



CHAPTER II

THEORY

BASIC KNOWLEDGE OF TIRE MANUFACTURING (Kirk-Othmer, 1982)

For tire manufacturing, the first stage starts from compounding of rubber and chemicals by banbury mixer. The rubber compound or stock are preformed by many forming machines such as calender or extruder. All of preformed materials are tire components for example, tread, sidewall, bead, steel belt, etc, that are supplied to tire assembly line. In the study of tire curing process, the understanding of dimensional, profile of material used that affect the heat transfer during tire vulcanization is important. In general, tread component is made from rubber compound that has poor thermal diffusivity and its thickness part is in tire structure. For curing or moulding process, one has to know how the curing machine works. In part of rubber compound, one has to know what is occurring or changing during vulcanization. Appendix C. shows the schematic of tire manufacturing plant.

Understanding of the above will enable one to specify the system of energy balance during tire curing process. So that, the basic knowledge involved in this work are divided into three main parts.

1. RUBBER COMPOUND FORMING
2. VULCANIZATION
3. HEAT TRANSFER

The details are discussed below. :

1. RUBBER COMPOUND FORMING

For the fabrication of most rubber products, the mixed compound must be formed in some way to prepare it for vulcanization. In some instances, the batch sheets as obtained from the mixing mills may not require processing other than to cut disks or rectangular pieces from the sheets, which are then suitable for charging into a mould. In most cases, however, the mixed compound must be processed into a form suitable for further fabrication. The most important of these processes are calendering and extrusion.

a.) CALENDERING. In general, calendering is comprised of

three separate operations : the formation of sheeted rubber, coating of fabric or other material, and the frictioning of fabric. The simplest calender consists of three parallel rolls rearranged one over the other. The openings between the rolls are adjustable, and the rolls are hollow and can be heated or cooled and operated at varying speeds. Also the speeds of the top and bottom rolls can be made the same as the middle roller slower. The calender operator must learn how to make the compound adhere to or follow one or the other rolls of the calender. In general, rubber sticks to a fast roll before it sticks to a slow roll, to a hot roll before a cold roll, and to a rough roll before a smooth roll.

Sheeted components are generally produced on a three-rolls calender with the middle and the top rolls as the forming roll and the bottom roll as the carrier or doubling roll. Preciseness in gauge is important in sheet component. Generally, the formation of calender sheet is limited in gauge because of trapped air or blisters. In order to minimize blister formation, the calender operator reduces the gauge of the sheet and plies to final gauge. Special devices, eg, a bankbar, are used to squeeze the air out. There are many different arrangements for handling the finished sheet from the calender, with

a belt wind up or on drums, depending upon the type of product being made. In sheet calendering, the control of the roll temperature is very important.

Coating operations are performed on either three-or four-roll calenders. The three-roll calender applies the coat to one side of the fabric and the four-roll calender coats both sides of fabric. The top roll of the three-roll calender or the bottom roll and offset rolls of the four-roll calender are run at odd speed to the center roll, usually two-thirds as fast. The roll crown of the the calender

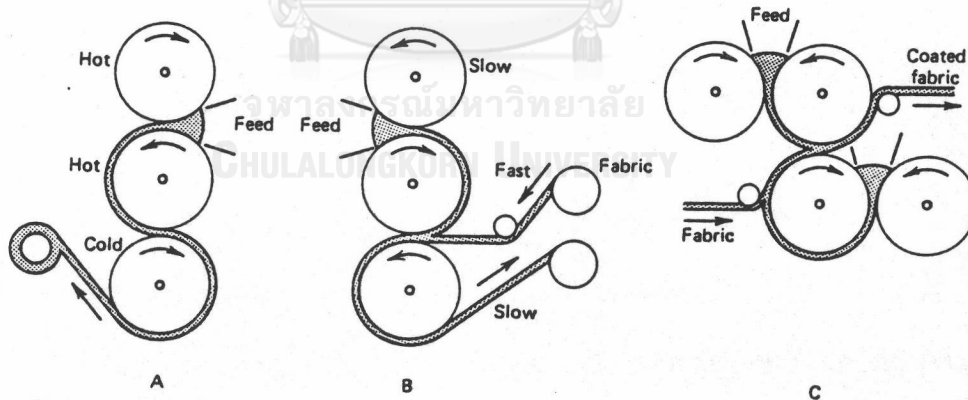


Figure 2.1 Arrangement of calender rolls. A, preparation of sheeting; B and C, preparation of coated fabric.

