MATHEMATICAL MODELING AND DYNAMIC SIMULATION OF TEMPERATURE DISTRIBUTION IN A CHAMBER FURNACE

BY

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MSc/ENG/14465/2007-2008

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AHMADU BELLO UNIVERSITY, ZARIA

NIGERIA

DECEMBER, 2011

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MSc/ENG/14465/2007-2008

A THESIS SUBMITTED TO THE
SCHOOL OF POSTGRADUATE STUDIES,
AHMADU BELLO UNIVERSITY, ZARIA
NIGERIA

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF

MASTER OF SCIENCE IN CHEMICAL ENGINEERING

DEPT OF CHEMICAL ENGINEERING
AHMADU BELLO UNIVERSITY, ZARIA
NIGERIA

DECEMBER, 2011

DECLARATION

I declare that the work in the thesis entitled "**MATHEMATICAL MODELING AND DYNAMIC SIMULATION OF THE TEMPERATURE DISTRIBUTION IN A CHAMBER FURNACE**" has been performed by me in the Department of Chemical Engineering under the Supervision of Engr. Prof. A.S.Ahmed and Engr. Dr. P.C. Okonkwo.

The information derived from the literature has been duly acknowledged in the text and a list of references provided. No part of this thesis was previously presented for another degree at any university or institution of learning.

OLADOSU WASIU AJIBOLA	_____	_____
Name of Student	Signature	Date

CERTIFICATION

This thesis entitled **"MATHEMATICAL MODELING AND DYNAMIC SIMULATION OF TEMPERATURE DISTRIBUTION IN A CHAMBER FURNACE"** by **OLADOSU, WASIU AJIBOLA** meets the regulations governing the award of the degree of Masters of Ahmadu Bello University, Zaria, and is approved for its contribution to knowledge and literary presentation.

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Dean, Postgraduate School

DEDICATION

This work is dedicated to my entire family members especially my father, Alhaji Abdul Lateef Oladosu, my mother Hajia S. Oladosu and my wife Hajia Saratu Oladosu. May Almighty ALLAH (SWT) reward them Abundantly. (Amin).

ACKNOWLEDGEMENT

All praise is due to Allah; we praise him and seek his help, and beg for his forgiveness, we seek refuge of Allah from the evil of our souls, and from the wickedness of our deeds.

Whosoever Allah guides cannot be led astray, and whosoever is led astray shall find none other to guide him. I bear witness that none has the right to be worshipped but Allah and Muhammad (S.A.W) is his slave and messenger.

I would like to start by expressing my sincere appreciation and gratitude to my supervisors, Engr. Prof. A.S.Ahmed and Engr. Dr. P.C. Okonkwo for their tireless efforts, insightful comments and constructive criticisms. They have always played fatherly roles to me by giving invaluable advice and sense of courage that have sharpened my life for the better. I am very grateful to both of them.

I wish to express my gratitude to all academic staff of the Department of Chemical Engineering ABU, Zaria especially Dr. I.A. Mohammed-Dabo, Head of Department, Chemical Engineering ABU, Zaria for their insightful comments and meaningful contributions.My ultimate appreciation and gratitude go to my parents, Alhaji Abdul Lateef Oladosu and Hajia Sidiqat Oladosu for their unlimited support; physically, morally and for their advise. My deep appreciations go to my wife, Saratu Oladosu and my children, Aishat & Muhammad for their moral support. I would also like to express my profound gratitude and appreciations to all non-academic staff of Chemical Engineering Dept. LAUTECH Ogbomosho for the successful conduct of the experimental work in their laboratory, may Almighty Allah bless you abundantly.

I wish to thank my following relatives for their moral support: my brothers Engr. K.O. Oladosu, Engr. T.T. Oladosu, Tubosun, Jelili and Deji, my sisters, Serifat, Medinat to mention but a few.

Finally, I would like to offer my indebtedness to the authors and publishers of all the reference literatures I have consulted during this research work.

ABSTRACT

Chamber furnaces are widely used in heat treatment. The correct prediction of the temperature variation and distribution within the chamber is of high significance to ensure good quality of the products being fired and reduce energy consumption. A software by trade name COMSOL was used to model and simulate the temperature distribution in a chamber furnace at different positions using finite element method *(FEM)* together with adaptive meshing and error control. An experimental chamber furnace was employed with five thermocouples to measure temperature values at different positions. In the chamber furnace, heat was transferred by both conduction and radiation. The results of the modeling were compared with the experimental values and it was found that there were disparities. The result of the simulated temperature at position (-0.125, -0.15,0) after 10mins was 525K whereas the measured temperature at the same position was 353K., Also the results of the simulated temperature at position (0,-0.15,0) after 10mins was 360K whereas the measured temperature at the same position was 358K.The average temperature distribution of the simulated result was 442K whereas the measured temperature was 355.2K. The disparity was due to contamination and degradation of furnace refractory lining which result from the reduction and re-oxidation of silica found in the refractory after lengthen in duration of heating of the chamber furnace.

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LIST OF SYMBOLS AND ABBREVIATIONS

δts	Time-scaling coefficient (s)
ρ	Density (kg/m^3)
C_p	Heat capacity (J/(kg.K))
k	Thermal conductivity(J.K/ m3)
Q	Heat source (J)
γ	Ratio of specific heats
p	Pressure (N/m^2)
η	Dynamic viscosity (Ns/m^2)
q_i	Conductive heat flux (W/m^2),
T	Temperature (K)
n	Normal vector of the boundary, pointing out from the domain.
q_0	Inward heat flux (W/m^2), normal to the boundary, from external sources.
q_r	Net influx from radiation (W/m^2).
q_s	Energy transferred from other parts of the boundary through a thin, highly conductive shell (W/m^2).
H	Heat transfer coefficient (W/(m^2·K).
T_{inf}	External wall temperature (K)
V	Voltage (V)
T_{sim}	Simulation temperature (K)
T_{mes}	Measured temperature (^{o}C)

CHAPTER 1

1.0 INTRODUCTION

A furnace is a device used for heating. In American English, the term furnace on its own is generally used to describe household heating system based on a central furnace (known as either a boiler or a heater in British English), and sometimes as a synonymy for kiln, a device used to fire clay to produce ceramics.

The temperature distribution inside a chamber furnace is not sometime known and as result there is no prediction of the extent of uniform firing of article using such furnace. It is necessary to be able to predict the extent to which article will be uniformly fired in a furnace .One of the state of the art effort in process engineering is the computer simulation of chemical processes, COMSOL software is used to predict the temperature distribution in the chamber furnace and analyze the energy flows in the chamber .These computational model would have a great value in increasing the understanding of the temperature distribution in the furnace and reduce the number of experiments which is traditionally performed in the laboratory.

1.1 PROBLEM STATEMENT

The temperature distribution inside a chamber furnace is not normally known and as a result there is no prediction of the extent to which article is uniformly fired using such furnace. The research project is to study the mathematical modeling and dynamic simulation of the temperature distribution in a chamber furnace.

1.2 AIM AND OBJECTIVES

The primary aim of this research is to develop dynamic model to simulate the temperature distribution of a chamber furnace.

The specific objectives are:

a) To model the temperature distribution in a furnace chamber

b) To simulate the developed model using a graphical software package knows as COMSOL

c) To test the accuracy of the computer model obtained using data obtained from a laboratory furnace model.

1.3 JUSTIFICATION

The results expected in this work will help:

1. To improve the design of chamber furnace in terms of energy efficiency and productivity.
2. To optimize thermal performance and reduce cost in firing operation.
3. To improve heat treatment processes and fired products quality

1.4 SCOPE OF STUDY

The scope of the work include:

a) To Identify and propose the mathematical equations that correctly describe temperature distribution in chamber furnaces.

b) To simulate temperature–time profiles in the chamber furnace at different positions and planes

c) To test the model using experimental data

CHAPTER 2

2.0 LITERATURE REVIEW

The heat energy required to fire a furnace may be supplied directly by combustion of fossil fuels or electrical heating elements such as resistant wire and rods. In the design of a typical fossil fuel fired furnace, for example the radiant section, convection section, burner, soot blower, and stack are of utmost importance. (Chew, 1997)

Mathematical modeling plays a very important role in contemporary chemical engineering. This has come about because of recent theoretical advances in chemical engineering combined with advances in computing machines. It is now possible in many cases to develop and solve sophisticated and accurate mathematical description of many chemical engineering processes (Mcketta, 1977)

Since the economic usually favours mathematical modeling and simulation of complex chemical and physical phenomena, as compared to caring out these processes experimentally, the simulation approach seems to be of increasing value. Of course, it is neither possible nor desirable to eliminate engineering problem involve a combination of mathematical modeling and the use of data from carefully planned and executed experiment (Mcketta, 1977).

2.1 INDUSTRIAL FURNACE

An industrial furnace or direct fired heater is equipment used to provide heat for a process or can serve as reactor which provides heats of reaction. Furnace designs vary as to its function, heating duty, type of fuel and method of introducing combustion air. However, most process furnaces have some common features.

Fuel flows into the burner as shown in Fig.2.2 and is burnt with air provided from an air blower. There can be more than one burner in a particular furnace .These can be arranged in cells which heat a particular set of tubes. Burners can also be floor mounted, wall mounted or roof mounted depending on design. The flames heat up the tubes, which in turn heat the fluid inside in the first part of the furnace known as the radiant section or firebox. In this chamber where combustion takes place, the heat is transferred mainly by radiation to tubes around the fire in the chamber. The heating fluid passes through the tubes and is thus heated to the desired temperature. The gases from the combustion are known as flue gases. After the flue gases leaves the firebox, most furnace designs include a convection section where more heat is recovered before venting to the atmosphere through the stack. Heat Transfer Fluid (HTF) commonly use their furnaces to heat a secondary fluid with special additives like anti-rust. This heated fluid is then circulated round the whole plant to heat exchangers to be used wherever heat is needed instead of directly heating the product line as the product or material may be volatile or prone to cracking at the furnace temperature. (Hogg, 1997)

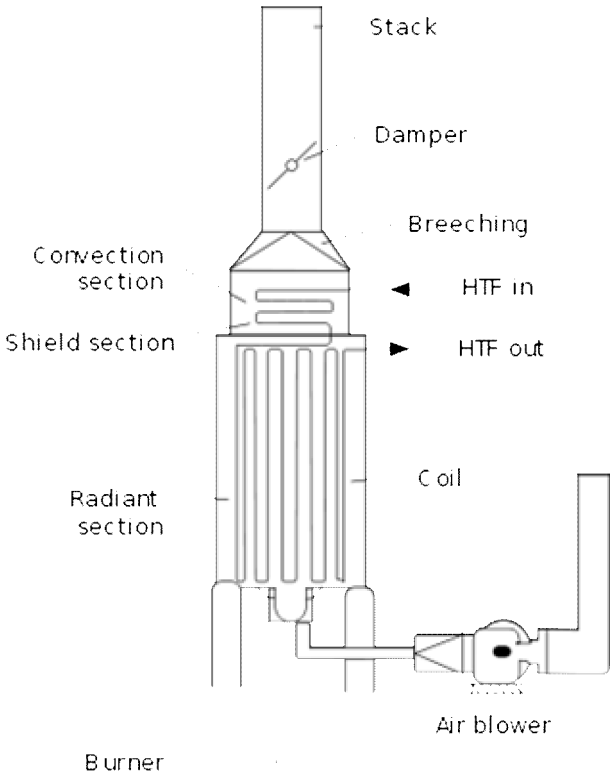


Figure 2.1 : Industrial process furnace

2.1.1 Radiant Section

The radiant section is where the tubes receive almost all its heat by radiation from the flame. In a vertical, cylindrical furnace, the tubes are vertical. Tubes can be vertical or horizontal, placed along the refractory wall, in the middle, etc., or arranged in cells. Studs are used to hold the insulation together and on the wall of the furnace. They are placed about 1 ft (300 mm) apart in fig. 2.2 . The tubes, shown above, which are reddish brown from corrosion, are carbon steel tubes and run the height of the radiant section. The tubes are a distance away from the insulation so radiation can be reflected to the back of the tubes to maintain a uniform tube wall temperature. Tube guides at the top, middle and bottom hold the tubes in place.

2.1.2 Convection Section

The convection section is located above the radiant section where it is cooler to recover additional heat. Heat transfer takes place by convection here, and the tubes are finned to increase heat transfer. The first two tube rows in the bottom of the convection section and at the top of the radiant section is an area of bare tubes (without fins) and are known as the shield section, so named because they are still exposed to plenty of radiation from the firebox and they also act to shield the convection section tubes, which are normally of less resistant material from the high temperatures in the firebox (Chew, 1997). The area of the radiant section just before flue gas enters the shield section and into the convection section is called the bridge zone. Crossover is the term used to describe the tube that connects from the convection section outlet to the radiant section inlet. The crossover piping is normally located outside so that the temperature can be monitored and the efficiency of the convection section can be calculated. The sight glass at the top allows personnel to see the flame shape and pattern from above and visually inspect if flame impingement is occurring. Flame impingement happens when the flame touches the tubes and causes small isolated spots of very high temperature.

