MODELING A CYLINDRICAL RUBBER BLOCK OF TYRE TREAD COMPOUND FOR PREDICTING THE TEMPERATURE PROFILE UNDER HEATING CONDITION

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DECLARATION OF THE CANDIDATE & SUPERVISOR

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The above candidate has carried out research for the Master's thesis dissertation under my supervision

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Signature of the supervisor: Date: 20/02/2020

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ABSTRACT

In the rubber industry, curing is very important parameter. There are many methodologies are used industrially in order to predict the optimum curing time of rubber product. The methodologies are mainly two types as practical and numerical approaches. In the practical approach, it is used a lot of manual activities to collect the temperature distribution within the rubber product. It is time consuming and non-economical method. Therefore, most of the industries are attempting to develop numerical models for the rubber curing. Nowadays the trend is to develop software-based numerical modellings to predict not only the temperature distribution but also state of cure of the rubber product.

In this research it was attempted to predict the temperature profile of cylindrical tread rubber block using a well-known software called Solidwork. The accuracy of the model was verified by practically measured data. In order to match practical temperature profile, with the modelled figures, the thermal properties were changed. Even though there are several thermal properties such as thermal conductivity and specific heat capacity, the critical thermal property is the thermal diffusivity.

Based on the results, the prediction of temperature profile with the default settings of the software and fixed thermal properties would not be possible.

Keywords : rubber compound, simulation model, thermal diffusivity

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LIST OF ABBREVIATIONS

M_L	Minimum Torque
M_H	Maximum Torque
tc_{90}	Optimum Cure Time
Cp	Specific Heat Capacity
DSC	Disc Scanning Calorimeter
DMA	Dynamic Mechanical Analyzer
t_{s2}	Induction Time
MDR	Moving Die Rheometer
ODR	Oscillating Disc Rheometer

1. INTRODUCTION

1.1 Background

Rubber industry is very vital industry which is developing and expanding. It all started with rubber and relevant other materials. Also, there are specific machineries and equipment behind the industry. Rubber compound is one of the basic materials in the industrial chain.

Rubber compounds are made by mixing polymer, fillers and chemicals. It is being used different machineries for this mixing. After mixing, it is produced compound sheets as the mixing output. These sheets outs are moved to produce the corresponding green rubber product. The rubber product can be a sheet, solid or hollow item.

In any rubber product, curing is very importance step which provides all the corresponding properties at the final product. The properties are mainly tensile strength, hardness and abrasion resistance etc. Those properties are related to the quality and the performance of the final product.

There are three fundamental requirements for the curing. They are the temperature, pressure and specific time. This specific time is called “Curing time”. There are a lot of approaches are being practiced for selecting the curing time of a rubber product.

In this study, it was based on the tire industry. Tire is a composite material which is consisted a lot of components. They are rubber compounds, Nylon and steel wires etc. To prepare a pneumatic tire, it is first produced green tire and that moves to a mould for the curing. In the mould, a pressure and temperature are applied for specific time for curing.

Selecting this curing time is one of the most challengeable things in tire industry. For curing the rubber compound, there are three main properties to be considered. They are thermal conductivity, specific heat capacity and density. Thermal conductivity is the ability to conduct heat. Specific heat capacity is the quantity of heat required to raise the temperature of a substance by one degree Celsius.

Rubber is not a good conductive material hence on a thick rubber item, with time and position, temperature is changed. In a tire as well, there are some parts which is having thicker dimensions. Side or the shoulder of a tire is one of such critical parts. Tire is needed to be kept in the mould until those thicker critical parts are obtained the required temperature level. That only confirms the proper curing of the tire as final product.

This temperature distribution of a tire from position to position is changed due to many reasons. The thermal properties of tire, relevant components and heating methodology are some of the fundamental things which effect on the temperature distribution within the tire.
Currently most of the tire industries are used practical method to check this temperature distribution within the tires. Some thermo couples or temperature probes are placed inside of the tire while it is being cured. Then with the time, the temperature distribution is observed. This temperature distribution is called, "Temperature Profile".
This practical approach creates a lot of disadvantages due to higher time consumption, loss of energy and materials. That is one of the main reasons for selecting this project which targets to find an alternative method of predicting the temperature profile.

1.2 Research Objectives

There are two main objectives in this thesis.

1. Develop an accurate software-based model for rubber curing of cylindrical tread rubber block
2. Prediction of temperature profile on the critical position of the above cylindrical tread rubber block

1.3 Tires

The history of the tire goes to the era of Sumerians. It is more than 5000 years ago. It was initially a wheel which had been made by stone. Later, the wheel was converted current available product with lot of innovations and developments.

For now, there are two main types of tires. They are solid and pneumatic tires. In Sri Lanka, there are tire industries for pneumatic as well as solid tires. There are set of manufacturing companies which are involving pneumatic tire industry for global and domestic market. For the moment, Sri Lanka is the market leader for the Solid tires. Solid tires are mainly exported to USA, Italy, Germany and Belgium. It is covered 20% of the global market share of the solid tires. [1]

1.3.1 Pneumatic Tire

The pneumatic tire is designed to provide a flexible cover with an impermeable lining to contain and restrain the compressed air. This cover is provided with a rubber tread portion that is designed to withstand the cutting and abrasive wear of road contact and to protect the tire against puncture and loss of air. [2]

For now, there are three types of pneumatic tires in the world

1. Radial tires
2. Bias Belted tires
3. Diagonal/Bias tires

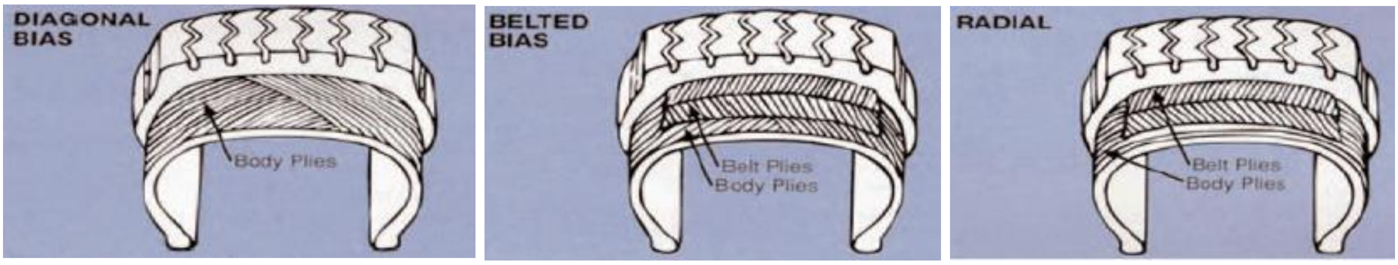

Figure 1-1 Types of Pneumatic Tires in the World

1.3.1.1 Radial Tire

This is one of the latest types of tire in the pneumatic tire industry. The body ply cords are laid radially from bead to bead. The plies are mainly steel or other fabric material such as Nylon or Polyester. Breaker or belt is mandatory in radial tires since the growth is needed to be controlled under inflation condition.

Compared to other types, this type is having advantages as below.

- Gives low rolling resistance.
- Generates less heat.
- Better high-speed performance
- Improve wear and handling

Also, there are some disadvantages as well:

- Complex construction.
- High material and manufacturing cost.

1.3.1.2 Diagonal/Bias Tire

This is the oldest type of the tire in the pneumatic tire industry. When it is needed higher load bearing or higher stiffness, this type of tire is recommended. Tire cords of this type of tires are extended diagonally across the tire from bead to bead. There are advantages as well as disadvantages as shown below.

The advantages are:

- Simple construction
- Easy to manufacture

The disadvantages are:

- Shear occurs between plies
- Poor wear characteristics

1.3.1.3 Bias Belted Tire

This is one of the improved versions of the Bias tire. Tire cords of this type of tires are extended diagonally across the tire from bead to bead and it is having breakers or belts under the tread area.

The advantages are:

- Restrict the outer diameter growth
- Improved wear & handling due to stiffness in the tread

The disadvantages are:

- High material and manufacturing cost

1.3.1.4 Components of the Pneumatic Tire

There are lot of components are available on a pneumatic tire. Some of the main components are shown as below. They are Body ply, Breakers, Tread, Sidewall, Chafer, Apex, Inner Liner and Bead.

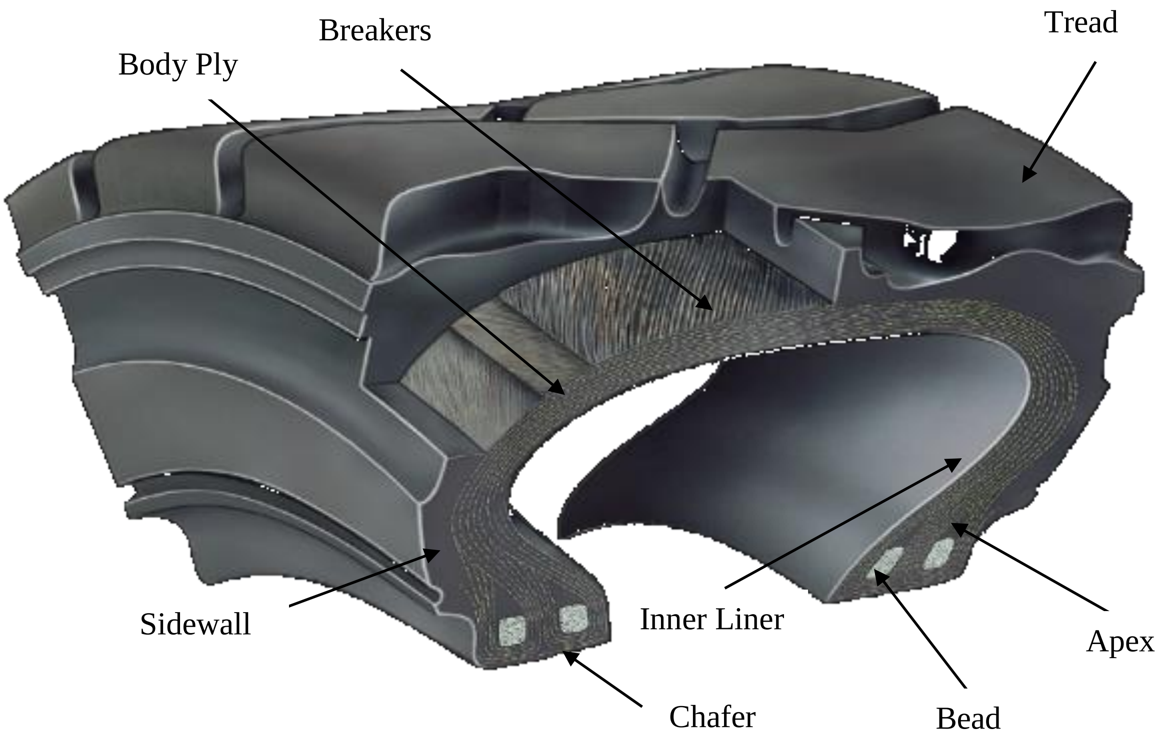

Figure 1-2 Components of Pneumatic Tire

1.3.1.5 Functions of the Components of the Pneumatic Tire

As shown in the above image, each one of the above components are having corresponding function. Most of them are affecting to the performance of the final product.

Bead:

This is the component which keeps the tire fix to the tire. If this is not in proper manner, tire can be slip around the wheel.

Chafer:

This is used to protect the bead and the body ply. When tires are mounted to the rim, some mounting tools are used. Also, while tire is being used, it can make some damages onto the bead are. From all those damages, chafer protects the inner components.

Apex:

It is provided the stiffness on the bead area. For some applications, the stiffness of a tire is required. Therefore, apex is being used. In some cases, it is used not only one apex but also few apexes as well.

Inner Liner:

This is keeping the air in side of the pneumatic tire. The main polymer is butyl rubber. Based on the requirement, sometimes, it is used Bromo-butyl or Chloro-butyl as well.

Body Ply:

These are provided the reinforcement to the tire. There is different type of materials are being used as body plies. Some of common materials are Nylon, Steel and Polyester.

Breaker/Belt:

These are used to control the growth of the tire and increase the impact resistance.

Sidewall:

It protects from cracks due to impact or other environmental factors.

Tread:

This provides the required mileage and the traction. Based on the requirement, the type of the polymer, carbon black and other ingredients of the tread compound are differed. Since this is the part which directly contacts on the ground, tread part is very important.