rolls in coating operation is very important. The Z calender (see part C of Fig. 2.1) ensures more precise control of the calendering operation. The rolls of this calender are in the Z arrangement, but instead of the pairs being horizontal or vertical, the rolls are inclined at an angle to facilitate feeding and working around the calender.

Friction compounds are rubber coating produced by frictioning on a calender that forces the rubber among and into the interstices between the fibers as a result of the calender speed and roll pressure faster than the top or bottom rolls. Friction compounds are normally compounded to be soft and sticky. This result is obtained by the use of tackifying oils and extra softening of the base rubber. The fabric to be impregnated should be kept hot. These friction compounds are used in ply building in tires.

b.) **EXTRUSION** An extruder consists essentially of a power-driven screw rotating in stationary cylinder. A hopper for feeding the compound is located near the driven end of the screw and a head is provided on the cylinder at the end of the screw. A variety of dies shaped to produce the desired cross section can be adapted to

the head. The cylinder is jacketed for temperature control and, for large size screws, the center section is bored for the same purpose.

The extruder can be warm-fed or cold-fed. Extruders handling cold feed, i.e, at room temperature , are made differently than those handling warm feed. With cold-feed extruders, the extra length is needed to break down the rubber compound sufficiently for smooth extrusions. The screw flights are also shallower for effective compound softening and cooling.

The extruder can be fed by hand or by a force-feed system consisting of two feed rollers at the top of the feed box to force the compound into the screw and minimize air blisters in the extrusion. The newer extruders contain vacuum systems to eliminate trapped air and moisture.

For tread and sidewall components, the extruder is too large, the rubber compound remains in the barrel too long and may scorch because of the unnecessary work done on it. Since cold-feed extruders perform work on the compound in addition to conveying and forming it, the stock temperature increases. Therefore, compounds to be cold-fed are more highly plasticized than normal stocks in order to prevent excessive heat generation and scorch in the extruder.

Because of the considerable elastic component of compounded rubber in the unvulcanized state, appreciable expansion occurs when the material is forced through a die. Thus the opening in the die is much smaller than the corresponding dimensions of the extruded part. Since the swell at the die varies with the compound of the material being extruded, the die must be tailored to fit the properties of the particular compound to be used.

c.) **TIRE ASSEMBLY LINE** Following the forming of the components by calendering, extrusion or deposition from a cement, some articles can be vulcanized directly without further treatment such as, sheeted material suitable for gasketing. For tire product, assembly steps, which vary from simple to complex, may be required.

A typical tire - building operation for a radial passenger tire requires the following materials : An extruded section of tread having a suitable contour. The extrusion of steel cord coated on both sides with rubber compound and cut at an angle of ca 20 degree to the direction of the cord length, this cutting is bias - cut. The steel cord coated is steel belt component. Plies consisting of pick cord fabric or weftless cord fabric coated on both sides with rubber by

calendering and cut from a long roll at an angle of ca 0 degree to the direction of the roll length; this cutting can be called radial cut. These cut strips are spliced forming a continuous band of the required width. Two-bead assemblies built from wire insulated with a hard or semihard rubber compound (apex compound); the bead assembly is wrapped with one or more layers of frictioned square woven fabric.