2.1.3 Furnace Burner

The burner in the vertical, cylindrical furnace as shown in fig.2.2 is located in the floor and fires upward. Some furnaces have side fired burners, such as in train locomotives. The burner tile is made of high temperature refractory and is where the flame is contained. Air registers located below the burner and at the outlet of the air blower are devices with movable flaps or vanes that control the shape and pattern of the flame, whether it spreads out or even swirls around. Flames

should not spread out too much, as this will cause flame impingement. Air registers can be classified as primary, secondary and if applicable, tertiary, depending on when their air is introduced. The primary air register supplies primary air, which is the first to be introduced in the burner. Secondary air is added to supplement primary air. Burners may include a premixer to mix the air and fuel for better combustion before introducing into the burner. Some burners even use steam as premix to preheat the air and create better mixing of the fuel and heated air. The floor of the furnace is mostly made of a different material from that of the wall, typically hard castable refractory to allow technicians to walk on its floor during maintenance.

A furnace can be lit by a small pilot flame or in some older models, by hand. Most pilot flames nowadays are lit by an ignition transformer (much like a car's spark plugs). The pilot flame in turn lights up the main flame. The pilot flame uses natural gas while the main flame can use both diesel and natural gas. When using liquid fuels, an atomizer is used, otherwise, the liquid fuel will simply pour onto the furnace floor and become a hazard. Using a pilot flame for lighting the furnace increases safety and ease compared to using a manual ignition method (like a match).

2.1.4 Sootblower

Sootblowers are found in the convection section. As this section is above the radiant section and air movement is slower because of the fins, soot tends to accumulate here. Soot blowing is normally done when the efficiency of the convection section is decreased. This can be calculated by looking at the temperature change from the crossover piping and at the convection section exit. Sootblowers utilize flowing media such as water, air or steam to remove deposits from the tubes. This is typically done during maintenance with the air blower turned on. There are several different types of sootblowers used. Wall blowers of the rotary type are mounted on furnace walls protruding between the convection tubes. The lances are connected to a steam source with

holes drilled into it at intervals along its length. When it is turned on, it rotates and blows the soot off the tubes and out through the stack.

2.1.5 Insulation

Insulation is an important part of the furnace because it prevents excessive heat loss. Refractory materials such as firebrick, castable refractories and ceramic fibre, are used for insulation. The floor of the furnace are normally castable type refractories while those on the walls are nailed or glued in place. Ceramic fibre is commonly used for the roof and wall of the furnace and is graded by its density and then its maximum temperature rating. An example of a castable composition is kastolite.

2.2 ELECTRIC ARC FURNACE

An electric arc furnace (EAF) is a furnace that heats charged material by means of an electric arc. Arc furnaces range in size from small units of approximately one ton capacity (used in foundries for producing cast iron products) up to about 400 ton units used for secondary steelmaking. Arc furnaces used in research laboratories and by dentists may have a capacity of only a few dozen grams. Industrial electric arc furnace temperatures can be up to 1,800 degrees Celsius, while laboratory units can exceed 3,000 °C. Arc furnaces differ from induction furnaces in that the charge material is directly exposed to an electric arc, and the current in the furnace terminals passes through the charged material. (Bosman, 1996)

2.2.1 Advantages of electric arc furnace

The use of electric arc furnace allows steel to be made from a 100% scrap metal feedstock, commonly known as "cold ferrous feed" to emphasize the fact that for an electric arc furnace,

scrap is a regulated feed material. The primary benefit of this is the large reduction in specific energy (energy per unit weight) required to produce the steel. Another benefit is flexibility: while blast furnaces cannot vary their production by much and are never stopped, EAFs can be rapidly started and stopped, allowing the steel mill to vary production according to demand. During the peak of global meltdown in 2009, an estimated quantity of only 1 million tonne was produced in USA employing BOF technique. Although steelmaking arc furnaces generally use scrap steel as their primary feedstock, if hot metal from a blast furnace or direct-reduced iron is available economically, these can also be used as furnace feed.

A typical steelmaking arc furnace is the source of steel for a mini-mill, which may make bars or strip product. Mini-mills can be sited relatively near to the markets for steel products, and the transport requirements are less than for an integrated mill, which would commonly be sited near a harbour for access to shipping.

2.3 BLAST FURNACE

A blast furnace is a type of metallurgical furnace used for smelting to produce industrial metals, generally iron. In a blast furnace, fuel and ore are continuously supplied through the top of the furnace, while air (sometimes with oxygen enrichment) is blown into the bottom of the chamber, so that the chemical reactions take place throughout the furnace as the material moves downward. The end products are usually molten metal and slag phases tapped from the bottom, and flue gases exiting from the top of the furnace.(Jones, 1994)

Blast furnaces are to be contrasted with air furnaces (such as reverberatory furnaces), which were naturally aspirated, usually by the convection of hot gases in a chimney flue. According to this broad definition, bloomeries for iron, blowing houses for tin, and smelt mills for lead would be classified as blast furnaces. However, the term has usually been limited to those used for

smelting iron ore to produce pig iron, an intermediate material used in the production of commercial iron and steel (Kang, 2008).

2.3.1 Modern Process of Blast Furnace

Modern furnaces are equipped with an array of supporting facilities to increase efficiency, such as ore storage yards where barges are unloaded. The raw materials are transferred to the stockhouse complex by ore bridges, or rail hoppers and ore transfer cars. Rail-mounted scale cars or computer controlled weight hoppers weigh out the various raw materials to yield the desired hot metal and slag chemistry. The raw materials are brought to the top of the blast furnace via a skip car powered by winches or conveyor belts.

There are different ways in which the raw materials are charged into the blast furnace. Some blast furnaces use a "double bell" system where two "bells" are used to control the entry of raw material into the blast furnace. The purpose of the two bells is to minimize the loss of hot gases in the blast furnace. First, the raw materials are emptied into the upper or small bell. The bell is then rotated a predetermined amount to distribute the charge more accurately. The small bell then opens to empty the charge into the large bell. The small bell then closes, to seal the blast furnace, while the large bell dispenses the charge into the blast furnace. A more recent design is to use a "bell-less" system. These systems use multiple hoppers to contain each raw material, which is then discharged into the blast furnace through valves. These valves are more accurate at controlling how much of each constituent is added, as compared to the skip or conveyor system, thereby increasing the efficiency of the furnace. Some of these bell-less systems also implement a chute in order to precisely control where the charge is placed(Fiveland, 2008).

The iron making blast furnace itself is built in the form of a tall chimney-like structure lined with refractory brick. Coke, limestone flux, and iron ore (iron oxide) are charged into the top of the

furnace in a precise filling order which helps control gas flow and the chemical reactions inside the furnace. Four "uptakes" allow the hot, dirty gas to exit the furnace dome, while "bleeder valves" protect the top of the furnace from sudden gas pressure surges. When plugged, bleeder valves need to be cleaned with a bleeder cleaner. The coarse particles in the gas settle in the "dust catcher" and are dumped into a railroad car or truck for disposal, while the gas itself flows through a venturi scrubber and a gas cooler to reduce the temperature of the cleaned gas.

The "casthouse" at the bottom half of the furnace contains the bustle pipe, tuyeres and the equipment for casting the liquid iron and slag. Once a "taphole" is drilled through the refractory clay plug, liquid iron and slag flow down a trough through a "skimmer" opening, separating the iron and slag. Modern, larger blast furnaces may have as many as four tapholes and two casthouses. Once the pig iron and slag has been tapped, the taphole is again plugged with refractory clay.

The tuyeres are used to implement a hot blast, which is used to increase the efficiency of the blast furnace. The hot blast is directed into the furnace through water-cooled copper nozzles called tuyeres near the base. The hot blast temperature can be from 900 °C to 1300 °C (1600 °F to 2300 °F) depending on the stove design and condition. The temperatures they deal with may be 2000 °C to 2300 °C (3600 °F to 4200 °F). Oil, tar, natural gas, powdered coal and oxygen can also be injected into the furnace at tuyere level to combine with the coke to release additional energy which is necessary to increase productivity.

2.4 CHAMBER FURNACE

A chamber furnace consists of vertical walls, cover, and a clodhopper or hearth that are lined with refractory materials. Furnace baffles (pipes 32–76 mm in diameter through which the boiler

water circulates) and an overhead or wall-mounted radiation super heater (in steam boilers) are installed on the interior surfaces of the chamber furnace. Fuel is fed into the chamber furnace, together with the air necessary for combustion, through jets mounted on the walls of the furnace and in its corners. During combustion of the powdered fuel, some of the ash is carried off by the flue gases from the furnace to the boiler-gas flues; the rest of it falls from the jet in the form of drops of slag, which are removed from the furnace as a granulated solid or a molten liquid, discharging from the furnace hearth through a tapping hole into a slag catcher filled with water. Semi enclosed chamber furnaces, which have a narrow section separating the furnace into two parts (a combustion chamber and a cooling chamber), are also made in large boiler units that operate on pulverized fuel.

2.4.1 Operation of Chamber Furnace

The furnace is fitted with a combined supply light and instrument switch. The light is on whenever the furnace is connected to the supply. The switch cuts off power to the control circuit. When the Chamber furnace as shown in fig. 2.2 is connected to the electrical supply, the supply light should glow. Operate the instrument switch is to activate the temperature controller. The controller becomes illuminated and goes through a short test cycle. The furnace door is closed and the temperature controller adjusted.

Unless a time switch is fitted and is off, the furnace starts to heat up. The heat light glows steadily at first and then flash as the furnace approaches the desired temperature or a program set point. To set the instrument switch is set it's off position to turn the furnace off. The controller display will go blank. If the furnace is to be left off unattended, the electrical supply is

isolated. Heating element life is shortened by use at temperatures close to maximum. The furnace should not be left at high temperature when not required (Rogers, 2003).

2.4.2 Applications of Chamber Furnace

- Applications in general industry include ferrous metal heat treatments such as annealing, hardening, tempering and stress relieving; and simulation of a larger industrial process, on a laboratory scale
- Applications in quality control include, testing of component materials or finished products
- Applications in tool making and maintenance include heat treatment of metal tools and tool steels
- Applications in coatings manufacturing include testing coatings for resistance to fire and longevity testing of finished coatings
- Firing of Ceramic wares
- Application in Metallurgical industries
- Use in Fractional distillation of Petroleum



Figure 2.2**:** Chamber Furnace

2.5 SIMULATION OF ENERGY BALANCES IN A HEAT TREATMENT FURNACE WITH MATLAB

To be able to describe energy transfer in the furnace, The furnace was divided into segments with fictitious walls. Energy balances for upper and lower combustion chamber, muffle, product and belt were accounted for. Energy balances were connected through conduction in the vertical direction and energy balances between the segments were connected over fictitious walls. The results illustrated that the mathematical model is capable of representing the process with good accuracy, (Andersons, 2007).

2.5.1 Heat transfer through insulation

Energy is transported through the isolating walls in the muffle and upper and lower combustion chamber to the surrounding by conduction and convection. The amount of energy transported

through the walls depends on the temperature of the surrounding atmosphere as well as the heat conductivity for the walls. Because the walls are built of many different materials with different conductivity a jointly temperature depending conductivity was calculated for the roof, upper side, lower side and floor.(Andersson,2007).

2.5.2 Combustion chambers

In the combustion chambers, fossil fuel is burned with an excess of air. The combustion generates carbon dioxide and water vapor. These carbon dioxide and water vapor molecules absorb and emit radiation which effects the radiation between the walls. Because the gases in the combustion chamber emit radiation, energy will be supplied to the walls of the furnace through these gases. Moreover, energy is also transported to the walls of the furnace through direct radiation from the flames (Martin,2007). The gases in the combustion chambers cannot absorb energy from short wavelength radiation therefore this energy is directly distributed to the furnace walls.

2.6 MODELING AND SIMULATION OF HEAT TRANSFER IN LOADED CONTINUOUS HEAT TREATMENT FURNACE

Heat up processing is the basic step for the workload in heat treatment for further processing. It is also an energy-intensive process. Thus, correct prediction of the temperature variation and distribution in the workload is significant to ensure the final quality of the parts and to reduce energy consumption and time as well. (Kang, 2004).There are some studies about the optimization of heat treating process in continuous furnace. FurnXpert'11 was developed to optimize furnace design and operation for many types of batch and continuous furnaces, such as

the continuous belt furnace for sintering process in powder metallurgy. The program mainly focused on the heat balance of the furnace, while, the load pattern of work pieces was just aligned load pattern in 2-dimensions. Han Xiaoliang established mathematical model for the heating of work piece in bogie hearth heat treatment furnace. The work piece was assumed to be one dimensional and only single work piece was considered. WanNini studied the heating up of steel tubes in a continuous furnace annealing furnace. The influence of moving speed and thickness of steel tubes are studied. The heat transfer was also assumed to be one dimensional and the load pattern is simply aligned in the width direction. In the heat treatment of parts such as castings and forging, the load pattern is complicated with multi parts stacked in order or disorder and the shapes of work pieces are also irregular. Then it is necessary to model the heat transfer inside the workload.

2.6.1 Mathematical model

The models for the heat transfer between workload and furnace, heat transfer inside the workload, the conduction inside work piece and also the combustion Model for gas-fired furnace can be borrowed from the CHT-fe. For the arranged load pattern there is radiation between furnace and work pieces radiation

Among work pieces, convection between furnace and work pieces, conduction between work pieces and conduction inside heavy sectioned work pieces. For Random load pattern there are two methods, one method is that the random load pattern is assumed to be arranged load pattern virtually and then the method for arranged load pattern can be used. The other one is based on measured results. If experiments can be done to measure the thermal history of the same load pattern, the equivalent thermal conductivity can be acquired by inverse method, i.e., the

equivalent thermal conductivity can be calculated by the temperature variation. The equivalent thermal conductivity considers conduction, radiation and convection inside the load. The load is assumed to be a mass with the equivalent thermal conductivity. The equivalent thermal conductivity is then used for the similar load pattern. **(**Rong, 2004).