1.5 Tire Curing Process

1.5.1 Tire Curing

Curing process or vulcanization is an essential in the production of rubber components. The process inserts chemical bonds between rubber chains to give required mechanical stability as well as improved properties such as elasticity, tensile strength, modulus, and chemical resistance.

For curing, there are three main parameters are to be considered. Those are the temperature, Pressure and the required time for the curing. In order to provide temperature, there are several heating sources are being used. Some of them are hot water, steam and electricity.
The pressure for the curing is defined in order to produce a quality product at the end.

The required time for the curing is calculated practically or theoretically. In practical approach, temperature distribution of the tire is observed placing thermo-couple wires on all critical areas of the product. Critical position is selected as the position which complete the curing at the end.
Most of the times, this critical area for pneumatic tire goes to mid of the shoulder area in the lug.

Internally, different tire manufactures have developed mathematical models which theoretically it can be predicted and calculated the curing cycle. Other than that there are software-based models as well which are being in the use to calculate the curing cycle.

1.5.2 Tire Curing press/oven

Tire curing is done by several methods. The two main types are press curing and oven curing. Whatever the curing method, it should be having a mould in order to get the required shapes of the lugs.

In press curing, the moulds are fixed to the press and tire is loaded for the curing onto the mould which is fixed in the press. For pneumatic tire, since the pressure is needed while it is being cured, it is used curing membrane. Pressure and the temperature are transmitted through this membrane.

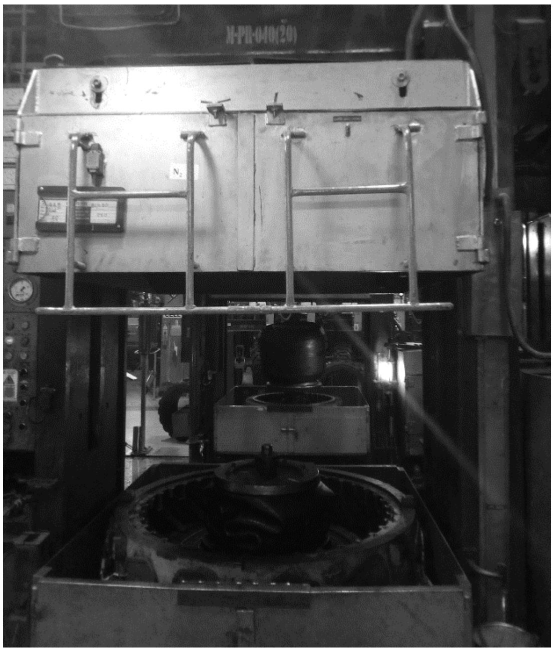

Figure 1-3 Tire Curing Press

Normally, there are two types of curing membranes. They are “Bladder” and “Air Bag”. Bladders are normally fixed to the mould while the air bags are not fixed to the mould.

When the presses are being used for the curing, these bladders have been fixed to the mould.

The other type is oven curing. In this technology the mould can be taken out of the oven box. As curing membrane, it is used air bag. Air bag is not fixed to the mould and it can be used as a mobile curing membrane.

Figure 1-4 Tire Curing Oven

1.5.3 Rubber moulding

For moulding of rubber, it is mainly used several technologies. They are compression moulding, transfer moulding and injection moulding.

Compression moulding: In this type of the moulding, a pre-weight product is placed in the mould and then it is applied a force to compress. The heat for the vulcanization is provided by electricity, hot fluid or steam.

Transfer moulding: This is one of form of the injection moulding. The compound which is needed to be cured is holding in a heated reservoir. Then a pressure is applied on the heated compound in order to fill the mould through sprues or rubbers.

Injection moulding: Here it is combining an extruder. This extruder heats and fluxes the rubber with a reservoir and mould.

Moulds are used in tire industry in order to get the required shape and dimensions. Moulds are made by metal. Most of the time, it is Aluminium or Mild steel.

In rubber industry there are several types of moulds as shown below.

1.5.3.1 Two-piece mould

Under this category, there are two pieces of the mould as top part and the bottom part. In the middle the cavity is there. This is very easy technology where the required shape of the final product can be obtained with-out much complications.

1.5.3.2 Segmented mould

Segmented moulds are having more than two parts. These parts are called segments. When the final rubber product is de-moulded, the segments are expanded and easily the unloading is executed.

This type of the mould is widely used in radial tire industry. After completing the curing, the shrinkage of the radial tires is comparatively low. Since this low shrinkage, it is difficult to de-mould using two-piece mould. Therefore, this segmented type moulds are introduced.

Figure 1-5 Segmented Mould

2. LITERATURE REVIEW

Rubber industry is a vast industry with lot of technologies are being in the use. There are several important steps in rubber product manufacturing. Rubber compound mixing, preparation of the green tire, curing and post curing are some of those steps. the curing is one of the most important activities. In order to predict the curing time, it had been developed several methodologies. The older method was the practical approach. This took longer time duration with lot of impact on the cost as well. Nowadays, people are involving developing more software-based modelling technologies. It is having the lot of advantages such as saving on time, money and the flexibility of the trials in the easy manner.

2.1 Rubber compound

Rubber compound is produced by mixing main polymer as the rubber with other ingredients. Based on the final requirement, it is selected the type of the main polymer. The other ingredients are mainly fillers and chemicals. For this, it is first generated a compound formula. It is included all the weight relative to the main polymer (Rubber). A generalized formula is shown below. [3]

Table 2-1 : Generalized Rubber Compound Formula

Ingredient	PHR
Rubber	100
Filler	50
Softener	5
Antioxidant	1
Stearic Acid	1
Zinc Oxide	5
Accelerator	1
Sulphur	2
Total	165

2.1.1 Rubber types

There are several types rubbers in the world. Mainly it is having two types such as synthetic and natural type rubbers. RSS, SLR are examples for the natural rubber while SBR, BR, NBR are some of the synthetic rubbers.

Properties of the final product is mainly related to the main rubber type in the compound. If the final product is needed some properties such as higher abrasion, better traction or low heat build up and accordingly the type of the main rubber is needed to be selected.

2.1.2 Fillers in rubber compounds

There are mainly two types of fillers. They are reinforcing fillers and non-reinforcing fillers. Carbon black is widely used reinforcing filler. That is the reason for most of the rubber compounds are black. The reinforcing fillers makes the final product stronger.

Calcium carbonate is example for non-reinforcing filler. Under this category, it is not expecting that much of strengthening. Basically, this type of fillers is used to reduce the cost of the compounds.

2.1.3 Chemicals in rubber compounds

In a rubber compound, there are several chemicals are being used. They are plasticizers, vulcanization chemicals, accelerators, activators, anti-degrading agents, processing aid etc. Each chemical is having its own function within the compound as well as at the final product.

2.2 Rubber mixtures

This is used to mix the ingredients in the rubber compounding such as rubber as the main polymer, fillers such as carbon black, silica, calcium carbonate with relevant chemicals. The mostly using machine is called internal mixer.

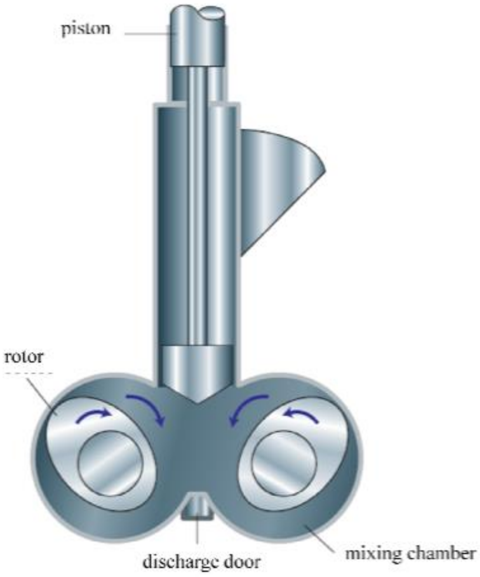

Figure 2-1 : Schematic Internal Mixer

Basically, this is a completely enclosed mixing chamber in which two spiral-shaped rotors are operated. In the rubber industry, there are two main types of rubber mixers. They are intermeshing and tangential type mixers.

2.2.1 Intermeshing Mixer

As per the image shows the gap between rotors is smaller compared to the tangential mixer. That make the excellent contact between rubber and the metal surfaces. Also, the higher shear and better heat transfer moves this much popular in rubber industry.

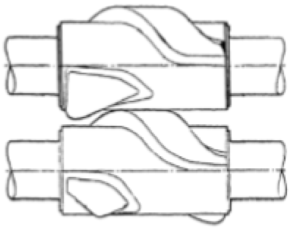

Figure 2-2: Rotors of Intermeshing Mixer

2.2.2 Tangential Mixer

As it is shown below, the gap between rotors is larger compared to the intermeshing mixer. That makes the lower contact between rubber and the metal surfaces. Also, compared intermeshing mixer, shear and heat transfer are lower.

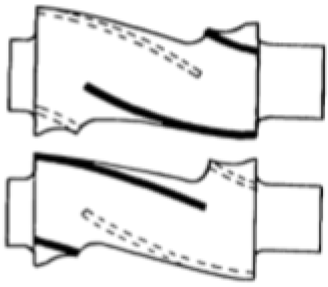

Figure 2-3 : Rotors of Tangential Mixer

2.3 Testing and equipments in rubber industry relevant to curing

2.3.1 Rheometer

In compound development studies or production control stages, the effect of the variation of the compound or curing characteristics are much important.

When the compound developments are ongoing, it can change the ingredients and check the corresponding vulcanization characteristics. Using rheometer, this can be easily identified. The Rheometer not only exhibits the curing characteristics of the Rubber Compound, but it also monitors the processing characteristics as well as the physical properties of the material. The "Cure Curve" obtained with a Rheometer shows the vulcanization and processing character of the compound.

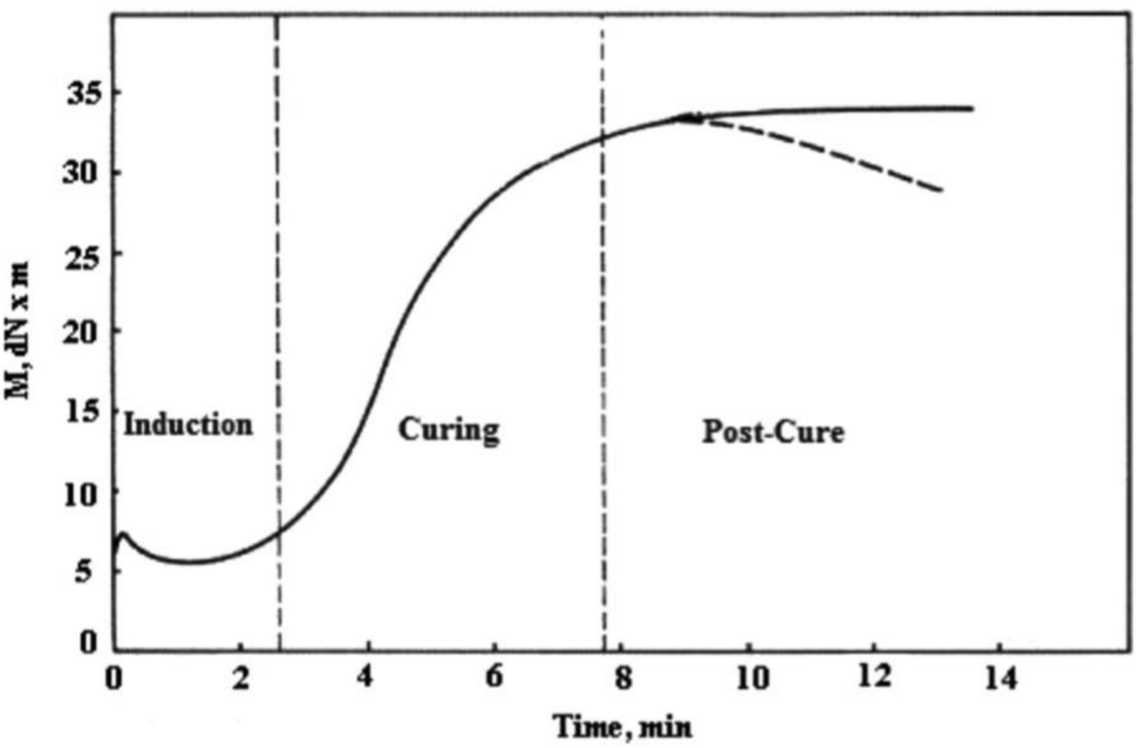

Figure 2-4 Typical Cure Curve of Rheometer

There are a lot of advantages of the rheometer. They can be listed as usage on different activities such as research and development, quality control, process control, to observe the effect of new ingredients, to optimization of the dose of the ingredients, assessment of the physical properties etc. There are two types of rheometers in the rubber industry.

