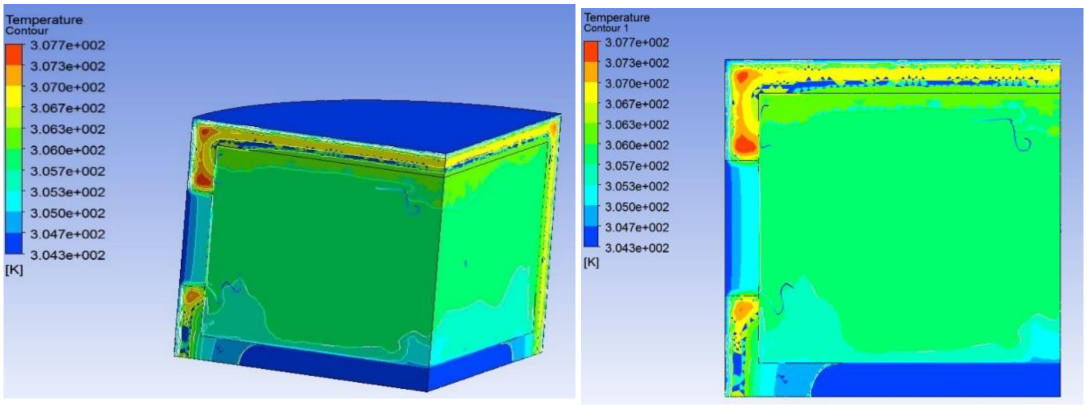
(E)


Temperature
Contour 1
3.075e+002
3.071e+002
3.067e+002
3.063e+002
3.059e+002
3.056e+002
3.052e+002
3.048e+002
3.044e+002
3.040e+002
3.036e+002
[K]
Temperature
Contour 1
3.075e+002
3.071e+002
3.067e+002
3.063e+002
3.059e+002
3.056e+002
3.052e+002
3.048e+002
3.044e+002
3.040e+002
3.036e+002
[K]

(F)



(G)



(H)

Fig. 3.8 Temperature Contour Full Model and Radial Cross Section after (A) 12 (B) 24 (C) 36 (D) 48 (E) 60 (F) 72 (G) 84 (H) 96 Hours

3.6 Calculation Methodology for Energy Calculation

After the achievement of center-point and average point temperature results, next work was to use these results for energy assessment of building designs. For this purpose, an energy calculation tool was developed by using integral area that gives a pattern of energy consumption assessment variation in different designs. It was developed using simulated result data of center-point temperature variation and doing integral of area between this curve and comfortable temperature with time axis. The results were scaled using some division factors to get the energy consumption index. A similar procedure but using different division factor, is used to calculate energy consumption index for winter.

3.6.1 Energy Consumption Index (ECI)

In this study, energy consumption of individual building design is assessed in terms of Energy Consumption Index (ECI), which is defined as area between variation of inside temperature and comfortable temperature for a time period of last two days out of four days' numerical simulation. Comfortable temperature is taken as 25 degrees Celsius.

Two different indices each for different seasons (summer and winter) were defined to identify and quantify energy consumption. These indices helped in identifying comparison of energy consumption between buildings with different constructional characteristics and also highlighted the buildings with excessive and minimum energy consumption.

ECI index for summer

Defined as $ECI = \frac{A-1200000}{8068.5}$

ECI index for winter

Defined as $ECI = \frac{A-2400000}{2492}$

Where A is the integral area between inside temperature variation and comfortable temperature for time period of last two days out of four days' numerical simulation as described earlier.

3.7 Impact of Different Building Characteristics on Energy Consumption Index (Deng et al. 2000, [13] pp. 9-12), (Florides et al. 2002, [11] pp. 303-315)

This section describes results of the effects of measures considered in energy consumption of a building that can be used to construct an energy efficient house. Factors affecting the energy consumption such as thickness of glass used in windows, thickness of wall, size of room, natural convection in the room, material used in walls, window wall ratio are reviewed.

.3.7.1 Effect of Percentage of Glass and Thickness of wall on ECI

In this section, an analysis of the impact of window-wall ratio and thickness of wall used in building on cooling or heating load depending on summer and winter respectively is presented. A number of cases were examined by varying conduction and convection heat transfer by varying thickness of wall and amount of glass in the design respectively. The results of the simulations are presented in the form of ECI in figure 3.9 & 3.10.