2.7 ESTIMATION OF FURNACE TEMPERATURE DISTRIBUTION USING DIGITAL PHOTOGRAPHIC IMAGES

Temperature measurement is an important requirement in many industrial process. . At present conventional devises and technique such as contact type sensor and pyrometers are used to measured the temperature of various sources of heat with several visible sources of heat such as the furnace , bursen burner, incandescent lamps and oil lamps. The installation of a sensor is difficult if not impossible. Large boilers,oven,furnaces of different types and other individuals heat sources generally use thermocouples to monitor temperature at strategic location to identify hots spots. Non –contact measurement techniques like pyrometer indicate temperature of the targeted location only. For getting overall temperature distribution it is required to scan the surface area using optical / radiation pyrometer but it is not advisable to keep the furnace door open for a long time . Thus there is a need to develop a low cost system useful in giving non-contact type of temperature estimation system giving point source temperature as well as the temperature distribution (Panditral,2009)

Digital still camera (DSC) have gained significant popularity in recent years . The development of digital cameras have opened up responsibilities of powerful new diagnostic technique employing two –dimensional imaging . Digital photographical is a fast technique and requires no other sensor , once the colour temperature correlation is established .

2.7.1 Source Image Acquisition

A consumer grade DSC is used to capture the images of various sources. It is desired that the device bandwidth should be greater than the source bandwidth and to verify if the camera is having adequate bandwidth , the camera CCD sensor spectral response is obtained . It is ensured that the camera has enough bandwidth to cover the visible range (400-700mm). Number of images of various heat source like muffle furnace , salt bath furnace ; bursen burner , oil lamps, domestic stoves etc are captured using the camera mentioned above.

2.8 THERMOCOUPLE

A thermocouple is a junction between two different metals that produces a voltage related to a temperature difference. Thermocouples are a widely used type of temperature sensor for measurement and control and can also be used to convert heat gradient into electricity. They are inexpensive and interchangeable, are supplied fitted with standard connectors, and can measure a wide range of temperatures. The main limitation is accuracy: system errors of less than one degree Celsius (C) can be difficult to achieve. (Jones, 2007)

Any junction of dissimilar metals will produce an electric potential related to temperature. Thermocouples for practical measurement of temperature are junctions of specific alloys which have a predictable and repeatable relationship between temperature and voltage. Different alloys are used for different temperature ranges. Properties such as resistance to corrosion may also be important when choosing a type of thermocouple. Where the measurement point is far from the measuring instrument, the intermediate connection can be made by extension wires which are less costly than the materials used to make the sensor. Thermocouples are usually standardized against a reference temperature of 0 degrees Celsius; practical instruments use electronic

methods of cold-junction compensation to adjust for varying temperature at the instrument terminals. Electronic instruments can also compensate for the varying characteristics of the thermocouple, and so improve the precision and accuracy of measurements.

Thermocouples are widely used in science and industry; applications include temperature measurement for kilns, gas turbine exhaust, diesel engines, and other industrial processes.

2.8.1 Principle of Operation of Thermocouple

In 1821, the German–Estonian physicist Thomas Johann Seebeck discovered that when any conductor is subjected to a thermal gradient, it will generate a voltage. This is now known as the thermoelectric effect or Seebeck effect. Any attempt to measure this voltage necessarily involves connecting another conductor to the "hot" end. This additional conductor will then also experience the temperature gradient, and develop a voltage of its own which will oppose the original. Fortunately, the magnitude of the effect depends on the metal in use. Using a dissimilar metal to complete the circuit creates a circuit in which the two legs generate different voltages, leaving a small difference in voltage available for measurement. That difference increases with temperature, and is between 1 and 70 microvolts per degree Celsius (μV/°C) for standard metal combinations.

2.8.2 Practical use of Thermocouple

Voltage–temperature Relationship

For typical metals used in thermocouples, the output voltage increases almost linearly with the temperature difference (ΔT) over a bounded range of temperatures. For precise measurements or measurements outside of the linear temperature range, non-linearity must be corrected. The nonlinear relationship between the temperature difference (ΔT) and the output voltage (mV) of a thermocouple can be approximated by a polynomial:

$$\Delta T = \sum_{n=0}^{N} a_n v^n \qquad 2.1$$

The coefficients a_n are given for n from 0 to between 5 and 13 depending upon the metals. In some cases better accuracy is obtained with additional non-polynomial terms. A database of voltage as a function of temperature, and coefficients for computation of temperature from voltage and vice-versa for many types of thermocouple is available online.

In modern equipment the equation is usually implemented in a digital controller or stored in a look-up table older devices use analog circuits.

2.8.3 Types of Thermocouple

Certain combinations of alloys have become popular as industry standards. Selection of the combination is driven by cost, availability, convenience, melting point, chemical properties, stability, and output. Different types are best suited for different applications. They are usually selected based on the temperature range and sensitivity needed. Thermocouples with low sensitivities (B, R, and S types) have correspondingly lower resolutions. Other selection criteria include the inertness of the thermocouple material, and whether it is magnetic or not. Standard thermocouple types are listed below with the positive electrode first, followed by the negative electrode.

K- TYPE

Type K (chromel{90 percent nickel and 10 percent chromium}–alumel)(Alumel consisting of 95% nickel, 2% manganese, 2% aluminium and 1% silicon) is the most common general purpose thermocouple with a sensitivity of approximately 41 µV/°C, chromel positive relative to alumel. It is inexpensive, and a wide variety of probes are available in its −200 °C to +1350 °C / -328 °F to +2462 °F range. Type K was specified at a time when metallurgy was less advanced than it is

today, and consequently characteristics may vary considerably between samples. One of the constituent metals, nickel, is magnetic. A characteristic of thermocouples made with magnetic material is that they may undergo a step change in output when the magnetic material reaches its Curie point (around 354 °C for type K thermocouples).

E-TYPE

Type E (chromel–constantan) has a high output (68 μV/°C) which makes it well suited to cryogenic use. Additionally, it is non-magnetic.

J-TYPE

Type J (iron–constantan) has a more restricted range than type K (−40 to +750 °C), but higher sensitivity of about 55 μV/°C. The Curie point of the iron (770 °C) causes an abrupt change in the characteristic, which determines the upper temperature limit.

TYPE-N

Type N (Nicrosil–Nisil) (Nickel-Chromium-Silicon/Nickel-Silicon) thermocouples are suitable for use at high temperatures, exceeding 1200 °C, due to their stability and ability to resist high temperature oxidation. Sensitivity is about 39 μV/°C at 900 °C, slightly lower than type K. Designed to be an improved type K due to increased stability at higher temperatures, it is becoming more popular, though the differences may or may not be substantial enough to warrant a change.

PLATINUM TYPES B, R, AND S

Types B, R, and S thermocouples use platinum or a platinum–rhodium alloy for each conductor. These are among the most stable thermocouples, but have lower sensitivity than other types, approximately 10 μV/°C. Type B, R, and S thermocouples are usually used only for high temperature measurements due to their high cost and low sensitivity.

CHAPTER 3

3.0 MATERIALS AND METHOD

3.1 EQUIPMENT

The equipment used for this research project are Personal Computer, COMSOL Software Chamber furnace ,Thermocouples, Digital temperature controllers.

3.2 MODEL SETTING

The chamber furnace is modelled as a rectangular slice with the dimensions as follows:

Table 3.1: Dimension of the chamber furnace

	Inner Dimension(m)	**Outer Dimension(m)**
W	0.36	0.56
L	0.40	0-69
H	0.32	0.57

3.2.1 The Heat Equation

The fundamental law governing all heat transfer is the first law of thermodynamics, commonly referred to as the principle of conservation of energy. However, internal energy, *U*, is a rather inconvenient quantity to measure and use in simulations. Therefore, the basic law is usually rewritten in terms of temperature, *T*. For a fluid, The resulting heat equation is:

$$\rho Cp\left(\frac{\partial T}{\partial t}\right) + \nabla.(-k\nabla T) = Q \text{---------} \quad 3.1$$

Where ρ is the density, C_p is the specific heat capacity, k is the thermal conductivity, T is the temperature, Q is the quantity of heat conducted and t is the time.

The General Heat Transfer application mode uses Fourier's law of conduction which states that the conductive heat flux, **q**, is proportional to the temperature gradient,

$$q_i = -k(\partial T/\partial x_i) \text{----------} \quad 3.2$$

$$n.k\,\Delta T = 0 \text{----------} \quad 3.3$$

$$-n_u.(-k_u \Delta T_u) - n_d.(-k_d\,\Delta T_d) = q_o + \varepsilon(G - \sigma T^4) \text{---------} \quad 3.4$$

Where n =surface normal vector k= Thermal conductivity T=Temperature, q_o=Heat source, ε=Surface Emissivity, G= irradiation flux, σ= Stefan's constant,

u= upward d= downward

3.3 MODEL PARAMETERS

The physical and electrical parameters used in the execution of the software were derived from the literature and are stated as follows:

Table 3.2: Parameters used in the modelling

PARAMETERS	AIR	FIREBRICKS	HEATING ELEMENT
Specific Heat Capacity(Cp)	1100J/kg/K	815J/kg/K	135J/kg/K
Thermal conductivity (k)	-	0.4W/m.K	121W/m.k
Density (ρ)	-	1300kg/m^3	18700kg/m^3
Emissivity (ε)	-	0.68	0.9
Temperature (T)	298K	-	-

3.4 SUB- DOMAIN SETTINGS

The sub-domain setting is used to enter the material property in the COMSOL software.

To enter material properties for conductive heat transfer, we go to the Physics menu, select Sub domain Settings to open the like-named dialog box, and then go to the Conduction as shown in the fig. 3.1:

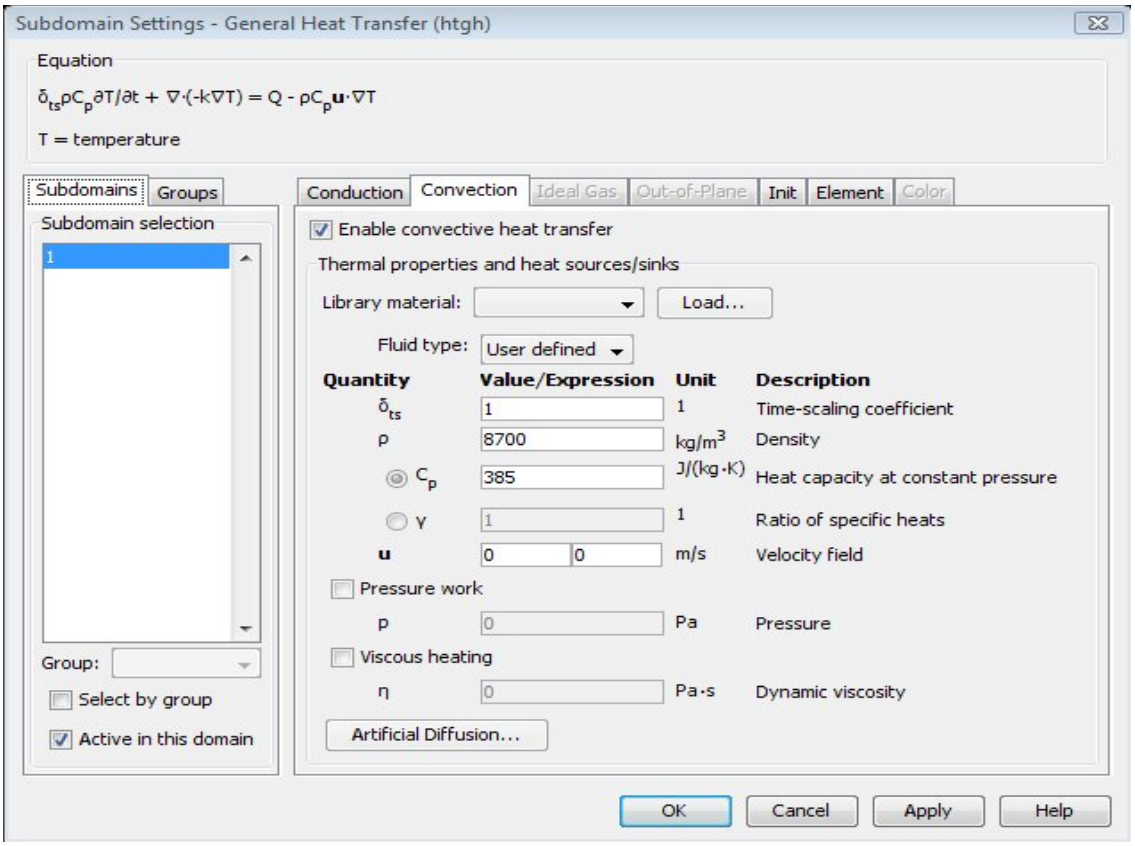


Figure 3.1: The Conduction page of the Sub -domain Settings dialog box

The sub domain quantities shown in Table 3.1are available on the Conduction page

Table 3.3**:** Sub- domain quantities

Quantity	**Variable**	**Description**
Δts	Dts	Time-scaling coefficient
P	Rho	Density
C*p*	C	Heat capacity
K	K	Thermal conductivity
Q	Q	Heat source
Γ	Gamma	Ratio of specific heats
P	P	Pressure
H	Eta	Dynamic viscosity

Time-scaling coefficient (δt)

This coefficient is normally 1, but you can change the time scale, for example, from seconds to minutes by setting it to 1/60.