With the use of the rheometer mainly two types of results can be obtained. They are torque values and time values.

For the torque value results, Minimum Torque (ML) and Maximum Torque (MH) are important. ML represents the stiffness and the viscosity of the unvulcanised compound. MH can be used to predict the hardness of the final cured product.

There are several time values as induction time (ts_2), scorch time (ts_5), optimum cure time (tc_{90}). Although several values are there, it is widely used ts_2 and tc_{90} in the rubber industry.

Processing safety is indicated by the ts_2 and tc_{90} gives a detail on the time of 90% curing completion.

2.3.1.1 Moving Die Rheometer

The Moving Die Rheometer (MDR) is designed to measure vulcanization of rubber compounds under isothermal test conditions with constant strain and frequency. There are several advantages in MDR machine.

Normally, the lower half of the die to perform an oscillating rotation of 0.5˚ with torque measured at the upper die by a torque transducer. The curing characteristics of the compound were then determined under different temperature condition.

In the vulcanization curve, represents ts_2, tc_{90}, ML and MH.

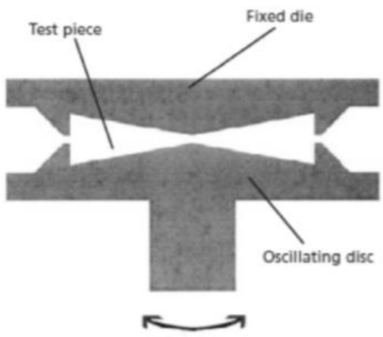

Figure 2-5 Moving Die Rheometer

2.3.1.2 Oscillating Disc Rheometer.

In Oscillation Disc Rheometer, the rotor is embedded in the test piece and is oscillated through a small specified rotary amplitude. This rotation provides a shear strain on the test piece and the torque (force) required to oscillate the disc depends upon stiffness (shear modulus) of the rubber compound. When crosslinks are formed during cure, the stiffness of the specimen is increased. Same output can be generated in the ODR in the same way of MDR.

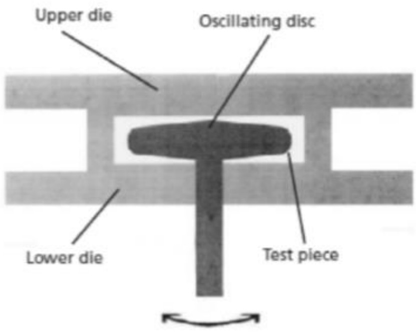

Figure 2-6 Oscillation Disc Rheometer

2.3.2 Thermocouple

A thermocouple is used as an electrical device. It is consisting of two dissimilar electrical conductors forming an electrical junction. A thermocouple produces a temperature-dependent voltage as a result of the thermoelectric effect. Then this voltage can be interpreted to measure temperature of position. Thermocouples are a widely used type of temperature sensor. [4]

2.3.3 Two roll mill

This one of the widely used machineries in rubber industry. Two smooth casted rolls are driven through the motor, keeping a gap between two rollers. The speed of the roller is not same since a shear is automatically generated whatever the material in between the rollers.

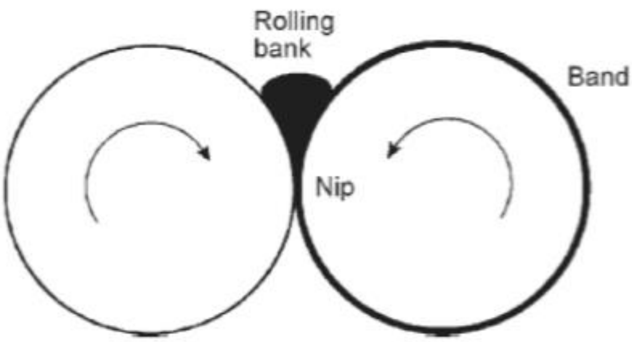

Figure 2-7 Schematic of a two-roll mill

The main purpose of the two-roll mill is to ensure that the added materials are evenly dispersed throughout the compound. The mill aids in two main steps of rubber processing- mastication and mixing. Mastication is when the raw polymer is sheared and the broken down to create an easier flow. This allows for better incorporation of materials, which leads to the mixing component, when the other materials for a compound are added. [5]

2.3.4 Disc Scanning Calorimeter (DSC)

This is a thermo analytical technique in which the difference in the amount of heat required to increase the temperature of a sample and reference is measured as a function of temperature. Throughout the experiment, temperature of sample and reference is maintained nearly constant. Over a temperature range, for a material, the specific heat capacity is varied. For the selected reference sample, it should be known the heat capacity variation under the scanning temperature range.

Figure 2-8 : TA Instrument. SDT-Q600 DSC

2.3.5 Dynamic Mechanical Analyzer (DMA)

Dynamic Mechanical Analyser is one of equipment which is being used to predict the curing characteristics. In rheometer, the curing characteristic are normally measured in isothermal condition. DMA can be used to predict the curing behaviour under different temperature conditions. There are six major components in the machine as a force motor, a drive shaft, a high sensitivity displacement detector, a sample fixture, a furnace and a temperature controller. Normally in DMA, data are collected approximately every 5 second in the isotherm period. As output, it provides shear storage modulus (G'), shear loss modulus (G'') and tan δ as a function of time.

2.4 Rubber Curing

Curing is one of the important steps in the rubber industry. Rubber compound is consisted molecules since it is a mixture of rubber, fillers and chemicals. With the application of the heat, these molecules are cross linked and the properties of the final cured or vulcanized product are enhanced due to those cross links.

The reaction is exothermic reaction and it is generated some amount of the energy due to this process. The rubber curing is highly non-isothermal process.

2.4.1 Heat transfer

Heat transfer is mainly conducted by three main methods.

Conduction, convection and radiation are those three.

The transfer of heat from one substance to another by direct contact is called conduction.

Transfer of heat through a fluid such as liquid or gas, caused by molecular motion is called convection.

Energy that is radiated or transmitted in the form of rays, waves or particles is called radiation.

2.4.2 Heat Conduction

Conduction of the heat from position to position is depended on many parameters. Temperature, Specific heat capacity and time are some of them. Based on these parameters the amount or the time for the transportation of the heat are differed.

Further there is one of the importance thermal property which is called thermal diffusivity. This is defined as the rate of transfer of the heat of a material from hot end to cold end. If a material is having high thermal diffusivity, that means, heat moves rapidly through the body. [6]

$$\alpha = \frac{K}{\rho . C_p}$$

Equation 2-1 Variation of the Thermal Diffusivity

Where, K: Thermal conductivity, C_p : Specific Heat Capacity, ρ = Density

ρ . C_p is called, volumetric heat capacity.

2.4.2.1 Transient Heat Conduction

As per the name represents by the “Transient”, in general, the temperature of the substance is varied with the time as well as the position.

Under the transient heat conduction, the governing equation is as below.

$$\rho Cp\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k.\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k.\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k.\frac{\partial T}{\partial z}\right) + Q$$

Equation 2-2 Governing Equation for transient heat conduction

t, T, ρ, Cp and k are representing, time, temperature, density, heat capacity and thermal conductivity. Q is the heat generation rate per unit volume. Heat generation is mainly due to the vulcanization reaction.

2.5 Rubber Curing Kinetics

There are many approached to describe the curing with using kinetics. Since the rubber curing is non-isothermal process, it is needed to be selected non-iso thermal curing kinetic model.

That is needed to be considered not only the time but also the temperature history in the curing kinetics.

2.5.1 Kinetic Models

When the vulcanization is taken place, it is generated cross links in between polymer chains. For kinetics of the vulcanization, one of the most famous method is Kamal and Sourour method. [7]

$$\propto = \frac{k.(t - ti)^n}{1 + k.(t - ti)^n}$$

Equation 2.3 Degree of Cure

k is the kinetic constant and n is the order of reaction. ti is called induction period. Under this time, chemical reaction does not taken place.

$$ti = t0\,.exp.(\frac{T0}{T})$$

Equation 2.4 Induction time period

Here, t0 and T0 are material constants.

$$k = k0 \, . exp. \left(\frac{-E}{R.T}\right)$$

Equation 2.5 Kinetic Constant

Here, E, R and T are activation energy, Gas constant and temperature.

Since vulcanization is isothermal approach following quasi-isothermal equation can be generated.

$$\propto i = \propto i - 1 + \int_{ti-1}^{ti} \left(\frac{d \propto}{dt}\right) dt_{T=Tm}$$

Equation 2.6 Quasi-Isothermal Model

Tm and $\frac{d\propto}{dt}$ are shown below.

$$Tm = \frac{Ti + Ti - 1}{2}$$

$$\boldsymbol{\frac{d \propto}{dt} = \frac{k.n.(t - ti)^{n-1}}{[1 + k.(t - ti)^{n}]^{2}}}$$

Further, total differential approach is given by the following equation.

$$\propto i = \propto i - 1 + \int_{Ti-1}^{Ti} \left(\frac{d \propto}{dt}\right)_{t} dT + \int_{ti-1}^{ti} \left(\frac{d \propto}{dt}\right)_{T} dt$$

Considering the kinetics of heating as well as cooling, following equation can be generated.

$$\frac{d \propto}{dt} = n.k^{1/n}.\propto^{\frac{(n-1)}{n}}.(1-\propto)^{(n+1)/2}$$

In the above equation, at the initial stage $\propto$ goes to “0”. In order to avoid this, following equation is generated.

$$\left(\frac{\propto i}{1-\propto i}\right)^{1/n} = \left(\frac{\propto i - 1}{1-\propto i - 1}\right)^{1/n} + \int_{ti-1}^{t} k^{1/n}.dt$$

2.6 Numerical Models

To simulate temperature distribution or the state of curing, numerical methods are being used in the rubber industry. In this approach, it is combined of kinetic and numerical equations together to get a solution.

2.6.1 Finite Element Methods (Computational Models)

For last few decades, with computerization the industry, there had been used a lot of initiatives on modelling and simulation. There are many reasons for the selection of the computational models in order to study the curing.

Traditionally in rubber industry, the curing is being analysed doing trials and errors by practical methods. People used to insert thermo-couple wires into the rubber products and observe the temperature profile in different locations of the product. Based on the temperature profile, it had been defined the curing cycle for the product. In this way, the product is scrapped obviously, and it takes a lot of money, energy and time at the end. In some cases, while the product is being under curing, the locations of the probes also can be mis placed. That can lead some errors of the readings at the end.

Need of the computational models was arrived on those requirements where easily it can be modelled whatever the complex geometry. In the meantime, it can be simulated different approached such as changing the heating mechanism, geometry of the product and properties of the materials where if that is to be done practically, it is difficult and impossible task.

The heating geometry can be optimized through software in order to maximize the heat distribution. Geometry of the product is also can be changed in the same manner, in order to get better homogenization of the heat throughout the body.

For optimization or reducing the curing time, different material properties or the combinations also can be simulated. At the end, prior to develop physical compounds or materials, the impact of the curing can be observed through the software in the simulation. Based on that, it can suggest to the compound or material developers to act accordingly.

Using commercially available software called NISA II, an internal software had been developed called, CURECAL.EXE. Mainly this was to predict the total cure of the rubber under the transient thermal condition. [7]

As it had been explained above, transient thermal condition is the temperature distribution with time and position. With the application of heat, the temperature of the rubber rises, and its rate of curing can be described by the Arrhenius function:

$$\mathrm{Cr} = z.\exp\frac{-\mathrm{E}}{R.T}$$

Equation 2-7 Arrhenius Equation for Cure rate

where Cr is the cure rate, E is the activation energy, R is the gas constant, T is the absolute temperature, and z is an arbitrary constant. It follows that the time to induce 1 unit of cure at temperature T is:

$$\mathrm{t} = \frac{1}{\mathrm{Cr}}$$

Equation 2-8 Time to induce one unit of cure

relative to some reference temperature To and time to, the time to induce one unit of cure at some other temperature T1 is :

$$\mathrm{t1} = t0.\exp\frac{-E}{R}\left(\frac{1}{T0} - \frac{1}{T1}\right)$$

Equation 2-9 Time to induce one unit of curing at given Temperature Range

$$\text{curing unit} = \frac{1}{t1}$$

If, at time t = 0, the total cure, C, at a point is zero, then at some time, t, the total cure becomes:

$$\mathrm{C} = \int_0^t (curing\ unit)\,.\,\mathrm{dt}$$

Equation 2-10 Total Cure Variation

CURECAL.EXE was used above equations with time and temperature in order to predict total cure. In the same way, a practical model was produced. It had been observed, 25% variation of practical and software-based model when it is compared cure level. The variation is due to the variation of the thermal conductivity and density with temperature. Also, since it was neglected the heat produced by the exothermic vulcanization reaction, some variation would have been occurred. [7]

ABAQUS was also had been used with written subroutine called UMATHT in order to develop a model for curing. [8]
This was attempted to solve the heat conduction equations and the rubber cure kinetics simultaneously. A simulation was conducted on a thick rubber article in the mould while it is being cured and, in the post, curing stage. The results had then been compared with experimental data. Mainly the temperature profile and the state of cured had been compared.