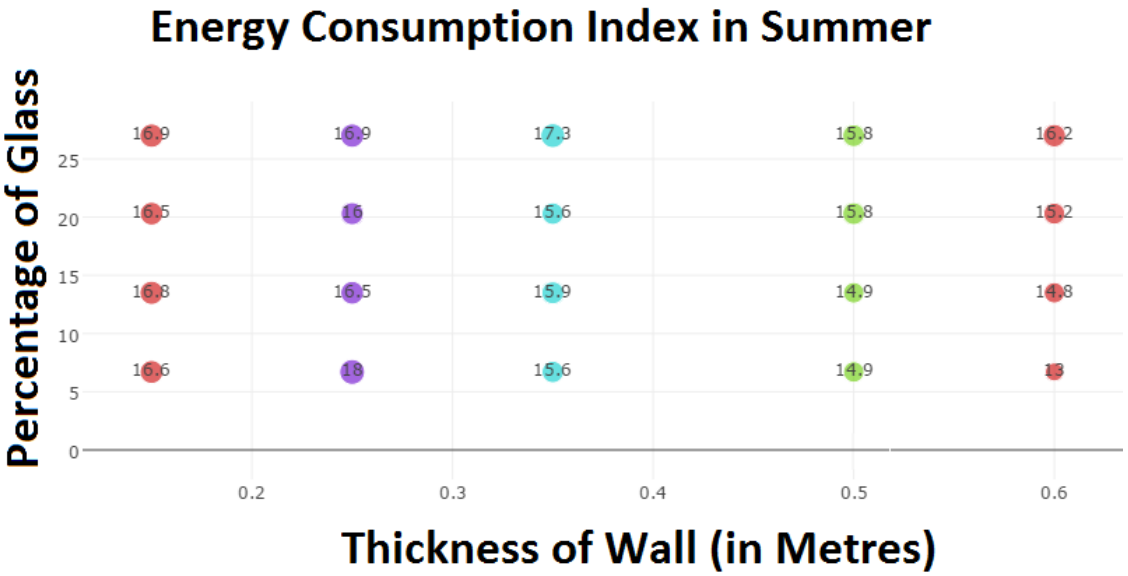


Fig 3.9 Relationship of ECIs with Window-Wall Ratio and Thickness of Wall for Summer

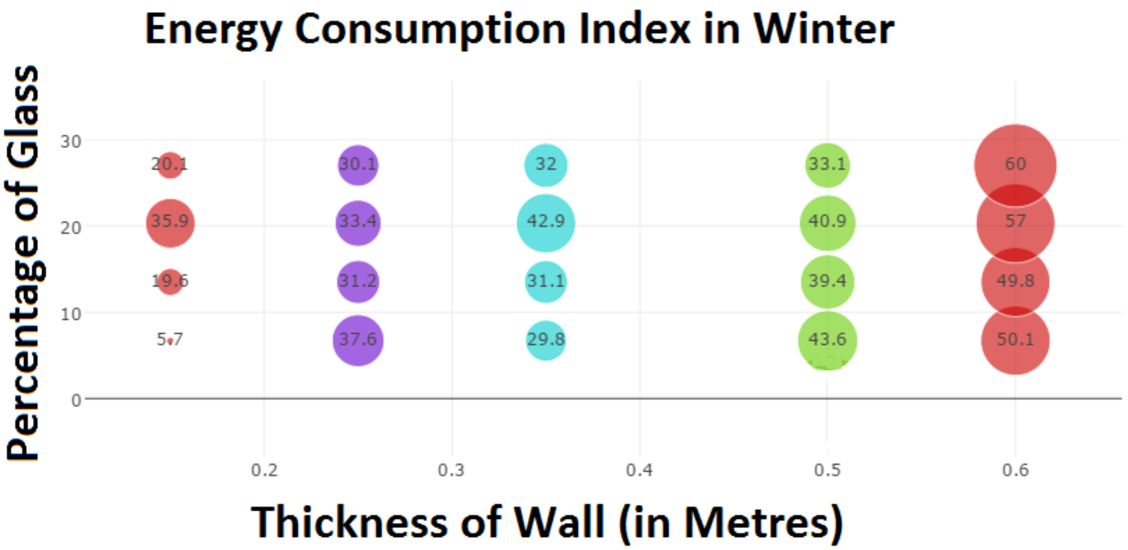


Fig 3.10 Relationship of ECIs with Window-Wall Ratio and Thickness of Wall for Winter

No clear pattern was observed from data in figure 3.9 and 3.10. It may be due to the fact that sample size (last two days out of four days' simulation) for which ECI is calculated is so small.