Density (ρ)

The density can be a function of the temperature, and also of the pressure in a coupled flow simulation. When Fluid type is set to Ideal gas, the density is defined through the ideal gas law.

Heat capacity (C*p)*

Cp describes the amount of heat energy required to produce a unit temperature change in a unit mass at constant pressure. The heat capacity is normally a function of temperature..

Thermal conductivity (*k)*

You can enter *k* either as a scalar, which is appropriate for fluids and isotropic solids, or as a tensor describing an anisotropic material. If you have activated a turbulence model, *k* is replaced by (*k* + *kT*) where *kT* is the turbulent heat conductivity.

Heat source (*Q)*

Q describes heat generation within the domain. Express heating and cooling with positive and negative values, respectively.

Ratio of specific heats (γ)

γ is the ratio of heat capacity at constant pressure, *Cp*, to heat capacity at constant volume, *Cv*. When using the ideal gas law to describe a fluid, specifying γ is enough to evaluate *Cp*. For common diatomic gases such as air, γ = 1.4 is the standard value.

Pressure (*p)*

The pressure, *p*, can be specified either if the fluid type is set to **Ideal gas**, or if the **Pressure work** check box has been selected. The pressure work term takes effect only if the pressure expression is a function of time or of at least one of the dependent variables in the model.

Dynamic viscosity(η)

The dynamic viscosity η is used together with the velocity expressions to evaluate the viscous heating when you have selected the corresponding check box.

3.5 BOUNDARY CONDITIONS

Boundary conditions define the interface between the model geometry and its surroundings. We can also set interface conditions on interior boundaries in a model geometry. For the physics

modes and the optional COMSOL modules, select from predefined boundary conditions. We can set different boundary conditions for each boundary.

To specify general boundary coefficients for any COMSOL Multiphysics model, we use the **Boundary Settings** dialog box

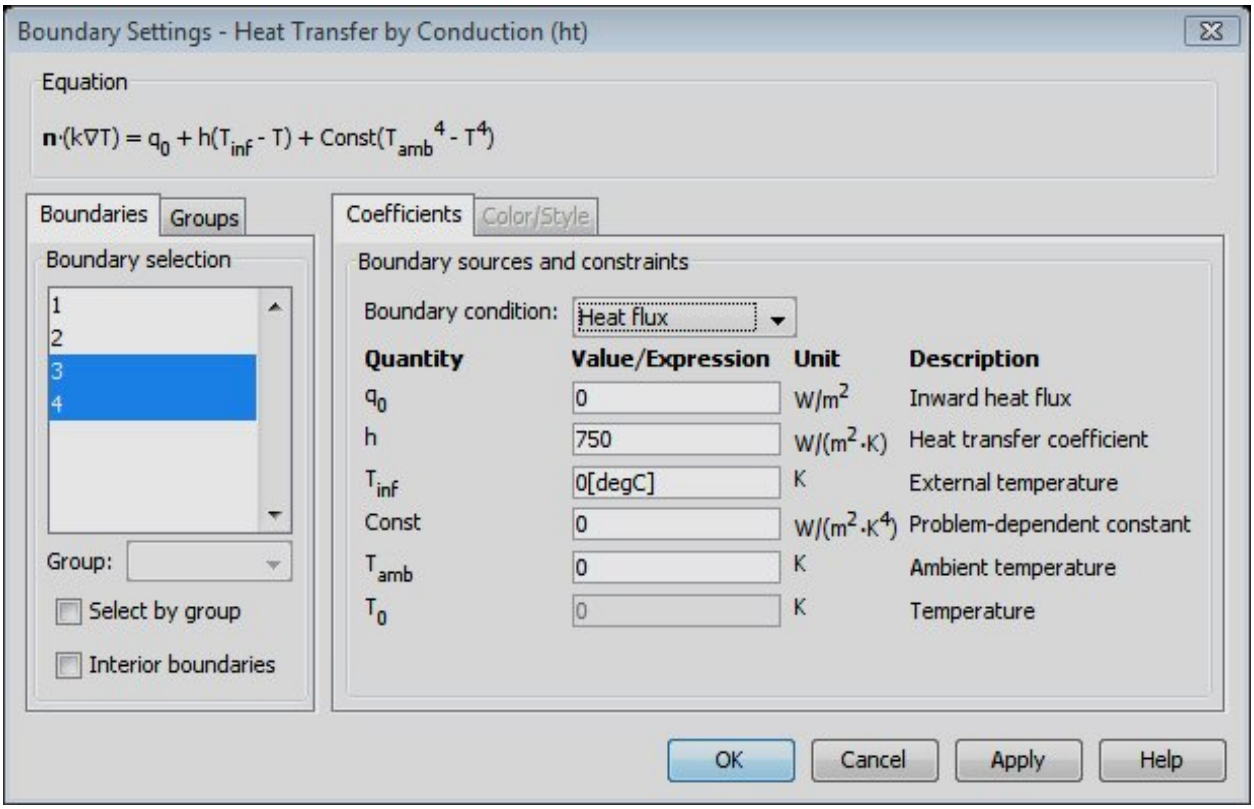


Figure 3.2: Boundary condition dialog box

The General Heat Transfer application mode supports boundary conditions of two fundamental types—the Dirichlet condition

$$T=T_o \text{ ---------- } 3.5$$

and the heat-flux (or Neumann) condition

$$n.q=q_o+q_r+q_s+h(T_{inf}- T_o) \text{ ---------- } 3.6$$

where

$$q=-k \Delta T+ \rho C_p T \text{----------} 3.7$$

q is the total heat flux vector (W/m^2).

•**n** is the normal vector of the boundary, pointing out from the domain.

•q_0 is inward heat flux (W/m^2), normal to the boundary, from external sources.

•q_r is net influx from radiation (W/m^2).

•q_s represents energy transferred from other parts of the boundary through a thin, highly conductive shell (W/m^2).

•h is a heat transfer coefficient ($W/(m^2 \cdot K)$).

- T_{inf} represent the external temperature

3.5.1 Interior and Exterior Boundaries

When specifying boundary and interface conditions, COMSOL differentiates between exterior and interior boundaries:

•An *exterior boundary* is an outer boundary of the modeling domain.

•A *interior boundary* is a dividing interface between two sub domains in the modeling domain.

Setting Conditions on Boundaries

In the Physics menu, choose Boundary Settings to open the Boundary Settings dialog box. In this tabbed dialog box you select boundaries and specify boundary conditions.

Setting Conditions on Interior Boundaries

By default we cannot set interface conditions on interior boundaries. COMSOL always ensures continuity of flux across interior boundaries, so in most cased there is no need to think about these conditions. To enable the specification of interface conditions on interior boundaries:

1 Go to the Physics menu and choose Boundary Settings.

2 Select the Interior boundaries check box.

For each application mode, the **Boundary condition** list show the applicable condition types for interior and exterior boundaries. If you select both types of boundaries, the list contains the conditions common to all boundaries.

3.6 Creating Meshes

A mesh is a partition of the geometry model into small units of simple shapes. It is possible to create *free*, *mapped*, *extruded*, *revolved*, *swept*, and *boundary layer meshes*. The mesh generator creating free meshes, also referred to as the *free mesher*, is the only mesher that can be used on all types of geometry objects.

3.7 PROCESSING AND VISUALIZATION MODE

COMSOL provides numerous processing and visualization tools including advanced graphics, data display and export function and a reports generator. It creates a wide variety of plots:

• Surface plots• Slice plots• Isosurface plots• Contour plots• Streamline plots•Pathline plotsthat describe particle traces• Principal stress/strain plots• Combinations of these plots

In addition, animations reveal the dynamics in a solution. Cross-section plots can interpolate within a domain to extract mesh-independent plots, and the software can also extend these plots in time or along parametric solutions. Domain plots provide similar capabilities for geometric domains. Global plots can visualize globally defined variables, typically solutions to ODEs and algebraic equations. We can also compute numerical integrals of model quantities as well as display and save post processing data.

3.7.1 Selecting a Plot Type

In the **Plot type** area we indicate which types to use in the plot. The **Geometry edges** check box is normally selected to show the geometry edges; clear this check box to exclude geometry edges, for example, with line plots on geometry edges.

3.7.2 Selecting a Solution

For an eigenvalue, parametric, or time-dependent problem, select which solutions to use for the visualization in the corresponding list. For time-dependent problems, you can select Interpolated from the list and then enter an arbitrary time within the simulation time frame in the time edit field.

Note that the selected plots are only rendered where the corresponding expression is defined. Thus, the plotted expressions must be defined on all of the selected geometries in order for the plot to be rendered on all selected geometries.

3.8 PROCEDURES FOR DEVELOPING THE MODEL

The procedures for developing the modeling and simulation of temperature distribution in a chamber furnace are as follows:

a) **Modeling Navigator**

i) Start ‘’COMSOL’’

ii) In the ‘’Space dimension’’ list select 3D (under the ‘’New’’ tab)

iii)From the list of application models select ‘’ Heat Transfer Module then General Heat Transfer then Transient analysis’’

iv) Click ‘’Ok’’

b) **Geometry Modeling**

i).Go to the ‘’ Draw’’ menu and select ‘’ Specify Objects then Rectangle’’

ii). Enter the inner dimensions of the rectangle, Enter ‘’0.36’’ in the W- field , ‘’0.40’’in the L- field and ‘’0.32’’ in the H-field . Repeat for the outer dimensions of the rectangle. Enter ‘’0.56’’ in the W-field , ‘’0.69 ‘’ in the L- field and ‘’0.57’’ in the H-field

iii). Click ‘‘Ok’’

iv).Click on ‘’Zoom Extents’’ button in the zoom menu toolbar to zoom into the geometry.

c) **Physics Setting**

Physics setting in COMSOL consists of two parts:

1. Sub- domain setting. The sub domain setting help us specify material properties , initial conditions and mode of heat transfer .

2. Boundary setting are used to specify what is happening at the boundaries of the geometry

Sub – domain Setting

i) From the ‘’PHYSICS’’ menu select ‘’sub-domain setting’’

ii) Select subdomain 1 in the ‘’subdomain selection’’ window

iii) Enter ‘’0.4’’ in the field for the thermal conductivity of fire bricks (k). Enter ‘’1300’’ in the field for density (ρ) . Enter ‘’815’’ in the field for the heat capacity of the fire bricks (C_p). Repeat the same for the rods(Heating elements) in each cases.

iv) Swith to ‘’ Init ‘’ tab . We specify intial temperature condition

v) Enter ‘’273.15 +25’’ in the initial value field

Boundary Setting

i) From the ‘’PHYSICS ‘’ menu open ‘’Boundary Setting’’

ii) Select the boundaries while holding down the shift key on the key board

iii) Apply the following boundary conditions

BOUNDARY	BOUNDARYCONDITION	COMMENT
1,2,3,4,5,6	Heat Flux	Enter T_f=273.15+25 h=0

iv) Click ‘’Ok’’

d) **Mesh Generation**

To minimize the computational time without compromising much accuracy of the solution , we must change the default meshing parameters

i) Go to the ‘’PHYSICS’’ menu and select Selection mode then select ‘’sub domain mode’’

ii) From the ‘’Edit menu’’ choose ‘’select all’’

iii) Click the ‘’Mesh button’’ on the left hand side of tool bar.

e**) Solve Mode**

To program the solver with proper time stepping and the final time

i) Choose ‘’Solver Parameter’’ from the solution

ii) In the ‘’Time stepping’’ section enter ‘’0 :10:120’’ in the time field

iii) Click Ok

iv) From the ‘’Solve’’ menu select ‘’Solve parameter’’(Allow few minutes for solution)

v) Choose Save from File then Save.

f) **Post Processing Mode**

i) From the ‘’Post processing’’ Menu, open ‘’Plot Parameters’’

ii) Under the ‘’surface’’ tab adjust the variable and change it to temperature in K

iii) Go to slice plot and enter the co-ordinates to the x,y,z planes

iv) Click apply

v) Click ‘’Ok ‘’ the 3D – temperature distribution will be display

3.9 EXPERIMENTAL WORK

The laboratory temperature measurement device used in this project is thermocouple which is used to determine the temperature distribution across the furnace. Five thermocouples were set up in the chamber furnace at different positions in the furnace chamber. Five digital temperature controllers were connected to the thermocouple at five different locations in the furnace chamber. Also temperatures were also measured at different time intervals of 10 minutes. We discovered that there is significant temperature distribution across the furnace in which there is disparity between the experimental result and the simulated result obtained. The first temperature were set at 900^{o}C for 120mins at a time intervals of 10min. The second were set at 1000^{o}C and different temperature were recorded at different location. The planes were divided into three for different temperature ranges.The experiment was conducted using generator because of the power failure .The experiment was conducted several times using the coordinate of the points in each of the 3- planes. The results of the modeling were compared with the experimental values and it was found that there were disparities. The result of the simulated temperature at position (-0.125, -0.15,0) after 10mins was 525K whereas the measured temperature distribution at the same position was 353K. The disparity was due to contamination and degradation of furnace refractory lining which result from the reduction and re-oxidation of silica found in the refractory after prolong heating of the chamber furnace.