The tire is built on a collapsible, rotatable drum. One layer of the radial cut cord is applied and rolled down in contact with the drum, and the ends are spliced with an overlap equivalent to the width of about two cords. A second layer is applied with the cords running at ca. 90° to those of the first ply. The previously assembled beads are then applied and the two - cord plies on the drum are folded over the bead assembly. Two additional plies are then applied as before with the cord direction alternating, and their edges then folded over the bead assembly. The first steel belt is applied over the body plies and the second steel belt is applied over the first belt. After two additional of steel belt, the extruded tread section which has been cut to the correct length and splice angle is made into a band by cementing the ends together. The last step of tire assembly is cover by extruded side wall, (called "side wall over

tread"), is then applied and rolled down with forcing. The tire -building drum is collapsed and the uncured tire or green tire is removed. A green tire or radial steel belted tire appears like a barrel with both ends open. In radial tires before the belted are applied, the green tire is generally expanded from a cylindrical to a toroidal shape. The steel belt and the tread are then applied to this toroidal shape. The tire is now ready for vulcanization or tire curing process. (Robert R. Barnhart., 1986)

2. VULCANIZATION

Vulcanization is an irreversible process during which a rubber compound, through a change in its chemical structure eg, cross-linking, becomes less plastic and more resistant to swelling by organic liquids. The results is that elastic properties are conferred, improved, or extended over a wide range of temperature. The term vulcanization was originally employed to denote the process of heating rubber with sulfur, but has been extended to include any process with any combination of materials which produces this effect. Vulcanization can be carried out under numerous conditions.

(Robert R. Barnhart., 1986)

a.) **CONDITIONS OF CURE** The combination of vulcanizing agents accelerator, activator, type of polymer, kind and amount of filler loading, and other accessory materials chosen for a particular compound determines its curing rate. The curing rate is measured by the rapidity with which the physical properties of the rubber compound develops with the time of heating. The method of determining the curing rate is to use a cure meter to obtain a torque-vs-curing time curve. The old method has been to cure test sheets for various time intervals at the desired vulcanizing temperature, test the stress-strain properties of the resulting vulcanizates, and plot the tensile strength and the force required to produce a particular elongation, for example, 300% modulus time of cure. In Figure 2.2 three cure-meter curves are shown illustrating the varying types of behavior encountered. The time required to attain the optimum cure is a measure of the rate of cure. Optimum cure is the state of vulcanization at which a desired property value or combination of property values is obtained. It is generally considered as the time required to attain 90 % of full torque or modulus development. Cure time is the time in minutes to reach the optimum cure. Any cure shorter than the optimum cure is an undercure, and any cure longer than the optimum is an overcure.