3.7.2 Effect of Thermal Mass

Wall of the building act as a heat storage medium as well as barrier to the heat flow. So, in order to reduce the indoor temperature variation there should be time delay in the heat flow which could be done by using low thermal conductivity material or high density-thermal capacity product material. A high density-thermal capacity product material indicates a high heat-storage capacity. In order to investigate this effect, I changed the material of the wall of the house with wood and concrete for the case of 6.7 percentage glass and 0.5 meters wall thickness for the summer. Table 3.2 shows the variation of Energy Consumption Index with the material of wall along with the thermal properties of the material.

Table 3.2 Thermal Properties along with ECI for Different Materials of Wall

MATERIAL	PROPERTY	VALUE	Energy Consumption Index(ECI)
CONCRETE	DENSITY (kg/m3)	2307	14.9
	SPECIFIC HEAT (J/Kg-K)	658	
	THERMAL CONDUCTIVITY (W/m-K)	1.3699	
BRICK	DENSITY (kg/m3)	1600	9.6
	SPECIFIC HEAT (J/Kg-K)	840	
	THERMAL CONDUCTIVITY (W/m-K)	0.7	
WOOD	DENSITY (kg/m3)	720	1.6
	SPECIFIC HEAT (J/Kg-K)	1250	
	THERMAL CONDUCTIVITY (W/m-K)	0.16	

CHAPTER 4

RESULTS DISCUSSION AND APPLICATION

4.1 Introduction

Numerical analysis was performed in this work to assess the inside temperature variation in various configuration. A Computational Fluid Dynamics (CFD) model of building was developed and its energy performance was compared to that of other designs with different constructional parameters.

First chapter summarizes the motivations and requirements which guided the development of the thermal model for comparing energy consumption. In addition, methodology behind the research was discussed. In second chapter, simplified 1-D and 2-D model along with assumptions and equations which were numerically solved by implementation in Matlab and Ansys was discussed. Third chapter presented the implementation of model in 3-D which has more resemblance with the real buildings. Sensitivity analysis conducted on several parameters in the model showed that there is some pattern in the energy consumption which was later presented in form of Energy Consumption Index.

This chapter contains a summary of research work presented in the thesis and discusses the resulting conclusions. In addition, it contains recommendations for future improvements in data sampling techniques and include more factors. These improvements would enable more accuracy of index table.

4.2 Discussion (Deng et al. 2000, [13] pp. 9-12), (Florides et al. 2002, [11] pp. 303-315)

The mode of heat transfer in the building contains conduction in all domains, natural convection within the enclosure of the building. Different constructional configurations of the building have different contributions of these modes of heat transfer. As discussed in before sections, the effects of this heat transfer is evaluated by center-point and average temperature variation of the building. Then I thought of a method to calculate the effect of this temperature variation on energy consumption of a building using ECI. The importance of ECI is that it contains weighing factors which attempt to weigh energy consumption of each building relative to each other. Each weighing factor in the chart represents a separate building analysis. This was done to cover all the uncertainties which may evolve during change of design from one to other. The size of bubble in chart corresponding to an individual building design can be compared to the other distributions to identify where it stands with respect to other designs.

No noticeable pattern relating the energy consumption index for these factors could be identified for building designs as shown in figure 3.9 & 3.10. Based on the results from simulation it was very difficult to correlate ECI to a number of factors that were expected to influence the energy consumption of building. The reason may be due to small sample size or it is just difficult to form any obvious correlation due to number of other factors also getting involved during simulation of these designs.

Therefore, study of dependence of ECI on geometric parameters presented in the thesis is more of a first attempt to demonstrate an application of outcome of 3-D simulation. Still study of these factors was important. Firstly, it helped us better understand the energy consumption situation. Secondly, it helped us to find some factors which were having significant effect on ECIs and results from these not so obvious simulations can also help us to set priority for future investigation to achieve a better energy consumption index table.