3.9.1 3D Cross-section slice plot

The 3D cross section slice plot visualizes a quantity in one or several planes in time along a parameter range. In the slice data the co-ordinate system area is used to specify the plane

orientation and position. The procedures for slice plot of the planes Y(-0.15) , Y(0) and Y(0.15) are as follows:

1. Click ‘’COMSOL’’ to open the Model Geometry
2. Click on the ‘’ Post processing Mode’’
3. Select Cross section Plot parameter
4. Click on ‘’Slice plot’’
5. Enter the Coordinates from ‘’ Y(-0.15)’’ plane
6. Enter the Coordinates from ‘’Y(0.0)’’ plane
7. Enter the Coordinates from ‘’ Y(0.15)’’ plane
8. Click Apply
9. Click Ok

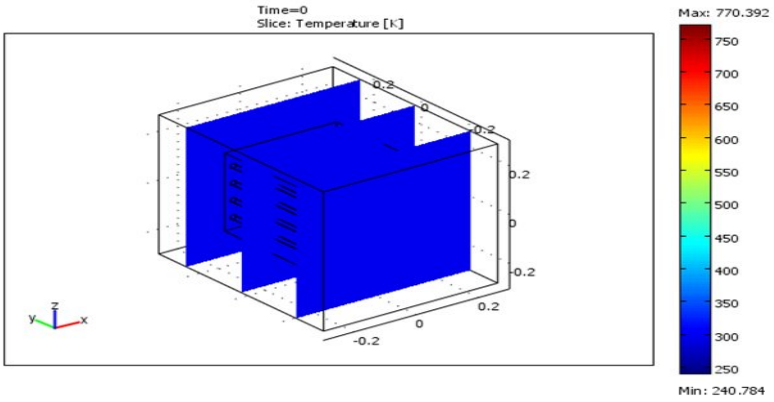


Figure : Diagram showing the 3D- planes and the temperature distribution in the furnace

CHAPTER 4

RESULTS AND DISCUSSION

4.1 RESULTS

When the furnace was mathematically described in terms of temperature distribution, the result from the COMSOL simulation were compared with temperatures measured using thermocouples in the laboratory chamber furnace. Temperature - Profile was made for both simulation and measured temperature. For the simulation and experimental procedures, the furnace was divided into 3 planes , The planes are Y(-0.15) , Y(0) and Y(0.15). The temperatures were measured at five different positions. The results of both simulation and the measured value are given below:

4.1.1 Graphical representation of the Simulation results of the temperature distribution in a Chamber furnace.

The results of the simulation of the temperature distribution in the furnace with time are indicated below .The co-ordinate probe plot of the chamber furnace has nines point for each plane as shown in Figures 4.1, 4.2 and 4.3 respectively.

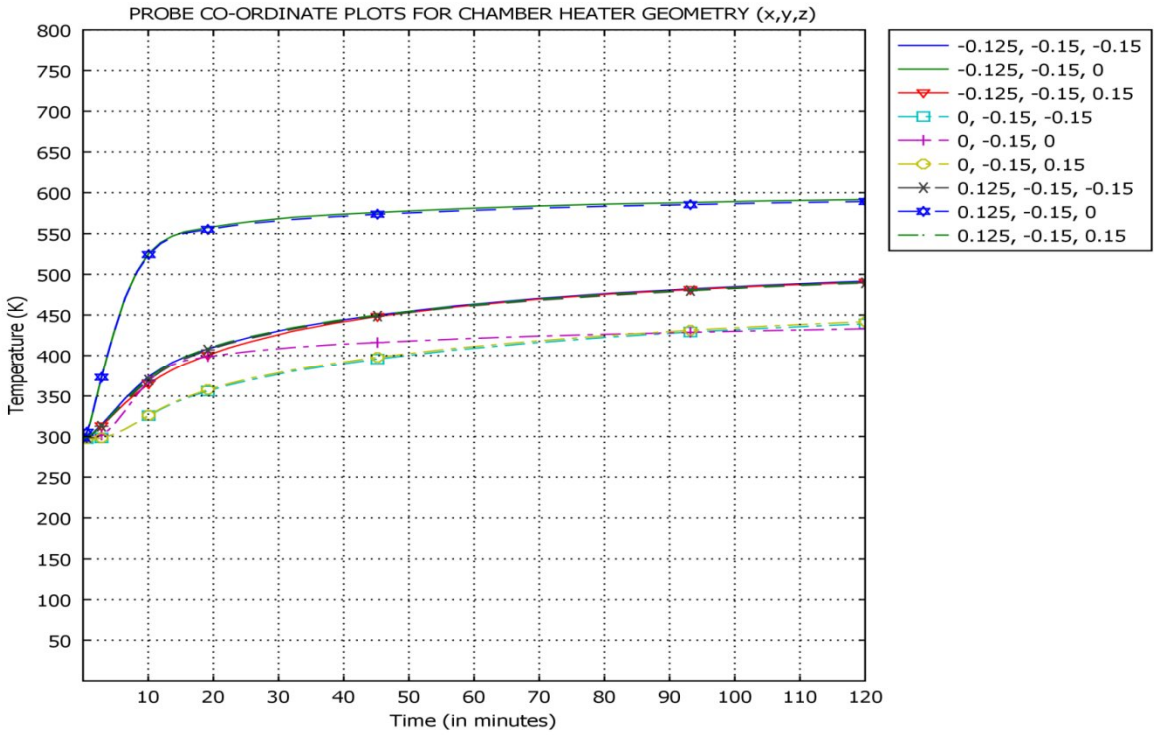


Figure 4.1: Co-ordinate Plot for Chamber Furnace at Plane Y(-0.15)

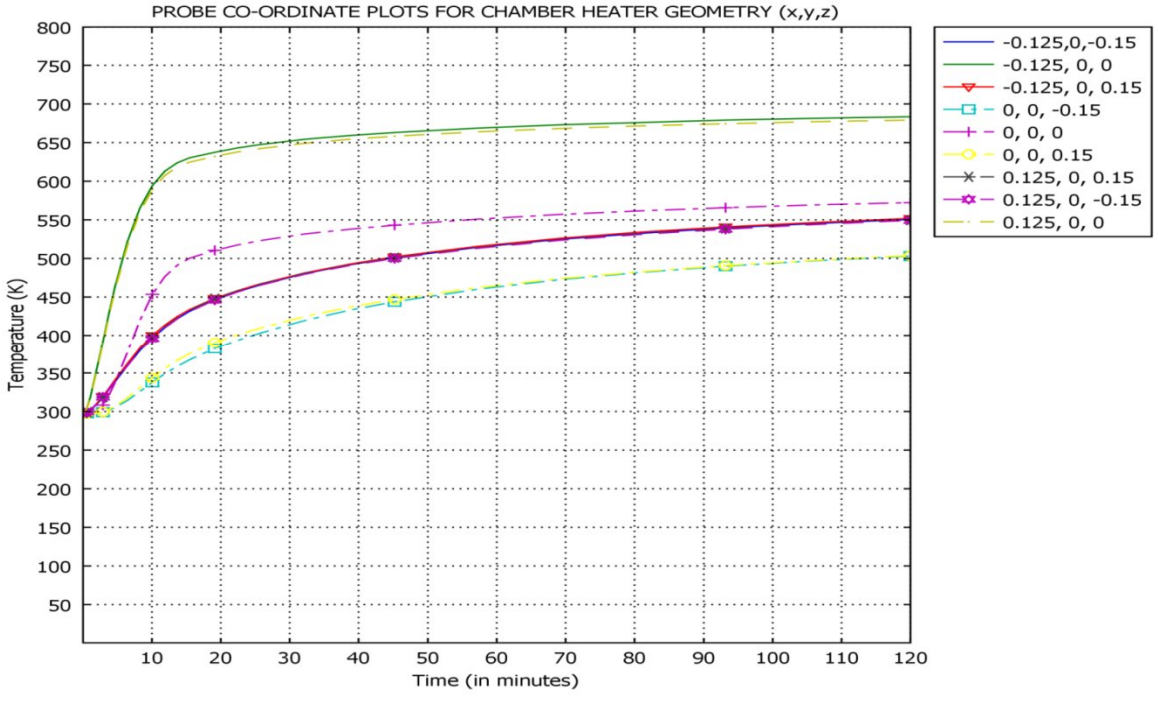


Figure 4.2: Co-ordinate Plot for Chamber Furnace at Plane Y(0)

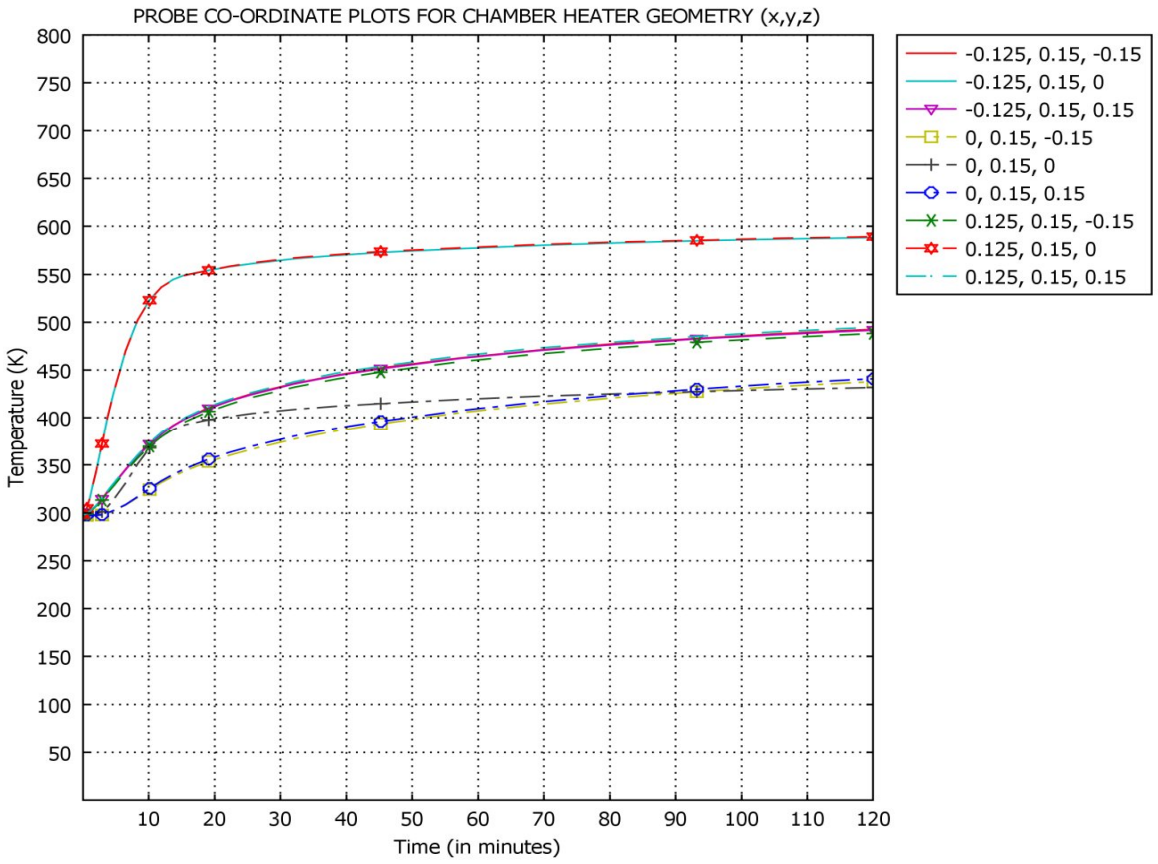


Figure 4.3: Co-ordinate Plot for Chamber Furnace at Plane Y(0.15)

4.1.2 Simulation and Experimental temperature distributed in a Chamber Furnace

The results of the simulation and the experimental temperature distribution in a chamber furnace are shown in table 4.1 below:

Table 4.1: SIMULATION AND EXPERIMENTAL TEMPERATURE DISTRIBUTION IN A CHAMBER FURNACE

a) PLANE Y(-0.15)

Position (m) (x,y,z) (-0.125,-0.15,0)			Position (m) (x,y,z) (0,-0.15,-0.15)		Position (m) (x,y,z) (0,-0.15,0.15)		Position (m) (x,y,z) (0.125,-0.15,0)		Position (m) (x,y,z) (0,-0.15,0)	
t(mins)	T_{sim} (K)	$T_{mes}(^oC)$	T_{sim}(K)	$T_{mes}(^oC)$	T_{sim}(K)	$T_{mes}(^oC)$	T_{sim}(K)	$T_{mes}(^oC)$	T_{sim}(K)	$T_{mes}(^oC)$
10.00	525.00	80.00	325.00	25.00	325.00	25.00	525.00	82.00	360.00	85.00
20.00	550.00	85.00	350.00	28.00	350.00	30.00	550.00	87.00	400.00	89.00
30.00	560.00	92.00	375.00	36.00	375.00	35.00	560.00	92.00	410.00	92.00
40.00	565.00	100.00	380.00	40.00	380.00	40.00	565.00	100.00	415.00	99.00
50.00	575.00	110.00	400.00	44.00	400.00	45.00	575.00	100.00	417.00	105.00
60.00	580.00	105.00	405.00	48.00	405.00	49.00	580.00	110.00	418.00	110.00
70.00	585.00	110.00	410.00	50.00	410.00	50.00	585.00	110.00	420.00	115.00
80.00	590.00	115.00	415.00	55.00	415.00	55.00	590.00	118.00	425.00	120.00
90.00	593.00	120.00	425.00	60.00	425.00	60.00	593.00	120.00	426.00	125.00
100.00	595.00	125.00	427.00	65.00	427.00	65.00	595.00	125.00	427.00	130.00
110.00	596.00	130.00	435.00	70.00	435.00	70.00	596.00	130.00	430.00	135.00
120.00	597.00	140.00	440.00	78.00	440.00	80.00	597.00	135.00	435.00	139.00

b) PLANE Y(0)