Instead of the other models, in this study, it had been used, incompatible meshes, thermal contact between rubber and mould and modified kinetic model.
In this study ABAQUS only was not compatible due to few reasons. Some of them are the incapability of variation of the generated heat, C_P and thermal conductivity are not only depending on the temperature but also depend on the state-of-cure, the need of state-of-cure.

In this study, it was developed modified Kamal and Sourour (K-S) model since the current K-S model cannot predict cure behaviour early stage of the curing reaction. In K-S model when the curing calculation is initiated, it is bit late and an initial non zero value for the curing should be considered in K-S model.
K-S model the expression for the degree of curing is as below.
k is the kinetic constant and n is the order of reaction.

$$\propto = \frac{k.(t - ti)^n}{1 + k.(t - ti)^n}$$

Equation 2-11 Degree of curing in K-S model

Three-dimensional finite element modelling was done on truck tyre curing process in the mould. [9] Mainly it had been considered the heat transfer in circumferential direction of the tire. For solving the heat conduction equation, it had been used standard Galerkin technique in a cartesian coordinate system. It was used implicit-Ө method to model the transient temperature field.
The basic software for this study was Geostar software. In order to determine the required parameters for the thermal simulation, several testings had been conducted. To determine heat

capacity, it was used a PL DSC system. Thermal conductivity was determined using a Taurus TCA 200 system and a Zwick ODR machine.
Practical results of the temperature variation and curing variation were compared with the software model. In this research, it had not been considered the post curing situation since the complexity of obtaining the heat transfer coefficient at the post curing condition.

In 1972, it was published a paper by Ambelang and Prentice, [10] of a digital method for calculating heat flow through vulcanizing tire. There it had been assumed, constant thermal diffusivity, constant rate of heat generation and constant boundary conditions.

Next Prentice and Williams, [11] published a paper with temperature-dependant thermal conductivity, the chemically generated heat as a function of temperature and the state of cure, the boundary conditions which varies with time.

Schlanger [12] introduced a one-dimensional model for tires with considering the cooling period as well.
Finite Element Evaluation of the state of cure in a tire was conducted with using the ABAQUS as the main software. [13] A subroutine was implemented as HETVAL. This provided more accurate results than the above methods due to the compatibility of FEA method with the complex shape of the tire, multilayer components and the variable boundary conditions.
Practical temperature profile and cure level were compared with software-based results. The maximum deviation of the temperature was 0.58K.

In the practical model, the required properties such as density, the heat capacity and the thermal diffusivity were determined. Then a new curing model was introduced.

It had attempted, the prediction of the curing time of an injection moulding item using computational technique with numerical simulation. [14] The model was considered as three-dimensional nature of a rubber product with considering variable order of reaction. Finding the required curing time experimentally, means time consuming and expensive procedure.
Hence most of the rubber industries are used numerical solutions.
In order to define the cure behaviour of the tire, it had been introduced different kinetic models.

There are two types of models;

1. Mechanistic kinetic model
2. Empirical model

Mechanistic kinetic model: It is needed to consider all the chemical reactions in the curing process under this model. It is not accepted this model for numerical simulations.

Empirical model: This is also called regression model. Under this model, it is ignored the chemical details in the cure system. Experimentally the data are collected and set them to mathematical function.

Ghoreishi and Naderi [15] used finite elements model for the simulation of the rubber curing process in the mould. They have found that neglection of the heat transfer in one direction would produce significant errors in calculating the temperature field and the extend of cure.

Arillaga [16] used the mould flow software to perform the simulation on injection moulding process of a simple item with uniform thickness.

Mould flow software had been used by Ramorino [17] to perform on three-dimensional finite element simulation for rubber injection moulding. In this study, it was described about rubber and its properties deeply. Also, the use of various experiments to find curing time and temperature had been explained.

The main properties are listed below.

Non-Newtonian fluid model constant: This was determined through viscometry test.

Curing parameters of kinetic model: These were determined through Rheometer testing

Temperature dependant specific heat capacity: This was obtained through Disc Scanning Calorimetry. Fluent software had been used for the numerical simulation. That was containing both the mould filling and the cure reaction process. Also, it was used a new User-Defined-Function (UDF) which had been developed in C program. As a result of this study, the average relative errors for the famous K-S model is 16.3%, while it has reduced to 9.59% using modified model.

2.6.2 Finite Difference Method

This is one of the methods which is used under numerical analysis. This is a discretization used for solving differential equations by approximating them with difference equations that finite differences approximate the derivatives.

Addressing following conditions, one of a study had been conducted using finite difference method. [18]

- Anisotropy of the heat transfer properties of composite materials: The properties of rubber compounds are depended on the temperature and the state of cure.
- Tires exhibit complicated layouts of different rubber compound layers and rubber/fibre layers: Tire is not a uniform material and it is consisted several components.
- The actual cure steps are as time varying boundary conditions, the entire cure cycle covers the cooldown of the tire out of the press: In all over the curing steps, the boundary conditions such as outside temperature can be varied.

For composite material, when FEM is applied on simulation, each material is needed to be considered separately with the corresponding properties. Sometimes, it may need to undergo experiments for obtaining the material properties.

3. EXPERIMENTAL METHODOLOGY

Although the project was initiated based on pneumatic tire industry, as initial stage, tire was not considered to deal with directly. Instead of tire, it was selected a rubber block with cylindrical shape.

Based on that it was defined, two experiments. One is practical methodology and other one is software-based methodology. In the practical method, a cylindrical tread rubber block with known dimensions was cured for known time.

In software-based method, Solidwork was used as the software and exactly same practical cylindrical tread rubber block was modelled. Then it was simulated the conditions as much as possible to get align with the practical model.

3.1 Materials for the Practical Trials

First practically, it was prepared a cylindrical rubber block and the details of the mould is as below.

3.1.1 Mold Materials

It was used steel for mould fabrication and the corresponding dimensions are as below.

Inside Cavity diameter: 90mm and Hight of the cavity: 100mm.

Outside diameter of the cylinder: 100mm

Top lid diameter: 130mm and the thickness:8mm

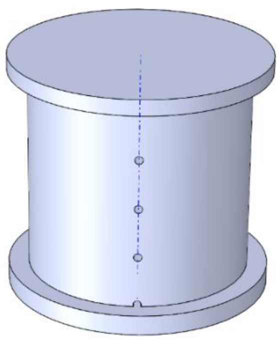

Figure 3-1 : Side view of the cylindrical mould

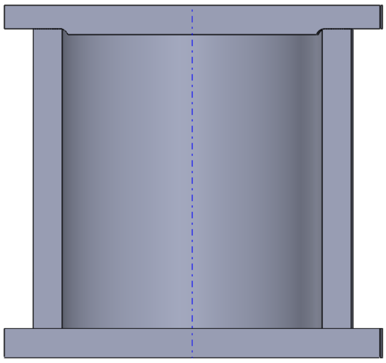

Figure 3-2 : Section view of the cylindrical mould

3.1.2 Rubber Compound

For practical cylindrical rubber block preparation, it was selected a tread rubber compound.

The density: 1130Kg/m3

Hardness: 66 Shore A

Weight: 800g

For the selected compound type, the main ingredients are carbon black: 50PHR , and main polymer as RSS, BR and SBR, 50,20 and 30PHR respectively.

3.1.3 Heating Press

For heating, it was used a lab curing press. The parameters are as below.

Heating: Top and Bottom

Heating source : Electrical (Elements), Voltage = 230 V, Ampere : 1.5 A

Temperature: 150˚C

3.1.4 Thermo-couple (Temperature Measuring Sensor.)

In this study it was used K-type for measuring the temperature within the cylindrical rubber block.

3.1.5 Two roll mill

After mixing the compounds in mixer, batch off sample was taken to prepare required green compound. Lab two roll mill was used for this.

The capacity of the mill: 1Kg

Mill gap: 3-4mm

3.2 Methodology of the Practical Trials

3.2.1 Procedure

It was selected a tread compound for preparation of the practical rubber block. Everything was initiated through formulation. It is included different ingredients in the above tread compound. The main ingredients are rubber, carbon black and chemicals.

Using Banbary mixer all the ingredients were mixed together. The sheet outs were taken out.

Basic testing were conducted in order to get the curing characteristics, density and rheological properties. Normally rheometer test and densometer test are recommended for this. Then it was observed the curing parameters with the density of the sample.

After that the rubber compound was milled to get thin sheet. Then, it was prepared the green rubber product in order to fill the mould cavity. The green rubber block was entered to the cavity of the mould.

Thermo couple wires were entered the marked positions of the green product through the holes of the mould as shown in Figure 3-3. Each wire was clearly labelled mentioning the correct position at the other end of the wire. The distance from outer surface to a known depth was very critical and that was considered closely.

The main temperature measuring positions were top, bottom, centre, mid of top-centre and mid of bottom-centre of the rubber block.

Then the press was closed, and the heating was conducted for 2 hours continuously.

Heating the green rubber block was from the top and the bottom. Continuously it was applied 150C temperature thought the given time frame. Temperature readings were collected in each 10 minutes interval.

Figure 3-3 : Practical Cylindrical Block Heating

Figure 3-4 Curing the rubber block inside the press

As shown in the above Figure 3-5, the curvature area of the cylindrical mould was properly covered by insulation material. McFoil sheets were used for this insulation.

Mainly the centre position temperature variation was considered since that is the critical position in the cylindrical rubber block. The data were collected in each 10 minutes for 120 minutes as mentioned above. This temperature distribution was recorded for three times. The average set of the values of the three readings were taken for the analysis.

3.3 Materials for the Software-based method

3.3.1 Software

"SolidWorks Simulation Professional, 2016" was used as the software for this study.

3.3.2 Boundary conditions

In the practical cylindrical block, the heating was conducted from top and the bottom. The curvature surface of the mould was insulated in order to reduce the thermal loss while the mould was being heated. The setting temperature for the top and bottom were 150˚C.

Same thermal loads were applied in the software-based model as well for the boundary condition. Top face and the bottom face were selected to apply continuous heating throughout the heating cycle.

3.3.3 Material properties

For the simulation, there are three main material properties as thermal conductivity, specific heat capacity and density. Since it is needed to find the ideal properties in each, some practical methods were used.

In order to find, the thermal conductivity, it was used Lee's disc method.

It was done through Materials Sciences and Engineering Department, University of Moratuwa.

There is no direct method of finding the specific heat capacity. It is needed to use a reference methodology to get the value on specific heat capacity. As reference, it was selected, Alumina. The main reason for this selection is for Alumina, it is available the C_p variation with temperature. In order to get unknown C_p on the selected tread compound, this reference was able to be used.

3.3.3.1 Density

In the rubber industry, the density of the rubber compound is being tested by using densometer.

The density is the mass of a material on a unit volume. Using densometer, the specific gravity which is the relative density based on water is measured. The selected tread rubber sample was undergone the same testing in order to find the density of the sample.

3.3.3.2 Thermal conductivity

In order to find thermal conductivity, there are few methods [19] and it was used Lee's disc method for this study.

It is used Lee's apparatuses for the purpose of finding thermal conductivity of several rubber samples.

Theory:

At steady state condition, heat transfer from bottom plate to top plate is equal to heat loss rate from top plate to air.