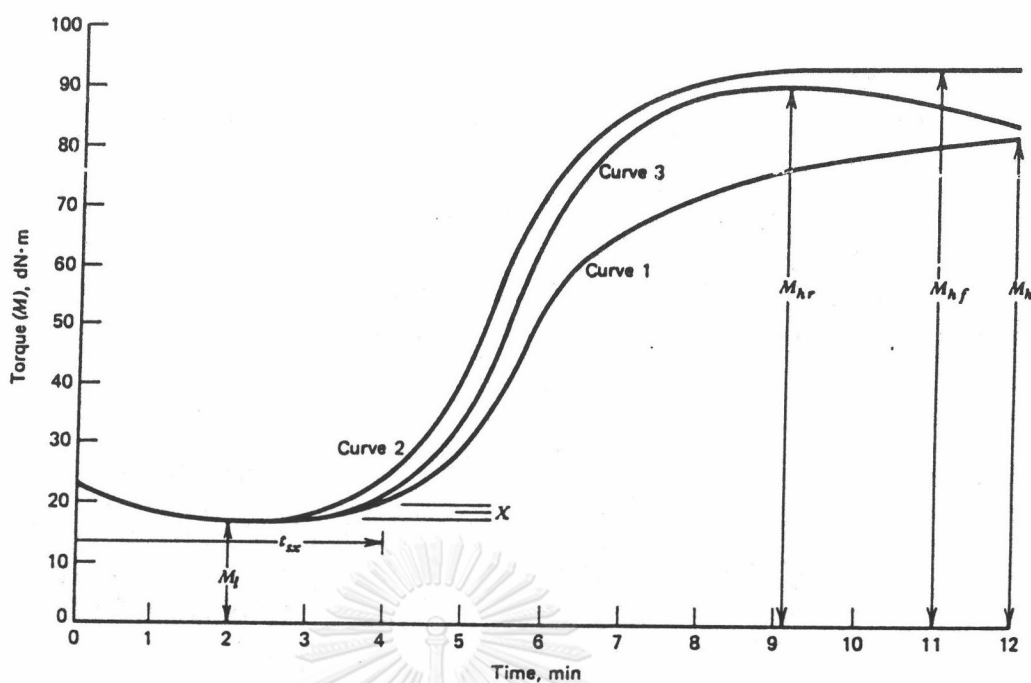


Figure 2.2 Curing curves. M = torque in dN.m; M_1 = min. torque, M_h = highest torque attained during specified period of time when no plateau or maximum torque is obtained (Curve 1), M_{hf} = max. torque when curve plateaus (Curve 2), M_{hr} = max. torque of reverting curve (Curve 3). t_{sx} = scorch time in min. to increase x units above M_1 .

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(Kirk-Othmer, 1982)

Extreme overcures may be of two type is illustrated by curve 3 in Figure 2.2 by the drop in torque beyond the max. This happens with most natural rubber, polyisoprene, or butyl compounds, and this type of overcure is called reversion. The physical properties of a reverted stock are lower hardness, and tensile strength and higher elongation.

In the other type of overcure, the stock continues to harden , the torque or modulus rises, and the tensile strength and elongation fall. This is characteristic of SBR and most other synthetic rubbers Curve 2 in Figure 2.2 represents a plateau or flat curing curve 1 represents a creeping torque or modulus curve, which has not reached optimum cure in the all test time.

The cure to be used on a particular product depends on the following factors:

1.) The size and shape of the product By all methods of curing except that of radio frequency, heat is supplied to the product at the surfaces. Rubber is a poor conductor of heat and thick may require long periods of time during vulcanization before the temperature of the center regions of the article is the same as the impressed temperature. This time lag or incubation time is a function of the size and shape of the article and the thermal diffusivity of the rubber. Factors affecting the problem of obtaining equivalent cures in specimens of various shapes have been summarized A nomograph has been developed that permits the estimation of incubation time for various shaped rubber articles. (Robert R.,1986)

The nomograph is accurate at 138 C with a ca 5% error for temperatures

of 138 °C, 33 °C. The most favorable shape for low incubation time is a sphere, and the most unfavorable shape is a thick flat slab of relatively large length and width. The second factor is the minimum dimension. In the case of the sphere this dimension is the diameter, and for the large flat slab is the thickness. Values for thermal diffusivities are given and all are quite low, eg, 0.0097 - 0.0845 cm²/min for natural rubber tread stocks to 0.0539 cm²/min for butyl. The thermal diffusivity values increase with increased pigment and decrease with increasing temperature. (D.A. Hills, 1970)

2.) The temperature of cure The effect of temperature on the vulcanization rate over the range of temperature from room temperature to the highest temperatures commercially can be represented by an Arrhenius - type plot relating the logarithm of the time required, ie, the reciprocal of the rate, to the reciprocal of the absolute temperature. The curves closely approach straight lines and correspond to an apparent activation energy of ca 84-105 (kg.J)/mol (ca 20-25 (kg.cal)/mol). The published data on this point are not altogether reliable, probably because of the difficulties

involved in determining the cure rates. Most investigators agree that some changes in the effect of temperature on cure rate result from changes in the curing system. As a rough approximation and for convenience in transposing cures from one temperature to another it is generally that the cure rate is doubled for a 10°C increase in the curing temperature. At $125\text{-}160^{\circ}\text{C}$, ie, the range in which most rubber products are vulcanized, this is a fairly reliable approximation.