Position (m) (x,y,z) (-0.125,0,-0.15)			Position (m) (x,y,z) (0.125,0,-0.15)		Position (m) (x,y,z) (0,0,0)		Position (m) (x,y,z) (-0.125,0,0.15)		Position (m) (x,y,z) (0.125,0,0.15)	
t(mins)	T_{sim} (K)	T_{mes} (^oC)	T_{sim} (K)	T_{mes} (^oC)	T_{sim} (K)	T_{mes} (^oC)	T_{sim} (K)	T_{mes} (^oC)	T_{sim} (K)	T_{mes} (^oC)
10.00	410.00	20.00	410.00	20.00	450.00	25.00	371.00	20.00	410.00	20.00
20.00	450.00	30.00	450.00	32.00	515.00	30.00	412.00	30.00	450.00	32.00
30.00	475.00	45.00	475.00	44.00	530.00	40.00	427.00	45.00	475.00	44.00
40.00	490.00	50.00	490.00	50.00	540.00	55.00	447.00	50.00	490.00	50.00
50.00	510.00	55.00	510.00	55.00	545.00	65.00	450.00	55.00	510.00	55.00
60.00	520.00	60.00	520.00	60.00	550.00	67.00	455.00	60.00	520.00	60.00
70.00	525.00	65.00	525.00	65.00	555.00	68.00	458.00	65.00	525.00	65.00
80.00	530.00	70.00	530.00	70.00	560.00	70.00	460.00	70.00	530.00	70.00
90.00	535.00	80.00	535.00	80.00	565.00	75.00	465.00	80.00	535.00	80.00
100.00	540.00	90.00	540.00	85.00	570.00	77.00	475.00	90.00	540.00	85.00
110.00	549.00	95.00	549.00	90.00	573.00	80.00	485.00	95.00	549.00	90.00
120.00	550.00	100.00	550.00	99.00	574.00	85.00	490.00	100.00	550.00	99.00

c) PLANE Y(0.15)

Position (m) (x,y,z) (-0.125,0.15,0)			Position (m) (x,y,z) (0,0.15,-0.15)		Position (m) (x,y,z) (0,0.15,0.15)		Position (m) (x,y,z) (0.125,0.15,0)		Position (m) (x,y,z) (0,0.15,0)	
t(mins)	$T_{sim(K)}$	$T_{mes}{}^{o}C$	$T_{sim(K)}$	$T_{mes}{}^{o}C$	$T_{sim(K)}$	$T_{mes}{}^{o}C$	$T_{sim(K)}$	$T_{mes}{}^{o}C$	$T_{sim(K)}$	$T_{mes}{}^{o}C$
10.00	525.00	80.00	325.00	20.00	325.00	20.00	525.00	82.00	325.00	87.00
20.00	550.00	85.00	350.00	30.00	350.00	25.00	550.00	87.00	410.00	90.00
30.00	560.00	90.00	360.00	35.00	375.00	32.00	560.00	90.00	420.00	92.00
40.00	575.00	95.00	380.00	44.00	380.00	35.00	570.00	95.00	425.00	95.00
50.00	580.00	101.00	400.00	49.00	400.00	44.00	575.00	102.00	427.00	100.00
60.00	580.00	108.00	405.00	53.00	405.00	49.00	580.00	108.00	428.00	102.00
70.00	577.00	110.00	410.00	58.00	410.00	53.00	577.00	110.00	425.00	105.00
80.00	580.00	115.00	425.00	60.00	425.00	57.00	580.00	115.00	400.00	108.00
90.00	585.00	120.00	426.00	68.00	426.00	60.00	585.00	125.00	405.00	110.00
100.00	590.00	125.00	427.00	73.00	427.00	68.00	590.00	125.00	410.00	120.00
110.00	590.00	130.00	430.00	80.00	430.00	73.00	590.00	132.00	420.00	125.00
120.00	597.00	138.00	435.00	100.00	435.00	79.00	595.00	139.00	425.00	130.00

4.2 DISCUSSION OF RESULTS

4.2.1 Temperature Distribution for plane Y (-0.15)

The results of simulated temperature distribution at position (-0.125,-0.15,0) after 10mins was 525K as shown in Fig.4.1 whereas the measured temperature distribution at the same position was 80^{o}C(353K) as shown in fig. 4.6. The variation in the temperature distribution may have due to the degradation of furnace refractory lining after prolong heating in the furnace chamber. Also the simulated temperature distribution at position (0,-0.15,0) after 50mins was 400K as shown in fig. 4.1 Whereas the measured temperature was 373K.The difference in the temperature distribution may have due to heat loses in the furnace, Thought there was rapid increase in temperature for both simulated results and measured values.

The results of the simulated temperature at position (0,-0.15,-0.15) after 30mins was 375K as shown in Fig.4.1 whereas the measured temperature at the same position was 36 ^{o}C(309K) , though the temperature increases rapidly in both cases. The variation in the temperature may have due to low efficiency of the chamber furnace.

4.2.2 Temperature Distribution for plane Y (0)

The simulated temperature distribution at position (-0.125, 0, 0.15) after 40mins was 447K as shown in fig. 4.2 whereas the temperature distribution for the measured value was 373K. The variation may have due to the heat loses from the furnace . However the temperature increases rapidly with time both for the simulated and the measured temperature distribution values .Also it was found that the simulation results in position (-0.125,0,-0.15) and (-0.125,0,-.15)are the same , this may due to energy transportation in those position were the same. The results of measurement of temperature distribution at 1000^{O}C for plane Y(0)

chamber increase rapidly than that of temperature at 900^{O}C .This may due to the heating effect in the chamber. Also the results of the measurement of temperature distribution at 1000 ^{O}C and 1100 ^{O}C at plane Y(0) are the same.

4.2.3 Temperature Distribution for plane Y (0.15)

The simulated temperature distribution at position (0, 0.15, 0.15) after 10mins was 325K as shown in fig. 4.3 but when compared with the measured temperature distribution it was 293K.The variation in the temperature is not too pronounced. This means that the simulated temperature shows agreement with the measured value.

The simulated temperature distribution at position (0, 0.15,0) after 10mins was 375K whereas the measured temperature distribution at the same position was 87 ^{O}C(360K).The variation in temperature distribution may have due to low efficiency of the furnace chamber.

Though there were rapid increase in temperature for both simulated and the measured values. . The results of measurement of temperature distribution at 900 ^{O}C in the positions (-0.125, 0.15,0) and (0, 0.15,-0.15) are not the same. This may contribute to the fact that the (-0.125, 0.15, 0) is very close to the heating element and there is rapid increase in temperature with time than the position (0,0.15,0.15). The same situation occurs in the positions (0.125,0.15,0) and (0,0.15, 0.15)

The results of the measurement of temperature at 900 ^{O}C in five different positions in the chamber increases rapidly with time, the increase is almost the same at 1000 ^{O}C. The results of measurement at 1100 ^{O}C is almost the same as the measured temperature at 1000 ^{O}C.

The measured temperature distribution at 900^{o}C for positions (-0.125-0.15,0) and (0.125,-0.15,0) increased rapidly with time compared to positions (0, 0.15, 0) and (0,-0.15,0). This is due to the fact that the position (-0.125, 0.15,0) is very close to the heating element than any of the other positions. Measured temperature at 900 ^{O}C and 1000^{O}C for plane Y(-0.15) are also the same. Also the measured temperature distribution at 1000^{O}C for plane Y(-0.15) were almost the same as that of 1100^{O}C.

CHAPTER 5

5.0 CONCLUSIONS AND RECOMMENDATIONS

5. 1 CONCLUSIONS

The following conclusions may be made from this work:

1. The temperature distribution in a chamber furnace was modelled and simulated using COMSOL software

2. The temperature distribution obtained from the simulation and those generated from the experiment carried out using a chamber furnace there were slight difference in the temperature values. The result of the simulated temperature at position (-0.125, -0.15,0) after 10mins was 525K whereas the measured temperature distribution at the same position was 353K, Also the result of the simulated temperature at position (0,-0.15,0) after 10mins was 360K whereas the measured temperature at the same position was 358K.The average temperature distribution was 359K. These were probably due to degradation of the refractory lining and the heat losses from the furnace chamber.

3. The results of the work show that for design purposes, especially where heat sensitivity materials are to be heated , the temperature distribution should be within a range when placed in a specific place in the chamber furnace

5.2 RECOMMENDATIONS

For better understanding and full exploitation of modeling and simulation of temperature distribution in a chamber furnace the following are recommended:

1. Further effort should be made to determine the total heat flux distribution generated in the chamber furnace for the same power supplied to the heating element

2. 3D modeling and simulation of chamber furnace can further be enhanced by taking into consideration the effect of the temperature gradient in the furnace

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APPENDIX A

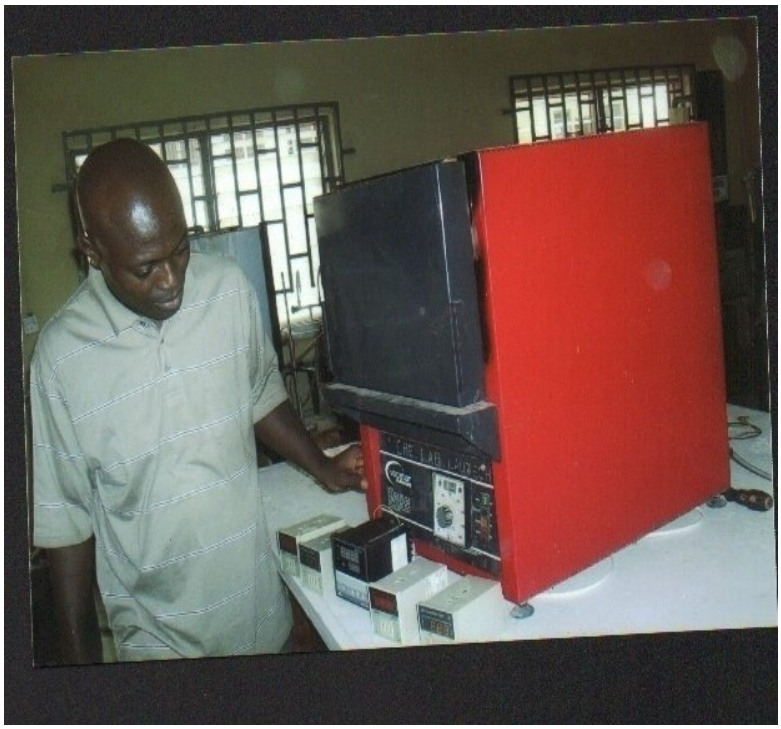


Figure A1 : Measurement of temperature distribution in the Chamber at different positions using Thermocouples

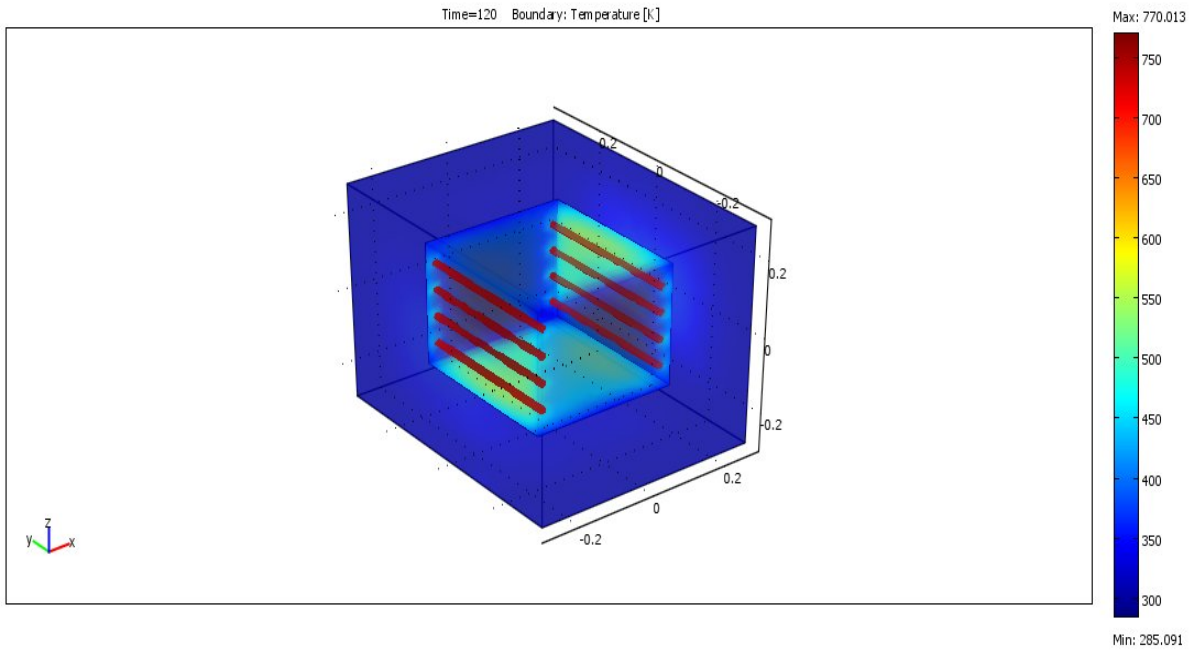


Figure A2: Diagram showing temperature distribution in the chamber furnace

APPENDIX B

RESULTS OF SIMULATION OF TEMPERATURE DISTRIBUTION IN A CHAMBER FURNACE.