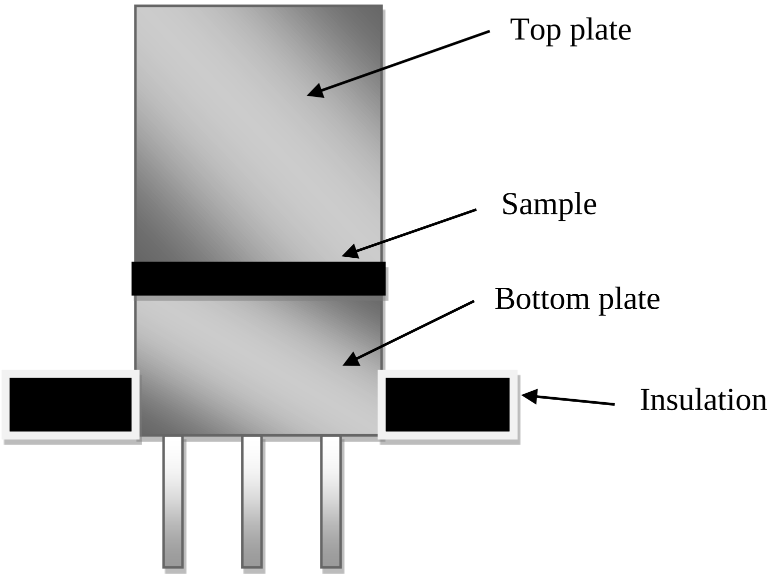

Figure 3-5 : Lee's Disc Apparatuses

Heat transfer rate at steady state condition from bottom plate to top plate = Heat loss from top plate to air

k= thermal conductivity

A= Area of the sample ($2856.9mm^2$)

x=thickness of the sample (2mm)

m=mass of the top plate (0.916kg)

c=specific heat of Copper ($0.38\ J/g^0C$)

$\frac{dT}{dt} = \text{Tan } \theta$ (from graph)

ΔT = Temperature of the bottom plate – Temperature of the top plate

Then heat transfer rate at steady state condition from top plate to bottom plate = $k.A.\frac{\Delta T}{x}$

Heat loss rate from top plate to air = m . c . $\frac{dT}{dt}$

$$k.A.\frac{\Delta T}{x} = m \,.\, c \,.\, \frac{dT}{dt}$$

Since dT/dt = Tan θ

$$k.A.\frac{\Delta T}{x} = m \,.\, c \,.\, \text{Tan } \theta$$

$$\text{Hence, } k = \frac{m \,.c\, .\text{Tan } \theta}{A.\frac{\Delta T}{x}}$$

Equation 3-1 Thermal Conductivity

Based on the above theories, thermal conductivity was calculated.

3.3.3.3 Specific Heat Capacity

Specific heat capacity is the quantity of heat required to raise the temperature of a substance by one degree Celsius. For rubber compound, finding the specific heat capacity is a difficult task. In this thesis, it was used a relative method to calculate the specific heat capacity. A material was selected with known specific heat capacity. The known material was selected as Alumina.

Then Disc scanning calorimeter was used for comparative study in order to find the specific heat capacity of the selected rubber compound. Tread rubber compound was selected for this study. Using Disc Scanning calorimeter, following procedure was followed to get an accurate value for the specific heat capacity.

3.3.3.3.1 Usage of Disc Scanning Calarimetry to measure heat capcity

First samples were prepared to run DSC test as per the standards ASTM D3418. Alumina was taken as the reference sample and with empty pan, machine was run. Then rubber sample was kept as test sample and run again with empty pan. The heat flow was collected with the variation of the temperature.

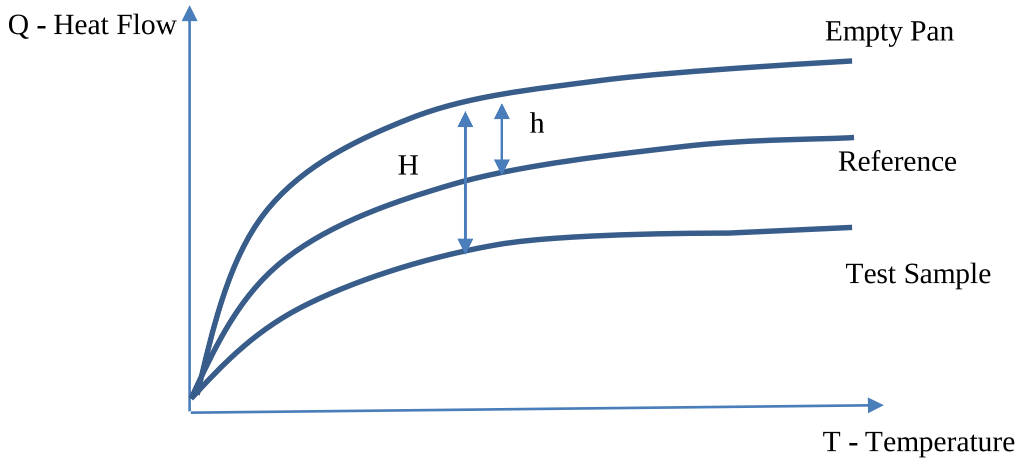

Figure 3-6 : Heat Flow Distribution with Temperature

The heat flow rate for the rubber sample can be shown as below.

$$Q_S = m_S \, . \, C_P S \, . \frac{dT}{dt}$$

Equation 3-2 Heat Flow rate of the rubber sample

Q_s = Heat flow rate

m_s = Weight of the sample

C_p S = Specific heat capacity of the sample

T = The temperature and t = time

In the same way, the equation can be set on reference sample as well.

$$Q_R = m_R \,.\, C_P R \,.\, \frac{dT}{dt}$$

Equation 3-3 Heat Flow rate of the reference sample

Q_R = Heat flow rate

m_R = Weight of the reference sample

$C_p R$ = Specific heat capacity of the reference sample

T = The temperature and t = time

Using the above equations and making some corrections on the energy flow rate, following equation can be generated.

$$Q_S - Q_{Correction} = m_S \,.\, C_P S \,.\, X$$

$$Q_R - Q_{Correction} = m_R \,.\, C_P R \,.\, X$$

$$\frac{Q_S - Q_{Correction}}{Q_R - Q_{Correction}} = \frac{m_S \,.\, C_P S \,.\, X}{m_R \,.\, C_P R \,.\, X}$$

$$\frac{m_S \,.\, C_P S}{m_R \,.\, C_P R} = \frac{Q_S - Q_{Correction}}{Q_R - Q_{Correction}}$$

$$C_P S = \frac{Q_S - Q_{Correction}}{Q_R - Q_{Correction}} \,.\, \frac{m_R \,.\, C_P R}{m_S}$$

H = $Q_S - Q_{Correction}$ and h = $Q_R - Q_{Correction}$,

$$\frac{Q_S - Q_{Correction}}{Q_R - Q_{Correction}} = \frac{H}{h}$$

H and h can be taken by the practical results.

Based on the literature, the variation of the specific heat capacity of Alumina is as below. [20]

$$C_P R = 148.57 - 3.421 \, x \, 10^{-3} \, x \, T - \frac{20409.6}{T}$$

Equation 3-4 Variation of the heat capacity of the Alumina with temperature

Here the T represents as temperature. For a given temperature, $C_P R$ is known based on the above equation. With the practical test, “H/h” can be calculated. Therefore, it can be found the $C_P S$ for a given temperature.

3.4 Methodology for the Software-based method

As the software, it was selected “Solidwork Simulation Professionals, 2016”, since most of the tire industries are being used this software for design purposes. Also, there is a user-friendly back ground which the user can have a freedom to adjust the design.

3.4.1 Procedure

Using the software, first it was modelled the cylindrical rubber block with the same dimensions to the practical rubber block.

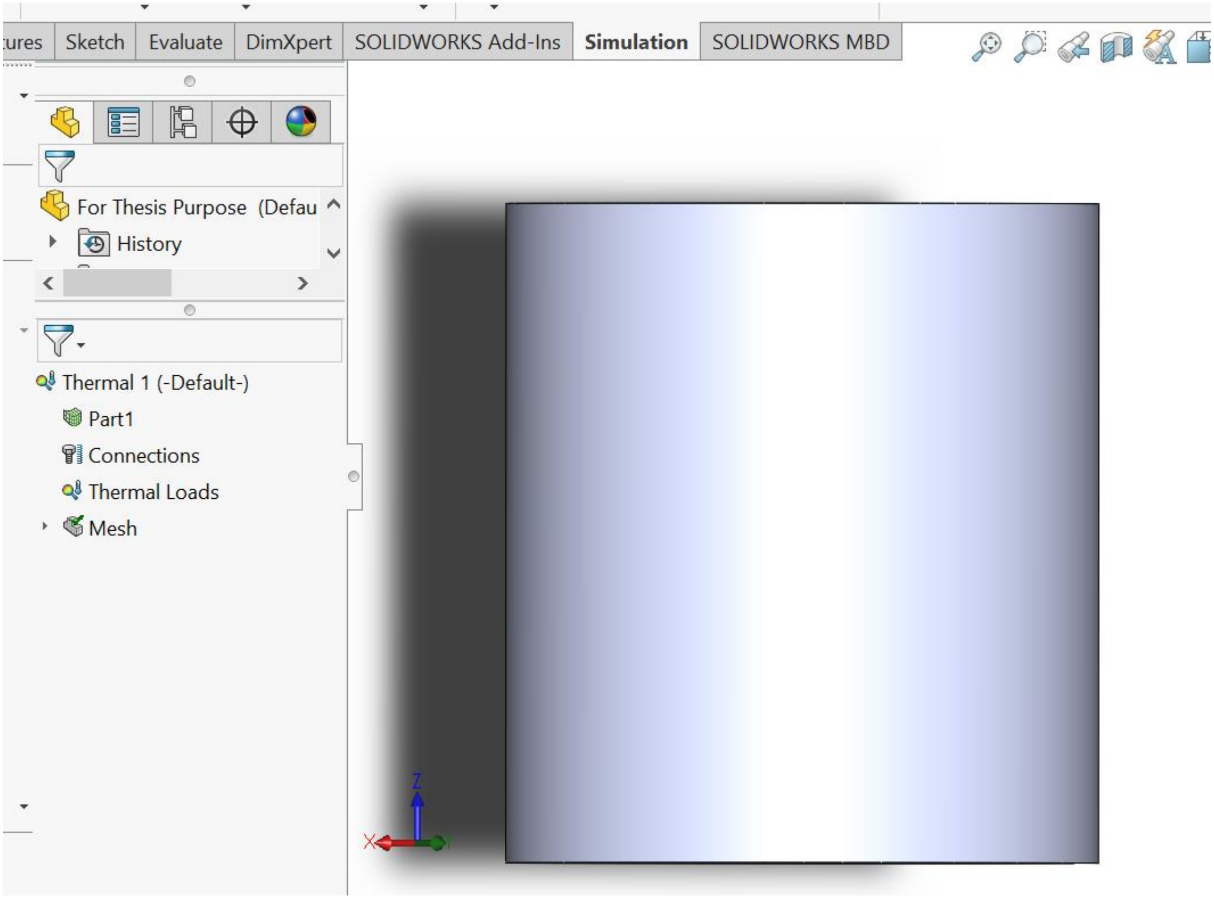

Figure 3-7 : Cylindrical Rubber Block

Then the material was assigned in the software library including the density, specific heat capacity and the thermal conductivity. The model was assigned the corresponding material.