In making a change from one curing temperature to another, any incubation time which is included in the curing time of the article must be subtracted before the new curing time is calculated. Thus if the curing time of an article is 65 min at 138°C , including an incubation time of 15 min, and it is desired to find the equivalent curing time at 149°C , the incubation time is first subtracted giving 50 min at 138°C . The time at 149°C that is equivalent to 50 min at 138°C is 23 min. To this is then added the 15 min incubation time giving a final cure of 38 min at 149°C . The reason for this procedure is that incubation time is independent of the temperature.

The temperature of cure selected for a particular product is determined by many factors, including the following. For mould cures it is advantageous to have the fastest possible mould turnover.

Thus the temperature chosen is usually the highest possible temperature consistent with the production of goods of satisfactory quality. The size of the product frequently determines the highest temperature that can be used. A product having a large volume of rubber has a more uniform cure throughout its cross section if a long, low temperature cure is used rather than a short, high temperature cure. Frequently for products of this type, a step-up cure is used in which a period of time at a low temperature is followed by another period at a higher temperature.

The maximum temperature is sometimes limited by the pressure which the equipment safely withstands, ie, for steam cures. The maximum temperature is frequently limited by the occurrence of manufacturing defects at high curing temperatures.

In hard rubber products, the danger of a violent exothermic reaction limits the maximum temperature. In bladder curing of tires, the maximum cure temperature not only depends upon the thickness of the tire, but it is also limited by its effect on the service life of the curing bladders.

Some of the reasons why the compounder does not run a full cure in the center region of the article are as follows:

The article may perform adequately in service when cured for a shorter time even though some degree of undercure exists in the thickest portions; the reduced curing time results in cost savings; and the amount of overcure at the surface is reduced.

Mould curing. compression moulding is the oldest method for making moulded parts. The uncured is formed to the approximate shape and placed in the individual cavities. As the mould is closed under pressure, the conforms to the shape of the cavity and the excess material is forced into a flash groove. The compression moulds may be either the simple flash type, the positive or plunger type, or the semipositive type. The plunger mould ensures that the full force of the press is applied directly on the rubber during moulding and curing. This is in contrast to the flash mould , where both the metal and the rubber bear the press force. The advantage of the plunger mould is in moulding very soft and very hard compounds. The disadvantages are that the amount of compound placed in the mould must be accurately controlled and the mould has poorer heat transfer. The semipositive mould incorporates some of the advantages of both the flash and positive moulds.

3. HEAT TRANSFER

The heat transfer process is the one important process for tire curing process. The heat energy is supplied from heat source including, steam inside the mould and hot water within the bladder.