4.3 Proposals for Future Work (Deng et al. 2000, [13] pp. 9-12), (Florides et al. 2002, [11] pp. 303-315)

Although, the results presented in this research are in terms of ECI may not be sufficient to use as it is but still it gave a platform for relating energy consumption of different designs. In the future, we expect further improvement of the idea in several ways. One possibility could be to redefine the definition of ECI and perform longer simulation runs to increase statistical significance. Other possibility could be to reconsider the dependence of ECI on relevant geometric parameters e.g. volume-surface area ratio, window-wall ratio, thickness of wall etc. It is suggested to treat each factor separately, so that ECI of them can be individually evaluated and compared. Yet another possibility could be to have other characteristics like wind flow and solar radiation on building

4.4 Conclusion (Deng et al. 2000, [13] pp. 9-12), (Florides et al. 2002, [11] pp. 303-315)

An Ansys Fluent simulation study of different designs of buildings has been undertaken. The study was based on ambient temperature data from weather station, supplemented by thorough study of factors affecting energy consumption of a building. ECIs based on all these designs have been obtained, and reported in form of nice bubble chart. Statistical distribution of ECIs developed from temperature variation data can be used for comparing the performance of individual design with respect to other. The figures have shown that some factors have dominating effect on ECIs. The configuration effect of these parameters on the ECI is studied comprehensively.

The conclusions are as follows:

ECI strongly depends on combined effect of conduction through wall and window and natural convection in the building. With increasing thickness of wall, the conduction will be weakened as a result of increased thermal resistance whereas with decreasing amount of glass, the natural convection will be weakened as a result of decreased area of surface acting as hot plate for convection in the building.

4.5 Application of ECI

Energy researchers always are in search of ways to quantify and compare the performance of a building. Several methods have been proposed. But almost all methods were related to quantifying the impacts of technology on energy performance. It is quite obvious till now from the results that energy consumption of building during life cycle strongly depends on the construction characteristics of a building. Therefore, this research primarily deals with the factors related to the construction which has some significant effect on performance of buildings.

In the absence of any benchmark it is very difficult to compare energy usage between different building designs. Especially a designer can’t run simulation every time before finalizing the design to see the temperature variation. Numerous methods were developed to keep a track of the energy efficiency of buildings. Many were based on the use of some reference design of building to determine the efficiency of buildings by comparing against that. However, my research methodology is based on assessing energy efficiency before construction. In order to assess this energy efficiency, my research proposes new index, Energy Consumption Index, based on internal temperature variation during different seasons; as well as other parameters of buildings such as thickness of wall, window-wall ratio and material of walls. Energy consumption index (ECI) provides a reference for comparing energy usage between different designs, and find a technique to reduce overall energy consumption. We use a simple example of efficiency scale as shown in figure 4.1

[14,16] to illustrate the application of ECI described above. A general building rating index indicator scale could be made on the basis of ECI so as to give credits to the designs which are more energy efficient than other. Fig. shows an example of scale which could be used for giving credits. Credits can be any like financing energy efficient buildings through government insured loans, rebate on taxes and utilities or expedited permitting of new construction, coupons for energy efficient products. This approach is not computationally burdensome and can be applied easily even by any non-technical individual.