Table B1: The temperature distribution simulated for plane Y(-0.15) section of the chamber furnace

Position(m) (x,y,z) (-0.125, -0.15,0.15)		**Position(m) (x,y,z) (-0.125, -0.15, 0)**		**Position(m) (x,y,z) (-0.125, -0.15, 0.15)**	
t(mins)	**T(K)**	**t(min)**	**T(K)**	**t(mins)**	**T(K)**
10.00	371.00	10.00	525.00	10.00	325.00
20.00	412.00	20.00	550.00	20.00	350.00
30.00	427.00	30.00	560.00	30.00	355.00
40.00	447.00	40.00	565.00	40.00	380.00
50.00	450.00	50.00	575.00	50.00	400.00
60.00	455.00	60.00	580.00	60.00	410.00
70.00	458.00	70.00	585.00	70.00	415.00
80.00	460.00	80.00	590.00	80.00	420.00
90.00	465.00	90.00	593.00	90.00	430.00
100.00	475.00	100.00	595.00	100.00	450.00
110.00	485.00	110.00	596.00	110.00	455.00
120.00	490.00	120.00	597.00	120.00	460.00

Table B2: The temperature distribution simulated for plane Y(-0.15) section of the chamber furnace

Position(m) (x,y,z) (0, -0.15, -0.15)		**Position(m) (x,y,z) (0, -0.15, 0)**		**Position(m) (x,y,z) (0, -0.15, 0.15)**	
t(mins)	**T(K)**	**t(min)**	**T(K)**	**t(mins)**	**T(K)**
10.00	325.00	10.00	360.00	10.00	325.00
20.00	350.00	20.00	400.00	20.00	350.00
30.00	375.00	30.00	410.00	30.00	375.00
40.00	380.00	40.00	415.00	40.00	380.00
50.00	400.00	50.00	417.00	50.00	400.00
60.00	405.00	60.00	418.00	60.00	405.00
70.00	410.00	70.00	420.00	70.00	410.00
80.00	415.00	80.00	425.00	80.00	415.00
90.00	425.00	90.00	426.00	90.00	425.00
100.00	427.00	100.00	427.00	100.00	427.00
110.00	435.00	110.00	430.00	110.00	435.00
120.00	440.00	120.00	435.00	120.00	440.00

Table B3: The temperature distribution simulated for plane Y(-0.15) section of the chamber furnace

Position(m) (x,y,z) (0.125, -0.15, -0.15)		**Position(m) (x,y,z) (0.125, -0.15, 0)**		**Position(m) (x,y,z) (0.125, -0.15, 0.15)**	
t(mins)	**T(K)**	**t(min)**	**T(K)**	**t(mins)**	**T(K)**
10.00	371.00	10.00	525.00	10.00	371.00
20.00	412.00	20.00	550.00	20.00	412.00
30.00	427.00	30.00	560.00	30.00	427.00
40.00	447.00	40.00	565.00	40.00	447.00
50.00	450.00	50.00	575.00	50.00	450.00
60.00	455.00	60.00	580.00	60.00	455.00
70.00	458.00	70.00	585.00	70.00	458.00
80.00	460.00	80.00	590.00	80.00	460.00
90.00	465.00	90.00	593.00	90.00	465.00
100.00	475.00	100.00	595.00	100.00	475.00
110.00	485.00	110.00	596.00	110.00	485.00
120.00	490.00	120.00	597.00	120.00	490.00

Table B4: The temperature distribution simulated for plane Y(0) section of the chamber furnace

Position(m) (x,y,z) (-0.125, 0, -0.15)		**Position(m) (x,y,z) (-0.125, 0, 0)**		**Position(m) (x,y,z) (-0.125, 0, 0.15)**	
t(mins)	**T(K)**	**t(min)**	**T(K)**	**t(mins)**	**T(K)**
10.00	410.00	10.00	595.00	10.00	371.00
20.00	450.00	20.00	640.00	20.00	412.00
30.00	475.00	30.00	650.00	30.00	427.00
40.00	490.00	40.00	660.00	40.00	447.00
50.00	510.00	50.00	665.00	50.00	450.00
60.00	520.00	60.00	670.00	60.00	455.00
70.00	525.00	70.00	675.00	70.00	458.00
80.00	530.00	80.00	677.00	80.00	460.00
90.00	535.00	90.00	678.00	90.00	465.00
100.00	540.00	100.00	679.00	100.00	475.00
110.00	549.00	110.00	680.00	110.00	485.00
120.00	550.00	120.00	680.00	120.00	490.00

Table B5: The temperature distribution simulated for plane Y(0) section of the chamber furnace

Position(m) (x,y,z) (0, 0, -0.15)		**Position(m) (x,y,z) (0, 0, 0)**		**Position(m) (x,y,z) (0, 0, 0.15)**	
t(mins)	**T(K)**	**t(min)**	**T(K)**	**t(mins)**	**T(K)**
10.00	340.00	10.00	450.00	10.00	371.00
20.00	380.00	20.00	515.00	20.00	412.00
30.00	415.00	30.00	530.00	30.00	427.00
40.00	435.00	40.00	540.00	40.00	447.00
50.00	450.00	50.00	545.00	50.00	450.00
60.00	460.00	60.00	550.00	60.00	455.00
70.00	470.00	70.00	555.00	70.00	458.00
80.00	475.00	80.00	560.00	80.00	460.00
90.00	478.00	90.00	565.00	90.00	465.00
100.00	490.00	100.00	570.00	100.00	475.00
110.00	500.00	110.00	573.00	110.00	485.00
120.00	505.00	120.00	574.00	120.00	490.00

Table B6: The temperature distribution simulated for plane Y(0) section of the chamber furnace

Position(m) (x,y,z) (0.125, 0., 0.15)		**Position(m) (x,y,z) (0.125, 0, -0.15)**		**Position(m) (x,y,z) (0.125, 0, 0)**	
t(mins)	**T(K)**	**t(min)**	**T(K)**	**t(mins)**	**T(K)**
10.00	410.00	10.00	410.00	10.00	595.00
20.00	450.00	20.00	450.00	20.00	640.00
30.00	475.00	30.00	475.00	30.00	698.00
40.00	490.00	40.00	490.00	40.00	655.00
50.00	510.00	50.00	510.00	50.00	660.00
60.00	520.00	60.00	520.00	60.00	665.00
70.00	525.00	70.00	525.00	70.00	670.00
80.00	530.00	80.00	530.00	80.00	675.00
90.00	535.00	90.00	535.00	90.00	676.00
100.00	540.00	100.00	540.00	100.00	676.00
110.00	549.00	110.00	549.00	110.00	678.00
120.00	550.00	120.00	550.00	120.00	678.00

Table B7: The temperature distribution simulated for plane Y(0.15) section of the chamber furnace

Position(m) (x,y,z) (-0.125, 0.15, -0.15)		**Position(m) (x,y,z) (-0.125, 0.15, 0)**		**Position(m) (x,y,z) (-0.125, 0.15, -0.15)**	
t(mins)	**T(K)**	**t(mins)**	**T(K)**	**t(mins)**	**T(K)**
10.00	525.00	10.00	525.00	10.00	365.00
20.00	550.00	20.00	550.00	20.00	400.00
30.00	560.00	30.00	560.00	30.00	435.00
40.00	570.00	40.00	575.00	40.00	450.00
50.00	575.00	50.00	580.00	50.00	452.00
60.00	580.00	60.00	580.00	60.00	453.00
70.00	577.00	70.00	577.00	70.00	455.00
80.00	580.00	80.00	580.00	80.00	456.00
90.00	585.00	90.00	585.00	90.00	457.00
100.00	590.00	100.00	590.00	100.00	458.00
110.00	590.00	110.00	590.00	110.00	458.00
120.00	595.00	120.00	597.00	120.00	459.00

Table B8: The temperature distribution simulated for plane Y(0.15) section of the chamber furnace

Position(m) (x,y,z) (0, 0.15, -0.15)		**Position(m) (x,y,z) (0, 0.15, 0)**		**Position(m) (x,y,z) (0, 0.15, 0.15)**	
t(mins)	**T(K)**	**t(min)**	**T(K)**	**t(mins)**	**T(K)**
10.00	325.00	10.00	325.00	10.00	325.00
20.00	350.00	20.00	410.00	20.00	350.00
30.00	360.00	30.00	420.00	30.00	375.00
40.00	380.00	40.00	425.00	40.00	380.00
50.00	400.00	50.00	427.00	50.00	400.00
60.00	405.00	60.00	428.00	60.00	405.00
70.00	410.00	70.00	425.00	70.00	410.00
80.00	425.00	80.00	400.00	80.00	425.00
90.00	426.00	90.00	405.00	90.00	426.00
100.00	427.00	100.00	410.00	100.00	427.00
110.00	430.00	110.00	420.00	110.00	430.00
120.00	435.00	120.00	425.00	120.00	435.00

Table B9: The temperature distribution simulated for plane Y(0.15) section of the chamber furnace

Position(m) (x,y,z) (0.25, 0.15, -0.15)		**Position(m) (x,y,z) (0.125, 0.15, 0)**		**Position(m) (x,y,z) (0.125, 0.15, 0.15)**	
t(mins)	**T(K)**	**t(min)**	**T(K)**	**t(mins)**	**T(K)**
10.00	325.00	10.00	525.00	10.00	365.00
20.00	400.00	20.00	550.00	20.00	400.00
30.00	425.00	30.00	560.00	30.00	435.00
40.00	440.00	40.00	570.00	40.00	450.00
50.00	450.00	50.00	575.00	50.00	452.00
60.00	465.00	60.00	580.00	60.00	453.00
70.00	470.00	70.00	577.00	70.00	455.00
80.00	475.00	80.00	580.00	80.00	456.00
90.00	478.00	90.00	585.00	90.00	457.00
100.00	475.00	100.00	590.00	100.00	458.00
110.00	470.00	110.00	590.00	110.00	458.00
120.00	490.00	120.00	595.00	120.00	459.00

APPENDIX C

Table C1: Measured Temperature distribution of the chamber furnace at 900^{o}C for plane Y(0)

Position (m) (x,y,z) (-0.125,0,-0.15)		**Position (m) (x,y,z) (0.125,0,-0.15)**		**Position (m) (x,y,z) (0,0,0)**		**Position (m) (x,y,z) (-0.125,0,0.15)**		**Position (m) (x,y,z) (0.125,0,0.15)**	
t(mins)	**T^{o}C**	**t(mins)**	**T^{o}C**	**t(mins)**	**T^{o}C**	**t(mins)**	**T^{o}C**	**t(mins)**	**T^{o}C**
10.00	20.00	10.00	20.00	10.00	25.00	10.00	20.00	10.00	20.00
20.00	30.00	20.00	32.00	20.00	30.00	20.00	30.00	20.00	32.00
30.00	45.00	30.00	44.00	30.00	40.00	30.00	45.00	30.00	44.00
40.00	50.00	40.00	50.00	40.00	55.00	40.00	50.00	40.00	50.00
50.00	55.00	50.00	55.00	50.00	65.00	50.00	55.00	50.00	55.00
60.00	60.00	60.00	60.00	60.00	67.00	60.00	60.00	60.00	60.00
70.00	65.00	70.00	65.00	70.00	68.00	70.00	65.00	70.00	65.00
80.00	70.00	80.00	70.00	80.00	70.00	80.00	70.00	80.00	70.00
90.00	80.00	90.00	80.00	90.00	75.00	90.00	80.00	90.00	80.00
100.00	90.00	100.00	85.00	100.00	77.00	100.00	90.00	100.00	85.00
110.00	95.00	110.00	90.00	110.00	80.00	110.00	95.00	110.00	90.00
120.00	100.00	120.00	99.00	120.00	85.00	120.00	100.00	120.00	99.00

Table C2: Measured Temperature distribution of the chamber furnace at 1000^{o}C for plane Y(0)

Position (m) (x,y,z) (-0.125,0,-0.15)		**Position (m) (x,y,z) (0.125,0,-0.15)**		**Position (m) (x,y,z) (0,0,0)**		**Position (m) (x,y,z) (-0.125,0,0.15)**		**Position (m) (x,y,z) (0.125,0,0.15)**	
t(mins)	**T^{o}C**	**t(mins)**	**T^{o}C**	**t(mins)**	**T^{o}C**	**t (mins)**	**T^{o}C**	**t(mins)**	**T^{o}C**
10.00	30.00	10.00	25.00	10.00	32.00	10.00	20.00	10.00	20.00
20.00	42.00	20.00	35.00	20.00	38.00	20.00	30.00	20.00	32.00
30.00	53.00	30.00	40.00	30.00	40.00	30.00	45.00	30.00	44.00
40.00	58.00	40.00	45.00	40.00	42.00	40.00	50.00	40.00	50.00
50.00	60.00	50.00	60.00	50.00	45.00	50.00	55.00	50.00	55.00
60.00	63.00	60.00	75.00	60.00	50.00	60.00	60.00	60.00	60.00
70.00	70.00	70.00	80.00	70.00	60.00	70.00	65.00	70.00	65.00
80.00	73.00	80.00	85.00	80.00	62.00	80.00	70.00	80.00	70.00
90.00	76.00	90.00	86.00	90.00	65.00	90.00	80.00	90.00	80.00
100.00	78.00	100.00	87.00	100.00	70.00	100.00	90.00	100.00	85.00
110.00	80.00	110.00	90.00	110.00	72.00	110.00	95.00	110.00	90.00
120.00	82.00	120.00	100.00	120.00	75.00	120.00	100.00	120.00	99.00