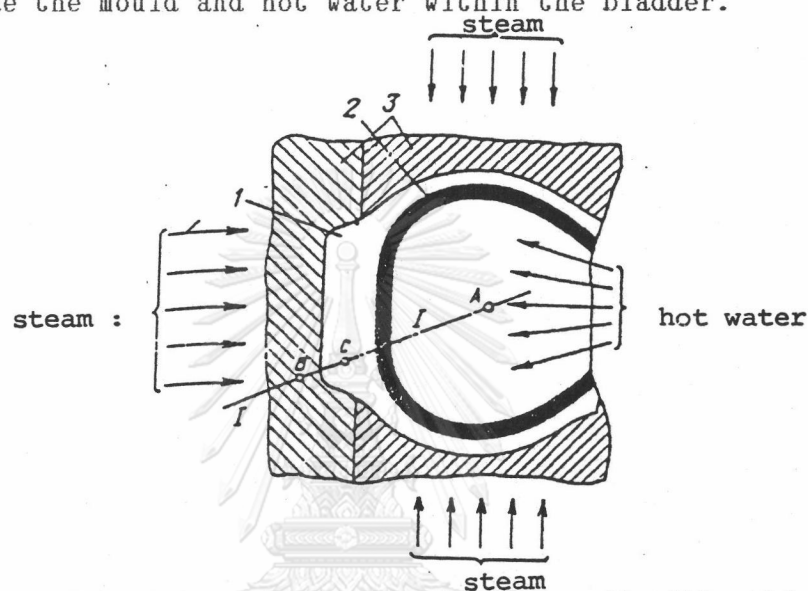


Figure 2.3 Fragment of vulcanization unit with a tire :1-Tire ;2-Bladder ; 3-Mould ;1-1 cross-section at thick-wall part

The theories of heat transfer are well established but their application to vulcanization process is rear. This is because, the complexity of tire structure and the interactions between the various thermal conductivity, the variation in thermal properties during vulcanization from one part of the structure to another. Especially, the interaction of the thermal properties of tread compound (i.e, thermal conductivity , thermal diffusivity, heat of

reaction) Physical properties of, mould material , mould profile and thermal convection of hot water also have an important effect.

By tradition, the process of heat transfer is classified into three basic energy transport by Conduction, Convection and Radiation. The basic laws of heat transfer are simple, but their application to real situation is usually a very complicated matter.

In this work, we are interested in heat energy transport by conduction only and define thermal axis as cylindrical coordinate (Figure. 2.4) for the purpose of reduction some complexity.

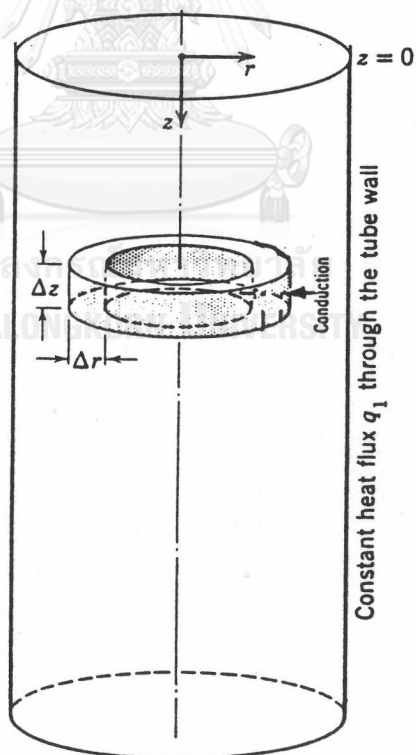


Figure 2.4 Shows thermal axis for cylindrical coordinate

; heat of reaction is excluded.

MODELLING AND NUMERICAL SIMULATION OF HEAT TRANSFER DURING
CURING PROCESS (Liang Xu and R.J. Crawford, 1992)

1. HEAT TRANSFER ANALYSIS

Heat transfer in the tire curing process involves unsteady-state heat flow. In theory during vulcanization process the heat is transferred from steam through a metal mould, then through a tread compound and is transferred from bladder surface through inner liner part. The heat transfer can be broken down into a series of modules as follows :-

- a.) Heat transfer between the inner surface of the mould and tread compound. (- boundary condition 1.)
- b.) Heat transfer through the green tire.
- c.) Heat transfer between the outer surface of the bladder and inner liner part. (- boundary condition 2.)

These three stages will be analysed in detail below.

The mathematical description of the heat transfer in tire curing process is complex because of the variation of the physical

and thermal properties of material. The simulation of the physical problem that corresponds to the actual tire curing process conditions is also complex.

For simplicity, it is necessary to make appropriate assumption in the simulation. During this work, the following initial assumptions were made for the purpose of simplification.:

a.) The heat transfer is one-dimensional, i.e. what happens at one point on the mould surface and the bladder surface are the same at all other points. This is reasonable because under normal circumstances the surface of the mould and bladder will be at a uniform temperature.

b.) The mould shape is cylindrical. In the mould, heat flow continuously on thermal axis which is radial axis of cylindrical system.

c.) The mould and bladder are effectively an infinite source of heat and are assumed to remain at the same temperature, and the interface temperature is known.

d.) Heat conduction along thermocouple wire.

e.) Thermal conductivity of tread compound represents conductivity of over all cross - section of green tire.