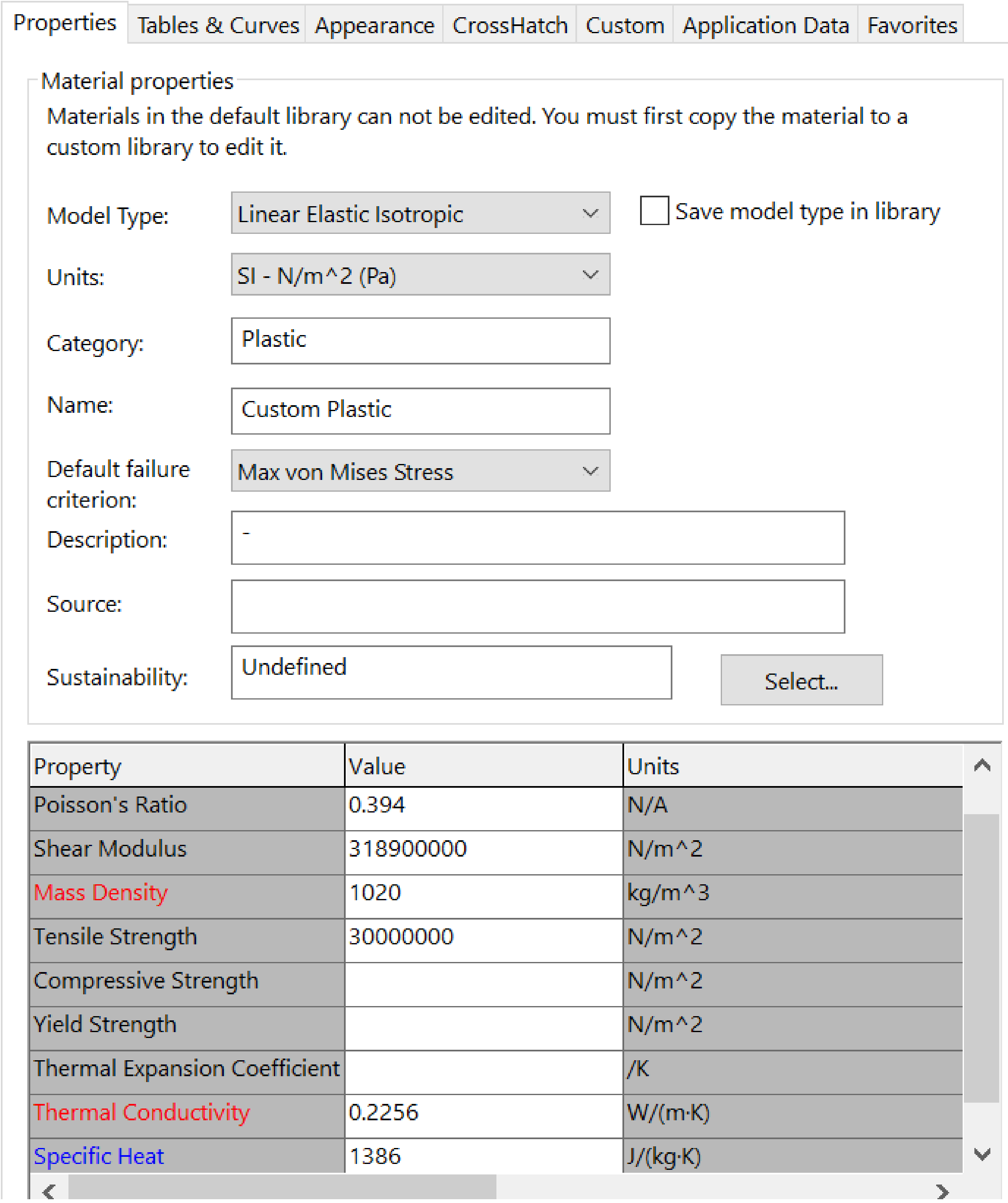

Figure 3-8 : Material Property Assigning

The thermal loads were applied from top and the bottom of the block.

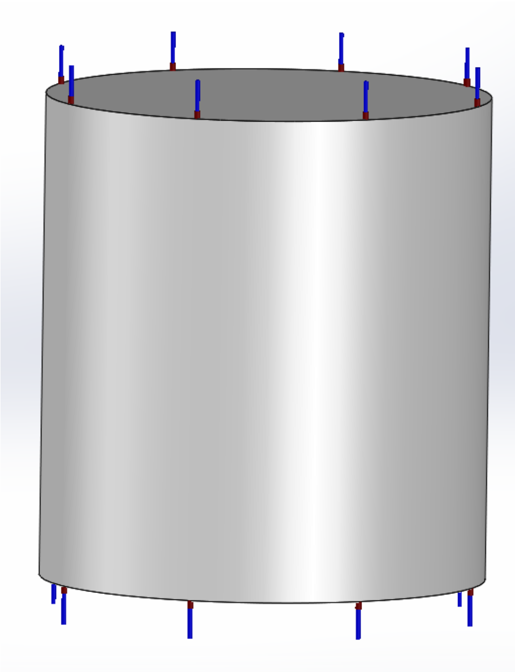

Figure 3-9 : Application of the thermal loads

The model was then undergone meshing. For that, there are several meshing types. It was selected the standard mesh size for this study. 150˚C heat was continuously applied for 2 hours' time from the top and the bottom as the thermal loads.

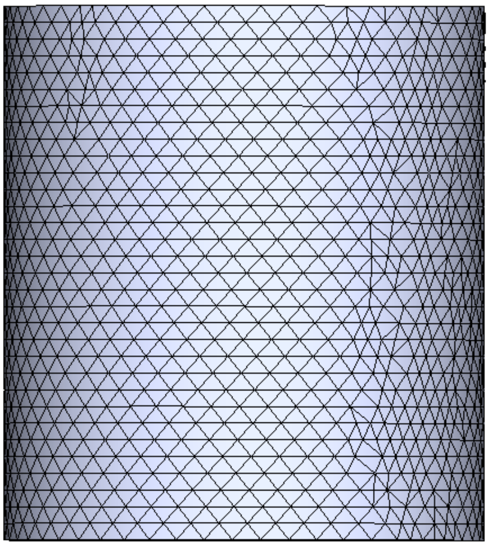

Figure 3-10 : Creating the meshing of the rubber block

Next the simulation was run, and the temperature distribution was observed. Mainly it was considered the temperature distribution of the centre position of the cylindrical block.

Time duration for the simulation was set to 7200sec and 120 readings were collected. Each minute the temperature at the centre point was measured.

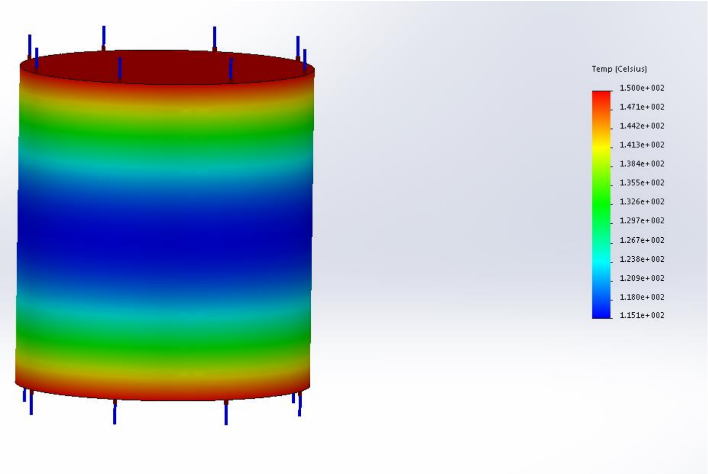

Figure 3-11 : Simulation of the tread block

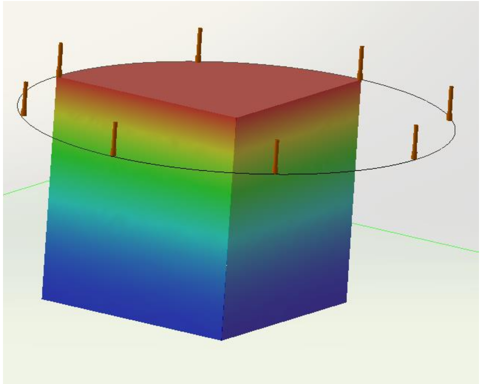

Figure 3-12 : Temperature measuring at centre point

The centre point was selected and placing a temperature reading probe, through the software the temperature distribution was taken. Then for set of material combination of thermal conductivity, density and specific heat capacity, a corresponding temperature profile is generated.

This temperature profile was compared with the practical temperature profile and until proper matching, the thermal properties within the software were changed.

4. RESULTS AND DISCUSSION

In the practical cylindrical block, the temperature profile relevant to the centre of the block was collected. Accordingly, in the software-model also the same position was selected. The temperature profile relevant to the point was collected.

First, practical temperature profile was compared to the temperature profile of the software model. The corresponding material properties were initially set as per the practical figures. Basically, the density, thermal conductivity and the specific heat capacity. Then several combinations of the above properties were adjusted in order to get close match with the practical temperature profile.

Though there are few thermal properties, all are represented by thermal diffusivity. At the end the temperature profile is affected only by the thermal diffusivity.

Table 4-1 : Thermal Property Variation - Trial 01

Thermal Property	Test v1	Test v2	Test v3	Test v4	Test v5
Thermal Conductivity (W/m.K)	0.1	0.2	0.3	0.4	0.5
Specific Heat Capacity (J/Kg.K)	500	1000	1500	2000	2500
Specific Gravity (Kg/m^3)	1130	1130	1130	1130	1130
Thermal Diffusivity (m^2/s)	1.77	1.77	1.77	1.77	1.77

As it is shown in the Figure 4-1, for changing the temperature profile, the only effecting factor is thermal diffusivity. Individual parameters such as thermal conductivity, specific heat capacity and density are not having an impact on the end results of the simulation.

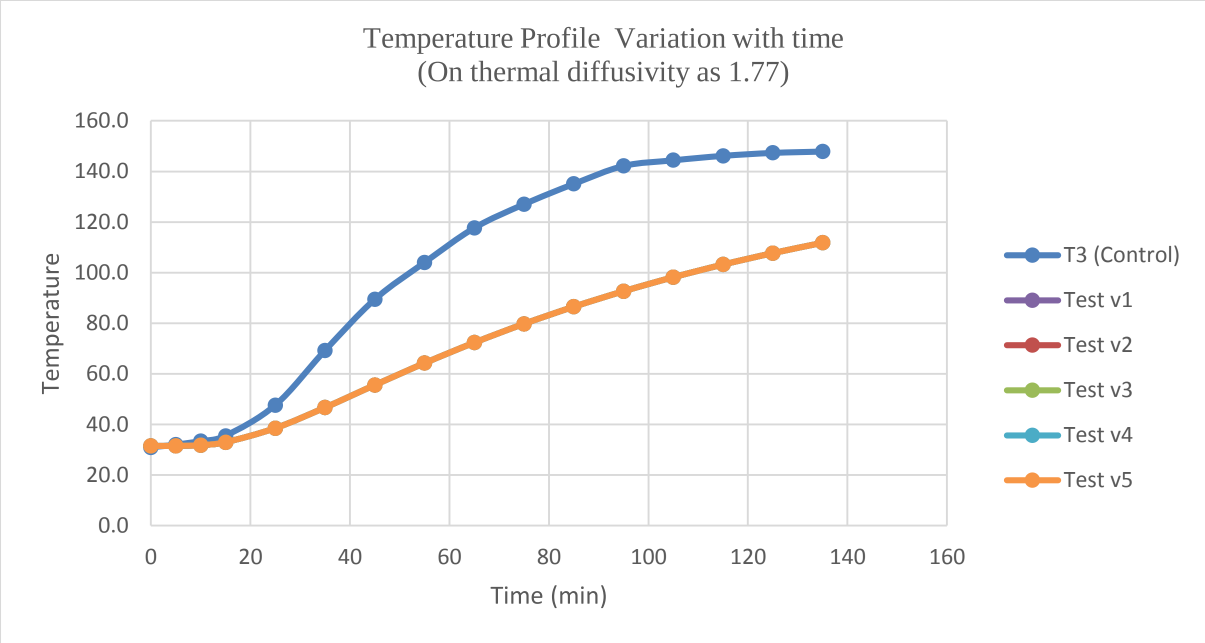

Figure 4-1 : Temperature profile variation with time keeping thermal diffusivity as constant

All the five graphs for "Test v1, v2, v3, v4 & v5" are coincided since they all are having same thermal diffusivity.

When the thermal conductivity is changed from 0.1 to 0.8 with changing the specific heat capacity from 125 to 3625, different temperature profiles were obtained.