Table C3: Measured Temperature distribution of the chamber furnace at 1100^{o}C for plane Y (0)

Position (m) (x,y,z) (-0.125,0,-0.15)		**Position (m) (x,y,z) (0.125,0,-0.15)**		**Position (m) (x,y,z) (0,0,0)**		**Position (m) (x,y,z) (-0.125,0,0.15)**		**Position (m) (x,y,z) (0.125,0,0.15)**	
t(mins)	**T^{o}C**	**t(mins)**	**T^{o}C**	**t(mins)**	**T^{o}C**	**t(mins)**	**T^{o}C**	**t(mins)**	**T^{o}C**
10.00	30.00	10.00	25.00	10.00	32.00	10.00	20.00	10.00	20.00
20.00	42.00	20.00	35.00	20.00	38.00	20.00	30.00	20.00	32.00
30.00	53.00	30.00	40.00	30.00	40.00	30.00	45.00	30.00	44.00
40.00	58.00	40.00	45.00	40.00	42.00	40.00	50.00	40.00	50.00
50.00	60.00	50.00	60.00	50.00	45.00	50.00	55.00	50.00	55.00
60.00	63.00	60.00	75.00	60.00	50.00	60.00	60.00	60.00	60.00
70.00	70.00	70.00	80.00	70.00	60.00	70.00	65.00	70.00	65.00
80.00	73.00	80.00	85.00	80.00	62.00	80.00	70.00	80.00	70.00
90.00	76.00	90.00	86.00	90.00	65.00	90.00	80.00	90.00	80.00
100.00	78.00	100.00	87.00	100.00	70.00	100.00	90.00	100.00	85.00
110.00	80.00	110.00	90.00	110.00	72.00	110.00	95.00	110.00	90.00
120.00	82.00	120.00	100.00	120.00	75.00	120.00	100.00	120.00	99.00

Table C4: Measured temperature distribution of the chamber furnace at 900^{o}C for plane Y(0.15)

Position (m) (x,y,z) (-0.125,0.15,0)		**Position (m) (x,y,z) (0,0.15,-0.15)**		**Position (m) (x,y,z) (0,0.15,0.15)**		**Position (m) (x,y,z) (0.125,0.15,0)**		**Position (m) (x,y,z) (0,0.15,0)**	
t(mins)	**T ^{o}C**	**t(mins)**	**T ^{o}C**	**t(mins)**	**T ^{o}C**	**t(mins)**	**T^{o}C**	**t(mins)**	**T^{o}C**
10.00	80.00	10.00	20.00	10.00	20.00	10.00	82.00	10.00	87.00
20.00	85.00	20.00	30.00	20.00	25.00	20.00	87.00	20.00	90.00
30.00	90.00	30.00	35.00	30.00	32.00	30.00	90.00	30.00	92.00
40.00	95.00	40.00	44.00	40.00	35.00	40.00	95.00	40.00	95.00
50.00	101.00	50.00	49.00	50.00	44.00	50.00	102.00	50.00	100.00
60.00	108.00	60.00	53.00	60.00	49.00	60.00	108.00	60.00	102.00
70.00	110.00	70.00	58.00	70.00	53.00	70.00	110.00	70.00	105.00
80.00	115.00	80.00	60.00	80.00	57.00	80.00	115.00	80.00	108.00
90.00	120.00	90.00	68.00	90.00	60.00	90.00	125.00	90.00	110.00
100.00	125.00	100.00	73.00	100.00	68.00	100.00	125.00	100.00	120.00
110.00	130.00	110.00	80.00	110.00	73.00	110.00	132.00	110.00	125.00
120.00	138.00	120.00	100.00	120.00	79.00	120.00	139.00	120.00	130.00

Table C5: Measured Temperature distribution in the chamber furnace at 1000 ^{o}C for plane Y(0.15)

Position (m) (x,y,z) (-0.125,0.15,0)		**Position (m) (x,y,z) (0,0.15,-0.15)**		**Position (m) (x,y,z) (0,0.15,0.15)**		**Position (m) (x,y,z) (0.125,0.15,0)**		**Position (m) (x,y,z) (0,0.15,0)**	
t(mins)	**T ^{o}C**	**t(mins)**	**T ^{o}C**	**t(mins)**	**T ^{o}C**	**t(mins)**	**T ^{o}C**	**t(mins)**	**T ^{o}C**
10.00	80.00	10.00	22.00	10.00	22.00	10.00	80.00	10.00	88.00
20.00	85.00	20.00	28.00	20.00	28.00	20.00	85.00	20.00	91.00
30.00	90.00	30.00	33.00	30.00	33.00	30.00	90.00	30.00	92.00
40.00	100.00	40.00	42.00	40.00	44.00	40.00	92.00	40.00	96.00
50.00	108.00	50.00	44.00	50.00	46.00	50.00	98.00	50.00	98.00
60.00	110.00	60.00	49.00	60.00	48.00	60.00	100.00	60.00	99.00
70.00	120.00	70.00	54.00	70.00	50.00	70.00	105.00	70.00	100.00
80.00	125.00	80.00	58.00	80.00	52.00	80.00	110.00	80.00	110.00
90.00	130.00	90.00	60.00	90.00	56.00	90.00	115.00	90.00	120.00
100.00	132.00	100.00	68.00	100.00	60.00	100.00	120.00	100.00	122.00
110.00	136.00	110.00	73.00	110.00	65.00	110.00	125.00	110.00	130.00
120.00	140.00	120.00	80.00	120.00	75.00	120.00	130.00	120.00	136.00

Table C6: Measured Temperature distribution. in the chamber furnace at 1100 ^{o}C for plane Y(0.15)

Position (m) (x,y,z) (-0.125,0.15,0)		**Position (m) (x,y,z) (0,0.15,-0.15)**		**Position (m) (x,y,z) (0,0.15,0.15)**		**Position (m) (x,y,z) (0.125,0.15,0)**		**Position (m) (x,y,z) (0,0.15,0)**	
t(mins)	**T ^{o}C**	**t(mins)**	**T ^{o}C**	**t(mins)**	**T ^{o}C**	**t(mins)**	**T ^{o}C**	**t(mins)**	**T ^{o}C**
10.00	90.00	10.00	25.00	10.00	25.00	10.00	85.00	10.00	89.00
20.00	92.00	20.00	28.00	20.00	26.00	20.00	90.00	20.00	91.00
30.00	100.00	30.00	32.00	30.00	29.00	30.00	95.00	30.00	92.00
40.00	105.00	40.00	42.00	40.00	35.00	40.00	98.00	40.00	96.00
50.00	110.00	50.00	44.00	50.00	40.00	50.00	100.00	50.00	98.00
60.00	115.00	60.00	49.00	60.00	43.00	60.00	104.00	60.00	99.00
70.00	120.00	70.00	54.00	70.00	48.00	70.00	108.00	70.00	100.00
80.00	125.00	80.00	58.00	80.00	53.00	80.00	110.00	80.00	110.00
90.00	130.00	90.00	62.00	90.00	60.00	90.00	115.00	90.00	120.00
100.00	132.00	100.00	65.00	100.00	62.00	100.00	120.00	100.00	122.00
110.00	135.00	110.00	75.00	110.00	65.00	110.00	125.00	110.00	130.00
120.00	140.00	120.00	80.00	120.00	70.00	120.00	130.00	120.00	136.00

Table C7: Measured Temperature distribution in the chamber furnace at 900 ^{o}C for plane Y(-0.15)

Position (m) (x,y,z) (-0.125,-0.15,0)		**Position (m) (x,y,z) (0,-0.15,-0.15)**		**Position (m) (x,y,z) (0,-0.15,0.15)**		**Position (m) (x,y,z) (0.125,-0.15,0)**		**Position (m) (x,y,z) (0,-0.15,0)**	
t(mins)	**T ^{o}C**	**t(mins)**	**T ^{o}C**	**t(mins)**	**T ^{o}C**	**t(mins)**	**T ^{o}C**	**t(mins)**	**T ^{o}C**
10.00	80.00	10.00	25.00	10.00	25.00	10.00	82.00	10.00	85.00
20.00	85.00	20.00	28.00	20.00	30.00	20.00	87.00	20.00	89.00
30.00	92.00	30.00	36.00	30.00	35.00	30.00	92.00	30.00	92.00
40.00	100.00	40.00	40.00	40.00	40.00	40.00	100.00	40.00	99.00
50.00	110.00	50.00	44.00	50.00	45.00	50.00	100.00	50.00	105.00
60.00	105.00	60.00	48.00	60.00	49.00	60.00	110.00	60.00	110.00
70.00	110.00	70.00	50.00	70.00	50.00	70.00	110.00	70.00	115.00
80.00	115.00	80.00	55.00	80.00	55.00	80.00	118.00	80.00	120.00
90.00	120.00	90.00	60.00	90.00	60.00	90.00	120.00	90.00	125.00
100.00	125.00	100.00	65.00	100.00	65.00	100.00	125.00	100.00	130.00
110.00	130.00	110.00	70.00	110.00	70.00	110.00	130.00	110.00	135.00
120.00	140.00	120.00	78.00	120.00	80.00	120.00	135.00	120.00	139.00

Table C8: Measured Temperature distribution in the chamber furnace at 1000 ^{o}C for plane Y (-0.15)

Position (m) (x,y,z) (-0.125,-0.15,0)		**Position (m) (x,y,z) (0,-0.15,-0.15)**		**Position (m) (x,y,z) (0,-0.15,0.15)**		**Position (m) (x,y,z) (0.125,-0.15,0)**		**Position (m) (x,y,z) (0,-0.15,0)**	
t(mins)	**T ^{o}C**	**t(mins)**	**T ^{o}C**	**t(mins)**	**T ^{o}C**	**t(mins)**	**T ^{o}C**	**t(mins)**	**T ^{o}C**
10.00	82.00	10.00	25.00	10.00	30.00	10.00	85.00	10.00	87.00
20.00	85.00	20.00	28.00	20.00	32.00	20.00	90.00	20.00	90.00
30.00	90.00	30.00	40.00	30.00	38.00	30.00	94.00	30.00	95.00
40.00	100.00	40.00	42.00	40.00	40.00	40.00	100.00	40.00	98.00
50.00	105.00	50.00	44.00	50.00	43.00	50.00	105.00	50.00	100.00
60.00	110.00	60.00	47.00	60.00	47.00	60.00	110.00	60.00	110.00
70.00	115.00	70.00	49.00	70.00	49.00	70.00	120.00	70.00	115.00
80.00	120.00	80.00	53.00	80.00	50.00	80.00	125.00	80.00	120.00
90.00	125.00	90.00	58.00	90.00	55.00	90.00	120.00	90.00	123.00
100.00	130.00	100.00	60.00	100.00	60.00	100.00	130.00	100.00	130.00
110.00	135.00	110.00	61.00	110.00	65.00	110.00	140.00	110.00	132.00
120.00	140.00	120.00	69.00	120.00	68.00	120.00	145.00	120.00	134.00

Table C9: Measured Temperature distribution in the chamber furnace at 1100 ^{o}C for plane Y (-0.15)

Position (m) (x,y,z) (-0.125,-0.15,0)		**Position (m) (x,y,z) (0,-0.15,-0.15)**		**Position (m) (x,y,z) (0,-0.15,0.15)**		**Position (m) (x,y,z) (0.125,-0.15,0)**		**Position (m) (x,y,z) (0,-0.15,0)**	
t(mins)	**T ^{o}C**	**t(mins)**	**T ^{o}C**	**t(mins)**	**T ^{o}C**	**t(mins)**	**T ^{o}C**	**t(mins)**	**T ^{o}C**
10.00	82.00	10.00	25.00	10.00	30.00	10.00	85.00	10.00	87.00
20.00	85.00	20.00	28.00	20.00	32.00	20.00	90.00	20.00	90.00
30.00	90.00	30.00	40.00	30.00	38.00	30.00	94.00	30.00	95.00
40.00	100.00	40.00	42.00	40.00	40.00	40.00	100.00	40.00	98.00
50.00	105.00	50.00	44.00	50.00	43.00	50.00	105.00	50.00	100.00
60.00	110.00	60.00	47.00	60.00	47.00	60.00	110.00	60.00	110.00
70.00	115.00	70.00	49.00	70.00	49.00	70.00	120.00	70.00	115.00
80.00	120.00	80.00	53.00	80.00	50.00	80.00	125.00	80.00	120.00
90.00	125.00	90.00	58.00	90.00	55.00	90.00	120.00	90.00	123.00
100.00	130.00	100.00	60.00	100.00	60.00	100.00	130.00	100.00	130.00
110.00	135.00	110.00	61.00	110.00	65.00	110.00	140.00	110.00	132.00
120.00	140.00	120.00	69.00	120.00	68.00	120.00	145.00	120.00	134.00