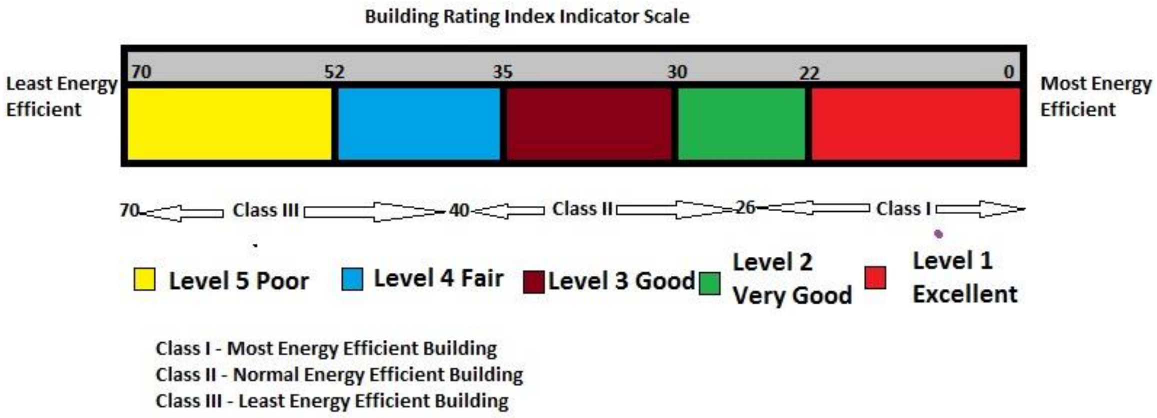


Fig 4.1 Building Rating Index Indicator Scale

This building rating index scale presented above is beneficial because it enables monitoring the energy consumption of a building during the construction stage without doing energy analysis of building. The energy consumption issue plays a most important role in the design of any building. Buildings are designed to provide occupants with thermal comfort with heating and air conditioning systems. Properly designed buildings can play an important role in energy savings of building during lifetime and can reduce the dependence on air conditioning systems for comfort. Designer has always a little control on the operation of the building but proper selection of characteristics can modify the energy demands of a building. Moreover, the earlier phases decisions during design of the building cost less and has more impact on the performance as compared to the after construction decisions. Consideration of my work by designer can improve the effectiveness of building design solutions.

REFERENCES

[1] Budziszewski, A., and Thoren, L., 2012, “CFD simulation of a safety relief valve for improvement of a one-dimensional valve model in RELAP5,” Masters thesis, http://publications.lib.chalmers.se/records/fulltext/178850/178850.pdf

[2] " CFD_theory" ce.utexas.edu. Google, 2002. Web. 23 Apr 2002.

[3] " Ansys, Heat Transfer Modeling" engr.uconn.edu. Google, 2006. Web. Dec 2006.

[4] Stetina, J., 2011, “Thermal Properties,” ottp.fme.vutbr.cz/vyuka/thermomechanics/therm_prop_non-met.pdf

[5] " Thermal Properties" engineeringtoolbox.com. Google, 2016. Web. 2 May 2016.

[6] Garg, N.K., 2007, Guidelines for use of glass in Buildings, New Age International Limited, New Delhi, India, Chap. 2.

[7] Khandelwal, M., and Lee, S., 2007, “One-Dimensional Thermal Model of cold-start in a polymer electrolyte fuel cell stack,” Int. J. Power Sources, 172(2), pp. 816-830

[8] Gothe, M.S., and Nagavi, S.K., 2015, “Comparative Study of 2-dimensional and 3-dimensional Static Analysis On Piston of IC engine using finite elements,” Int. J. Mechanical and Civil Engineering, 12(4), pp. 16-21

[9] Sun, J., and Fang, L., 2009, “Numerical simulation of concrete hollow bricks by the finite volume method,” Int. J. Heat and Mass Transfer, 52(23-24), pp. 5598-5607

[10] Tanaka, M., and Matsumoto, T., 1994, “Time-stepping boundary element method applied to 2-D transient heat conduction problems,” J. Appl. Math. Mod., 18(10), pp. 569–576

[11] Florides, G.A., and Tassou, S.A., 2002, “Measures used to lower building energy consumption and their cost effectiveness,” J. Appl. Energy., 73(3-4), pp. 299–328.

[12] Lombard, L.P., and Ortiz, J., 2008, “A review on buildings energy consumption information,” J. Energy and Buildings, 40(3), pp. 394–398.

[13] Deng, S.M., and Burnett, J., 2000, “A study of energy performance of hotel buildings in Hong Kong,” J. Energy and Buildings, 31(1), pp. 7–12.

[14] Schlueter, A., and Thesseling, F., 2009, “Building information model based energy/exergy performance assessment in early design steps,” J. Automation in Construction, 18(2), pp. 153–163.

[15] " Building Energy" bdg.nus.edu.sg Google, 2016. Web. 2 May 2016.

[16] Hui, S.C.M., 2008, “Building Energy Benchmarking,” ppt. University of Hong Kong, Department of Mechanical Engineering, pp. 1–50.