Table 4-2 : Thermal Property Variation - Trial set 02

Thermal Property	Test 01	Test 02	Test 03	Test 04	Test 05	Test 06	Test 07	Test 08	Test 09	Test 10	Test 11
Thermal Conductivity (W/m.K)	0.1	0.125	0.15	0.175	0.2	0.275	0.375	0.475	0.575	0.65	0.8
Specific Heat Capacity (J/Kg.K)	125	250	375	500	625	1000	1500	2000	2500	2875	3625
Specific Gravity (Kg/m^3)	1130	1130	1130	1130	1130	1130	1130	1130	1130	1130	1130
Thermal Diffusivity (m^2/s)	7.08	4.42	3.54	3.10	2.83	2.43	2.21	2.10	2.04	2.00	1.95

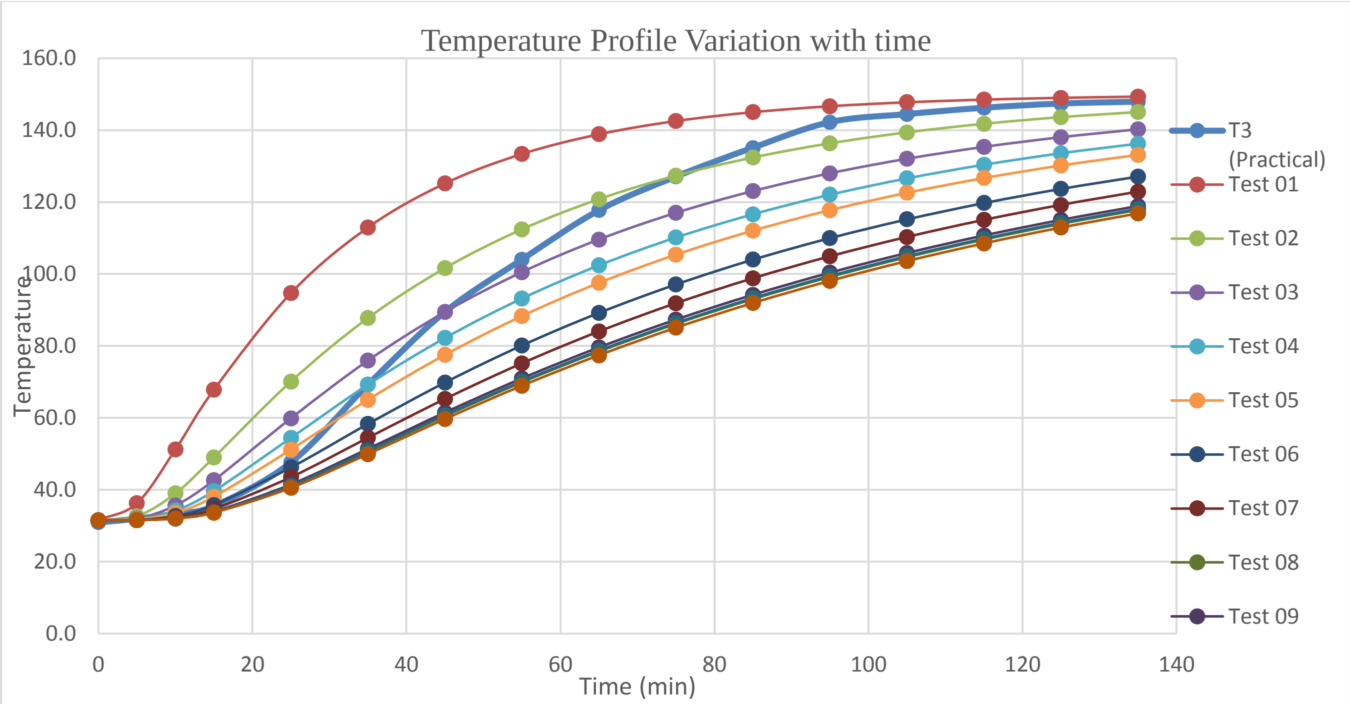

Figure 4-2 : Temperature profile Variation with time - Trial 02

“Test 03” was somewhat closer to the practical temperature profile. Therefore, based on the properties of “Test 03”, it was simulated some other combinations.

Table 4-3 : Thermal Property Variation - Trial set 03

Thermal Property	Test 3	Test 3.1	Test 3.2	Test 3.3	Test 3.4	Test 3.5	Test 3.6	Test 3.7	Test 3.8	Test 3.9	Test 3.10	Test 3.11
Thermal Conductivity (W/m.K)	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.14	0.13
Specific Heat Capacity (J/Kg.K)	375	500	625	750	875	1000	100	150	200	250	250	250
Specific Gravity (Kg/m^3)	1130	1130	1130	1130	1130	1130	1130	1130	1130	1130	1130	1130
Thermal Diffusivity (m^2/s)	3.54	2.65	2.12	1.77	1.52	1.33	13.27	8.85	6.64	5.31	4.96	4.60

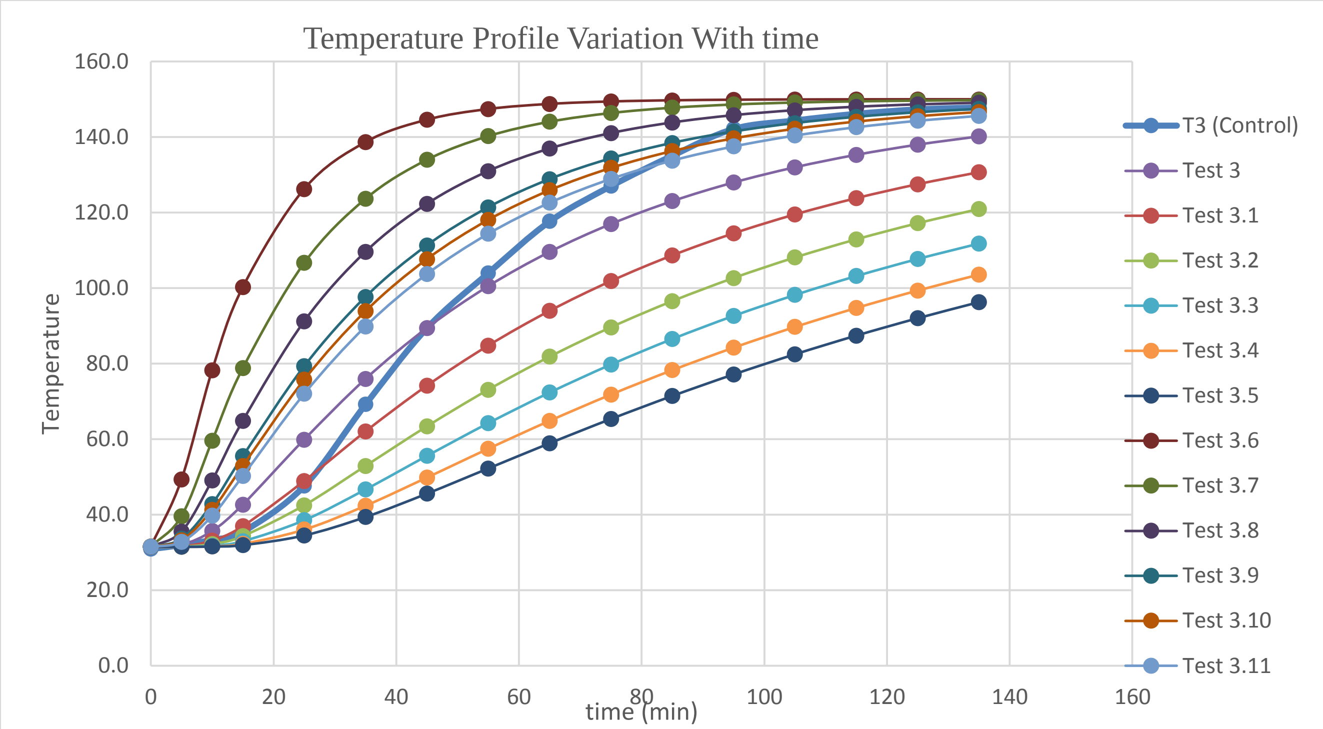

Figure 4-3 : Temperature profile Variation with time - Trial 02

As per the results, in the initial stage where the temperature range 35-60, practical profile matches with "Test 3.1" approximately.

When the temperature over 135˚C, it approximately matches the "Test 3.9".

The corresponding thermal properties are as below.

Table 4-4 Thermal properties for matching temperature profile

Thermal Property	Test 3.1 (For 35-60˚C)	Test 3.9 (Over 135˚C)
Thermal Conductivity (W/m.K)	0.15	0.15
Specific Heat Capacity (J/Kg.K)	500	250
Specific Gravity (Kg/m^3)	1130	1130
Thermal Diffusivity (m^2/s)	2.65	5.32

As per the above results, it was not be able to obtain a better relationship of the practical and the software-based modelling. Throughout the considered temperature range, the corresponding thermal properties are not fixed. It may need to change with the time.

Also “Table 4-4”, in order to align with practical temperature profile, “Specific Heat Capacity” was changed from 500 to 250, where at lower temperature range it is 500 and at higher temperature range it 250. Even though this will move to get align the temperature profiles of “Practical” and “Simulated”, based on the literature it is a contradiction.

5. CONCLUSION AND RECOMMENDATIONS

In order to predict the temperature profile of rubber product, using Solidwork as the software, it may need to consider following parameters. As per the observations, the rate of temperature increment is higher in practical block than it is in computer model. There are few reasons for this.

1) In this study, it was not considered the heat generation during the vulcanization. As it is known, rubber vulcanization is an exothermic reaction and some amount of heat can be generated during the vulcanization.

2) The thermal properties are temperature dependant based on the previous studies. Based on the complexity, that was not considered in this study.

3) It was set the boundary conditions as top and bottom of the cylindrical block. Still the mould is having circular cylindrical part around the rubber. Some of the heat from the top and bottom parts can be experienced to the rubber block through this surface as well.

4) In the modelling, the meshing was done using default standard mesh size in the software.

Those may be some of the reasons for the misalignment of the temperature profile of practical and software model.

Recommendations for further studies

Based on this research, following recommendations can be made for further studies.

1) The consideration of the heat generation during the vulcanization of the rubber is important.
2) Usage of the temperature dependent thermal diffusivity would be needed in the modelling. Also, in this study, it was found that specific heat capacity of the rubber was reduced with the temperature. That is a contradiction to the previous literatures.
   It would be better, if it can be further verified in future studies.

3) In the model, all the possible heat flows are needed to be considered. Basically, in this study, it was considered top and bottom heating only but since the rubber block is on a cylindrical mould, there would be a heat inflow from curvature sides as well.

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7. APPENDICES

a. Appendices A

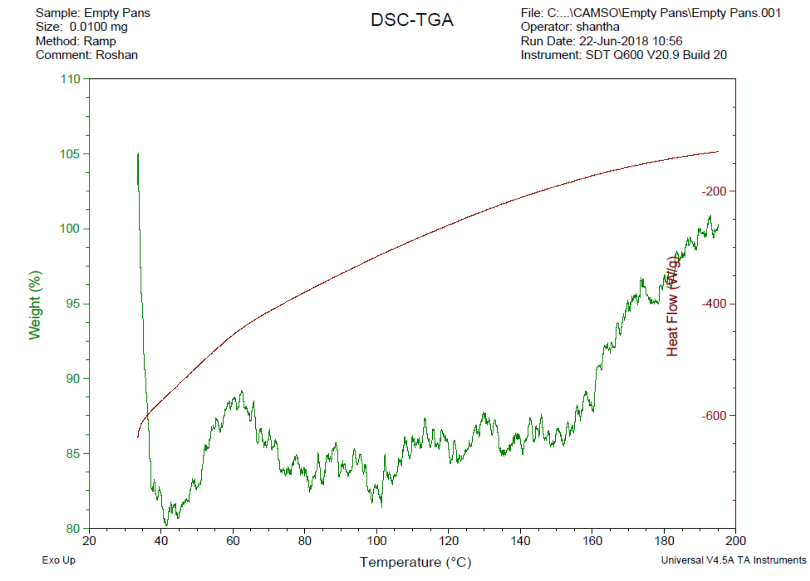

Figure 7-1 : DSC Curve for Empty pan

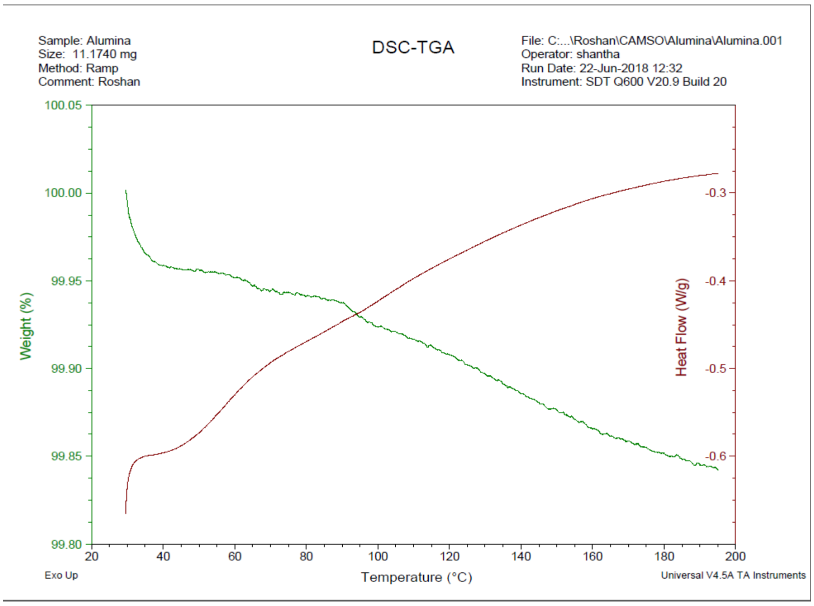

Figure 7-2 : DSC Curve for Reference sample

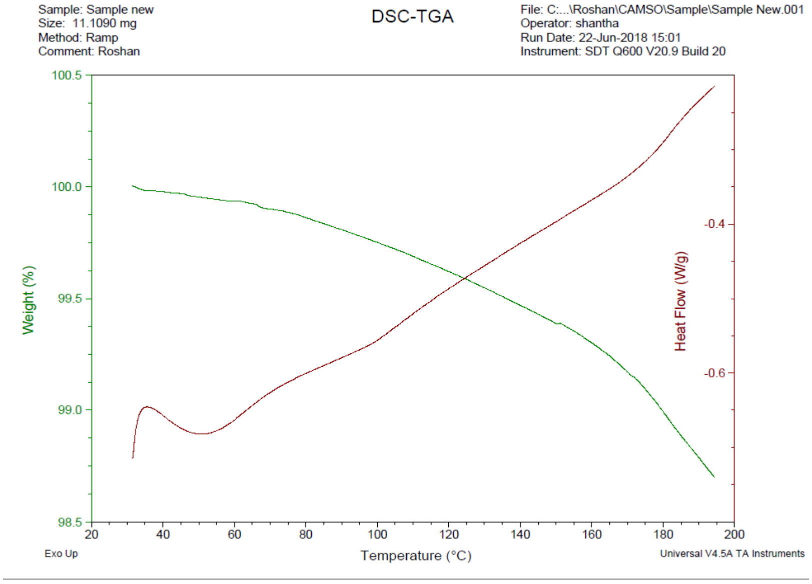

Figure 7-3 : DCS for Rubber Sample

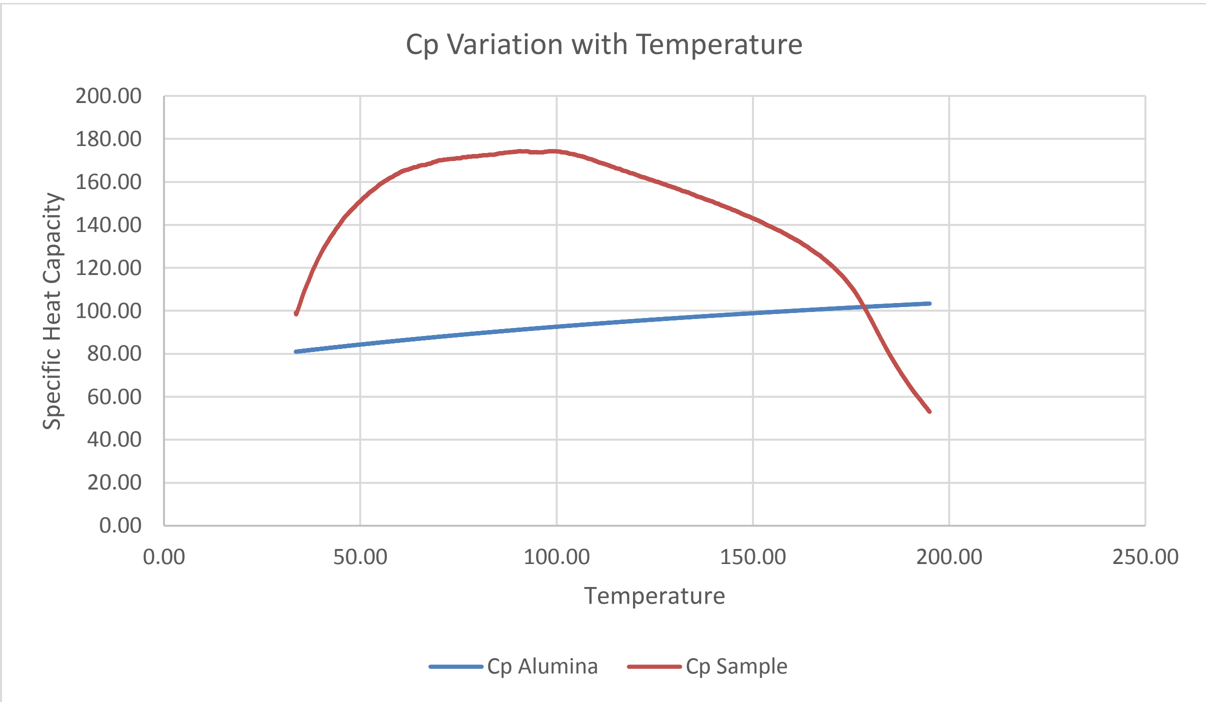

Figure 7-4 : Specific Heat Variation With time for Rubber Sample

b. Appendices B

Table 7-1 : Temperature of Practical block

Time (Min)	Test 01	Test 02	Test 03	Average Temperature
0	30.1	31.4	31.3	31.35
10	32.2	33.6	34.4	34
20	32.6	31.7	31.6	31.65
30	36.9	35	34.7	34.85
40	45	46.3	51.6	48.95
50	65.3	71.8	70.7	71.25
60	84.9	91.6	91.9	91.75
70	102.7	105.6	103.8	104.7
80	115.3	119.8	118	118.9
90	125	128.6	127.6	128.1
100	133.5	136.6	135.2	135.9
110	142.2	142.2	142.2	142.2
120	144.2	144.5	144.6	144.55

Table 7-2 : Temperature distribution with constant thermal diffusivity

	Practical Results	Test v1	Test v2	Test v3	Test v4	Test v5
TC		0.1	0.2	0.3	0.4	0.5
SC		500	1000	1500	2000	2500
SG		1130	1130	1130	1130	1130
Diffusivity x 10^7	Average	1.77	1.77	1.77	1.77	1.77
Increment (min)	T3 (Control)	T3 (Centre)	T3 (Centre)	T3 (Centre)	T3 (Centre)	T3 (Centre)
0	30.9	31.5	31.5	31.5	31.5	31.5
5	32.0	31.5	31.517	31.517	31.517	31.517
10	33.4	31.8	31.821	31.821	31.821	31.821
15	35.5	33.0	32.992	32.992	32.992	32.992
25	47.6	38.5	38.54	38.54	38.54	38.539
35	69.3	46.7	46.703	46.703	46.703	46.703
45	89.5	55.6	55.586	55.586	55.586	55.586
55	104.0	64.3	64.258	64.258	64.258	64.258
65	117.7	72.4	72.361	72.362	72.361	72.361
75	127.1	79.8	79.793	79.794	79.794	79.793
85	135.1	86.6	86.553	86.553	86.553	86.553
95	142.2	92.7	92.678	92.678	92.678	92.678
105	144.4	98.2	98.219	98.219	98.219	98.218
115	146.2	103.2	103.23	103.23	103.23	103.23
125	147.4	107.8	107.75	107.75	107.75	107.75

Table 7-3 : Temperature distribution with trial set 02

Thermal Property	Practical Results	Test 01	Test 02	Test 03	Test 04	Test 05	Test 08	Test 12	Test 16	Test 20	Test 23	Test 29
TC		0.1	0.125	0.15	0.175	0.2	0.275	0.375	0.475	0.575	0.65	0.8
SC		125	250	375	500	625	1000	1500	2000	2500	2875	3625
SG		1130	1130	1130	1130	1130	1130	1130	1130	1130	1130	1130
Diffusivity x 10^7	Average	7.08	4.42	3.54	3.10	2.83	2.43	2.21	2.10	2.04	2.00	1.95
Increment (min)	T3 (Center)	T3 (Center)	T3 (Center)	T3 (Center)	T3 (Center)	T3 (Center)	T3 (Center)	T3 (Center)	T3 (Center)	T3 (Center)	T3 (Center)	T3 (Center)
0	30.9	31.6	31.5	31.5	31.5	31.5	31.5	31.5	31.5	31.5	31.5	31.5
5	32.0	36.3	32.7	32.0	31.8	31.7	31.6	31.6	31.5	31.5	31.5	31.5
10	33.4	51.2	39.0	35.7	34.3	33.6	32.7	32.3	32.0	32.1	32.1	32.0
15	35.5	67.8	49.0	42.7	39.7	38.0	35.8	34.7	33.8	33.9	33.8	33.6
25	47.6	94.7	70.1	59.9	54.5	51.2	46.2	43.5	41.0	41.5	41.1	40.5
35	69.3	113.0	87.8	75.9	69.3	65.0	58.3	54.5	50.6	51.4	50.7	49.9
45	89.5	125.2	101.6	89.4	82.2	77.5	69.8	65.3	60.5	61.5	60.7	59.7
55	104.0	133.4	112.4	100.5	93.2	88.3	80.1	75.2	69.9	71.0	70.1	68.9
65	117.7	138.9	120.8	109.6	102.4	97.5	89.2	84.0	78.4	79.6	78.7	77.4
75	127.1	142.6	127.3	117.0	110.2	105.4	97.1	91.9	86.1	87.3	86.4	85.1
85	135.1	145.0	132.4	123.0	116.6	112.1	104.0	98.8	93.0	94.2	93.3	91.9
95	142.2	146.7	136.3	128.0	122.1	117.8	110.0	104.9	99.2	100.4	99.4	98.1
105	144.4	147.8	139.4	132.0	126.6	122.6	115.2	110.3	104.7	105.8	104.9	103.6
115	146.2	148.5	141.7	135.3	130.4	126.7	119.8	115.0	109.6	110.7	109.8	108.5
125	147.4	149.0	143.6	138.0	133.6	130.2	123.7	119.2	113.9	115.1	114.2	112.9
135	147.9	149.3	145.0	140.2	136.3	133.2	127.1	122.9	117.8	118.9	118.1	116.9

Table 7-4 : Temperature distribution with trial set 03

Thermal Property	Practical Results	Test 3	Test 3.1	Test 3.2	Test 3.3	Test 3.4	Test 3.5	Test 3.6	Test 3.7	Test 3.8	Test 3.9	Test 3.10	Test 3.11
TC		0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.14	0.13
SC		375	500	625	750	875	1000	100	150	200	250	250	250
SG		1130	1130	1130	1130	1130	1130	1130	1130	1130	1130	1130	1130
Diffusivity x 10^7	Average	3.54	2.65	2.12	1.77	1.52	1.33	13.27	8.85	6.64	5.31	4.96	4.60
Increment (min)	T3	T3	T3	T3	T3	T3	T3	T3	T3	T3	T3	T3	T3
0	30.9	31.5	31.5	31.5	31.5	31.5	31.5	31.5	31.5	31.5	31.5	31.5	31.5
5	32.0	32.0	31.646	31.548	31.517	31.507	31.503	49.313	39.598	35.515	33.614	33.2	32.832
10	33.4	35.7	33.161	32.211	31.821	31.651	31.574	78.273	59.578	49.074	42.833	41.246	39.717
15	35.5	42.7	36.985	34.315	32.992	32.313	31.953	100.27	78.829	64.867	55.482	52.894	50.295
25	47.6	59.9	48.935	42.479	38.54	36.08	34.516	126.24	106.68	91.199	79.3	75.743	72.018
35	69.3	75.9	62.066	52.912	46.703	42.408	39.393	138.66	123.69	109.62	97.667	93.904	89.867
45	89.5	89.4	74.169	63.382	55.586	49.854	45.582	144.58	134.02	122.29	111.31	107.69	103.73
55	104.0	100.5	84.792	73.091	64.258	57.493	52.249	147.41	140.3	130.98	121.4	118.1	114.41
65	117.7	109.6	93.978	81.839	72.362	64.882	58.917	148.76	144.11	136.95	128.86	125.95	122.62
75	127.1	117.0	101.88	89.637	79.794	71.836	65.349	149.41	146.42	141.04	134.37	131.86	128.94
85	135.1	123.0	108.68	96.559	86.553	78.294	71.438	149.72	147.83	143.85	138.45	136.33	133.8
95	142.2	128.0	114.51	102.69	92.678	84.252	77.147	149.87	148.68	145.78	141.46	139.69	137.54
105	144.4	132.0	119.52	108.12	98.219	89.731	82.471	149.94	149.2	147.1	143.69	142.23	140.42
115	146.2	135.3	123.83	112.93	103.23	94.761	87.42	149.97	149.51	148.01	145.34	144.14	142.63
125	147.4	138.0	127.52	117.19	107.75	99.375	92.014	149.99	149.7	148.64	146.55	145.58	144.33