[17] " Why is energy conservation so important?" article, https://forestcitymgmt.propertysolutions.com/media_library/2197/4fe8cd9db3ffe901.pdf

[18] " Why are energy efficient houses important?" article, http://www.unece.org/info/media/stories/save-energy.html

[19] " Modelization of CFD problems" article,http://tdx-new-pro.csuc.cat/bitstream/handle/10803/6685/05Jma05de09.pdf?sequence=5&isAllowed=y

[20] " Heat Transfer" article, http://energy-models.com/heat-transfer

[21] " Natural Convection and Buoyancy-Driven Flows" Ansys Fluent user guide section 13.2.5,https://www.sharcnet.ca/Software/Fluent6/html/ug/node572.htm

APPENDIX A

MATLAB SCRIPT FOR ONE-DIMENSIONAL HEAT TRANSFER

Code for Getting Coefficients for Temperature Modeling:

For Summer:

```
T=24*60*60;
w=2*pi/T;
t = 0:1*60*60:24*60*60;
Ut = [86.82903226 86.82903226 85.30645161 83.70967742 82.30967742 80.93548387
80.33870968 81.62258065 85.49354839 88.49677419 90.82580645 92.90645161
94.60645161 96.04516129 97.50967742 98.97096774 99.61935484 99.06451613
98.83870968 97.84516129 95.6 92.77096774 90.32903226 89.63870968 87.92903226];
cos_wt = [cos(w*t)];
cos_2wt = [cos(2*w*t)];
sin_wt = [sin(w*t)];
sin_2wt = [sin(2*w*t)];
a0 = trapz(t,Ut)/T;
a1= trapz(t,Ut.*cos_wt)*2/T;
b1= trapz(t,Ut.*sin_wt)*2/T;
a2= trapz(t,Ut.*cos_2wt)*2/T;
b2= trapz(t,Ut.*sin_2wt)*2/T;
```

For Winter:

```
T=24*60*60;
w=2*pi/T;
t = 0:1*60*60:24*60*60;
Ut = [45.50967742 45.50967742 44.73548387 43.96774194 43.14516129 42.30322581
42.07096774 41.67419355 41.74516129 45.76451613 51.91290323 55.90645161
58.80322581 61.07741935 62.85483871 63.99354839 64.40967742 63.9483871
61.23870968 57.31290323 53.57419355 51.90322581 50.70645161 48.86451613
47.24516129];
cos_wt = [cos(w*t)];
cos_2wt = [cos(2*w*t)];
sin_wt = [sin(w*t)];
sin_2wt = [sin(2*w*t)];
a0 = trapz(t,Ut)/T;
a1= trapz(t,Ut.*cos_wt)*2/T;
b1= trapz(t,Ut.*sin_wt)*2/T;
a2= trapz(t,Ut.*cos_2wt)*2/T;
b2= trapz(t,Ut.*sin_2wt)*2/T;
```

Code for One Dimensional Heat Transfer Model:

For Summer:

```
a_p=3.5*pi;
dx=0.05;
dt=30;
t_total=600*60*60;
t_max=24*60*60;
x=0:dx:10;
t=0:dt:t_total;
L=10;
x1=0.5;
x2=9.5;
k1=1.3699; %(W/m K)Thermal conductivity of concrete
k2=0.02619; %(W/m K)Thermal conductivity of air at
300K;http://www.engineeringtoolbox.com/air-properties-d_156.html
p1=2307;%Density of concrete http://www.engineeringtoolbox.com/concrete-properties-
d_1223.html
p2=1.2;%kg/m3 Density of air at 300K
c1=0.65*10^3;%(J/(kg K))Specific heat capacity of concrete
c2=1.005*10^3;%(J/(kg K))Specific heat capacity of air
w=(2*pi)/t_max;
t_save=60*60;
n_save=t_save/dt;
n_total=(t_total/dt)+1;
u_save = zeros(length(x),(t_total/t_save)+1);
t1=0:t_save:t_total;
 u_n(1,:) = (((90.7080-3.5124*cos(w*t)-
8.0526*sin(w*t)+0.7030*cos(2*w*t)+0.3338*sin(2*w*t))-32)*0.56+273.15);% made a
pseudo matrix for boundary conditions at x=1

k=k1+(k2-k1)*0.5*(1+tanh(a_p*(x-x1)))-(k2-k1)*0.5*(1+tanh(a_p*(x-x2)));
dkdx=(k2-k1)*0.5*(a_p*(sech(a_p*(x-x1))).^2-a_p*(sech(a_p*(x-x2))).^2);
p=p1+(p2-p1)*0.5*(1+tanh(a_p*(x-x1)))-(p2-p1)*0.5*(1+tanh(a_p*(x-x2)));
c=c1+(c2-c1)*0.5*(1+tanh(a_p*(x-x1)))-(c2-c1)*0.5*(1+tanh(a_p*(x-x2)));

r1=(dkdx)/(2*dx);
r2=(k)/(dx^2);
r3=dt./(p.*c);
alpha=(r1+r2).*r3;
beta=(-2*r2.*r3+1);
gamma=(r2-r1).*r3;

u1=zeros(1,length(x));
u2=zeros(1,length(x));
```

```
u1(1:length(x))=u_n(1,1);% set the initial temperature same at all points at level n=1,
gives initial condition at all the points

index=1;
for n=2:n_total

    u2(1)=u_n(1,n);% the temperature at x=1 at next time level
    u2(length(x))=u_n(1,n);% the temperature at x=last point at next time level

     for i=2:length(x)-1
 u2(i)=alpha(i)*u1(i+1)+beta(i)*u1(i)+gamma(i)*u1(i-1);% gives the temperature of rest
of points between x=1 and x=last point at next time level
     end
    u1=u2;
    if mod(n,n_save)==0
        index=index+1;
        u_save(:,index)=u1;
    end
end

    u_save(:,1) = (((90.7080-3.5124*cos(w*t(1))-
8.0526*sin(w*t(1))+0.7030*cos(2*w*t(1))+0.3338*sin(2*w*t(1)))-32)*0.56+273.15);%
saves the initial conditions in the temperature saving matrix.
    figure(1)
    plot(t1/(60*60),u_save(1,:),'color','r');hold on;
    plot(t1/(60*60),u_save(4,:),'color','g');hold on;
    plot(t1/(60*60),u_save(20,:),'color','b');hold on;
    plot(t1/(60*60),u_save(30,:),'color','k');hold on;
    plot(t1/(60*60),u_save(50,:),'color','y');hold on;
    plot(t1/(60*60),u_save(100,:),'color','c');hold on;
    plot(t1/(60*60),u_save(150,:),'color','m');
    xlabel('Time in hours  ')
    ylabel('Temperature in Kelvin');
title('Variation of temperature summer at different points in building using concrete ');
legend('0','0.2','1','1.5','2.5','5','7.5','Location','BestOutside');

figure(2)
    plot(x,u_save(:,1),'color','r');hold on;
    plot(x,u_save(:,100),'color','g');hold on;
    plot(x,u_save(:,200),'color','b');hold on;
    plot(x,u_save(:,300),'color','k');hold on;
    plot(x,u_save(:,400),'color','y');hold on;
    plot(x,u_save(:,500),'color','c');hold on;
    plot(x,u_save(:,600),'color','m');
    xlabel('Position of points ')
    ylabel('Temperature in Kelvin');
```

```
title('Variation of temperature summer at different times in building using concrete');
legend('1','100','200','300','400','500','600','Location','BestOutside');
```

For Winter:

```
a_p=3.5*pi;
dx=0.05;
dt=30;
t_total=600*60*60;
t_max=24*60*60;
x=0:dx:10;
t=0:dt:t_total;
L=10;
x1=0.5;
x2=9.5;
k1=1.3699;%(W/m K) Thermal conductivity of concrete
k2=0.02619;%(W/m K) Thermal conductivity of air at
300K;http://www.engineeringtoolbox.com/air-properties-d_156.html
p1=2307; %(kg/m3) Density of concrete http://www.engineeringtoolbox.com/concrete-
properties-d_1223.html
p2=1.2; %kg/m3 of air at 300K
c1=0.65*10^3; %(J/(kg K))Specific heat capacity of concrete
c2=1.005*10^3; %(J/(kg K))Specific heat capacity of air
w=(2*pi)/t_max;
t_save=60*60;
n_save=t_save/dt;
n_total=(t_total/dt)+1;
u_save = zeros(length(x),(t_total/t_save)+1);
t1=0:t_save:t_total;




u_n(1,:) = (((51.8250-5.5911*cos(w*t)-
9.4171*sin(w*t)+0.9032*cos(2*w*t)+2.4779*sin(2*w*t))-32)*0.56+273.15);

k=k1+(k2-k1)*0.5*(1+tanh(a_p*(x-x1)))-(k2-k1)*0.5*(1+tanh(a_p*(x-x2)));
dkdx=(k2-k1)*0.5*(a_p*(sech(a_p*(x-x1))).^2-a_p*(sech(a_p*(x-x2))).^2);
p=p1+(p2-p1)*0.5*(1+tanh(a_p*(x-x1)))-(p2-p1)*0.5*(1+tanh(a_p*(x-x2)));
c=c1+(c2-c1)*0.5*(1+tanh(a_p*(x-x1)))-(c2-c1)*0.5*(1+tanh(a_p*(x-x2)));

r1=(dkdx)/(2*dx);
r2=(k)/(dx^2);
r3=dt./(p.*c);
alpha=(r1+r2).*r3;
beta=(-2*r2.*r3+1);
```

```
gamma=(r2-r1).*r3;

u1=zeros(1,length(x));
u2=zeros(1,length(x));
u1(1:length(x))=u_n(1,1);

index=1;
for n=2:n_total

   u2(1)=u_n(1,n);
   u2(length(x))=u_n(1,n);


   for i=2:length(x)-1


      u2(i)=alpha(i)*u1(i+1)+beta(i)*u1(i)+gamma(i)*u1(i-1);

   end
   u1=u2;
   if mod(n,n_save)==0
      index=index+1;
      u_save(:,index)=u1;
   end
end
   u_save(:,1) = (((51.8250-5.5911*cos(w*t(1))-
9.4171*sin(w*t(1))+0.9032*cos(2*w*t(1))+2.4779*sin(2*w*t(1)))-32)*0.56+273.15);


   figure(1)
   plot(t1/(60*60),u_save(1,:),'color','r');hold on;
   plot(t1/(60*60),u_save(4,:),'color','g');hold on;
   plot(t1/(60*60),u_save(20,:),'color','b');hold on;
   plot(t1/(60*60),u_save(30,:),'color','k');hold on;
   plot(t1/(60*60),u_save(50,:),'color','y');hold on;
   plot(t1/(60*60),u_save(100,:),'color','c');hold on;
   plot(t1/(60*60),u_save(150,:),'color','m');
   xlabel('Time in hours  ')
   ylabel('Temperature in Kelvin');
title('Variation of temperature winter at different points in building using concrete ');
legend('0','0.2','1','1.5','2.5','5','7.5','Location','BestOutside');

figure(2)
   plot(x,u_save(:,1),'color','r');hold on;
   plot(x,u_save(:,100),'color','g');hold on;
   plot(x,u_save(:,200),'color','b');hold on;
```

```
    plot(x,u_save(:,300),'color','k');hold on;
    plot(x,u_save(:,400),'color','y');hold on;
    plot(x,u_save(:,500),'color','c');hold on;
    plot(x,u_save(:,600),'color','m');
    xlabel('Position of points ')
    ylabel('Temperature in Kelvin');
title('Variation of temperature winter at different times in building using concrete');
legend('1','100','200','300','400','500','600','Location','BestOutside');
```

APPENDIX B

UDF FUNCTION SCRIPT FOR AMBIENT TEMPERATURE

For the Summer:

```
#include "udf.h"
DEFINE_PROFILE(unsteady_temp,thread,position)
{
real w;
face_t f;
real t = CURRENT_TIME;
w =  7.2722e-05;
begin_f_loop(f, thread)
{
F_PROFILE(f, thread, position) = ((90.7080-3.5124*cos(w*t)-
8.0526*sin(w*t)+0.7030*cos(2*w*t)+0.338*sin(2.*w*t))-32.)*0.56 +273.15;
}
end_f_loop(f, thread)
}
```

For the Winter:

```
#include "udf.h"
DEFINE_PROFILE(unsteady_temp,thread,position)
{
real w;
face_t f;
real t = CURRENT_TIME;
w =  7.2722e-05;
begin_f_loop(f, thread)
{
F_PROFILE(f, thread, position) = ((51.8-5.6*cos(w*t)-
9.4*sin(w*t)+0.9*cos(2*w*t)+2.47*sin(2.*w*t))-32.)*0.56 +273.15;
}
end_f_loop(f, thread)
}
```