The fundamental laws of heat conduction take the form of a set of differential equations for temperature T . In this model, general finite difference approximation has been used for the solution of the partial heat transfer equation.

2. HEAT TRANSFER IN THE GREEN TIRE

The heat transfer in the green tire for cylindrical system can be described mathematically as follows: (Bird, Stewart and Lightfoot, 1960)

$$K_t \left(\frac{d^2 T}{dr^2} \right) + \frac{K_t}{r} \left(\frac{dT}{dr} \right) = \rho C_p \left(\frac{dT}{dt} \right) \quad (2-1)$$

T = Temperature ($^{\circ}\text{C}$)

r = Radius (m.)

K_t = Thermal conductivity of tread compound. ($\text{W}/\text{m}^{\circ}\text{C}$)

ρ = Density of tread compound. (Kg/m^3)

C_p = Specific heat of tread compound. ($\text{J}/\text{Kg}^{\circ}\text{C}$)

t = Time (sec.)

The mathematical solution of these heat transfer equation can be obtained using numerical analysis.

3. INITIAL AND BOUNDARY CONDITIONS

The initial conditions of the heat transfer problem of tire curing process are the initial temperature at all points in the mould surface, bladder surface and in the green tire, (see Fig 2.5)

$$T(r,t) \Big|_{t=0} = T(r,0) = T_o \text{ (Initial temperature of green tire)}$$

$$T(R_M,t) \Big|_{t=0} = T(R_M,0) = T_{M0} \text{ (Mould surface temperature)}$$

$$T(R_B,t) \Big|_{t=0} = T(R_B,0) = T_{B0} \text{ (Bladder surface temperature)}$$

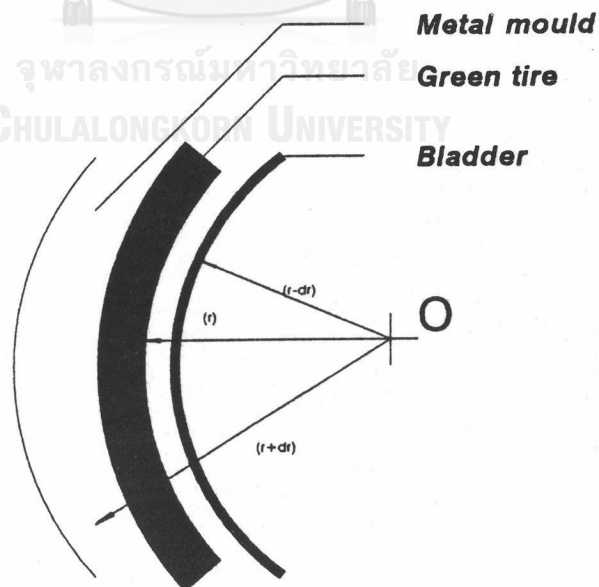


Figure 2.5 Cross - section of the cylindrical mould.

The boundary condition describes the temperature at each interface in the system as functions of time.

3.1 Boundary condition - 1 Heat transfer between the inner surface of the mould and tread compound. At the interface, the boundary condition is given by :

$$K_M \left. \frac{dT}{dr} \right|_{r=R_M} = K_T \left. \frac{dT}{dt} \right|_r \quad (2-2)$$

K_M = Thermal conductivity of mould

K_T = Thermal conductivity of green tire

3.2 Boundary condition - 2 Heat transfer between the outer surface of the bladder and inner liner part. At the interface, the boundary condition is given by :

$$K_T \left. \frac{dT}{dr} \right|_r = K_B \left. \frac{dT}{dr} \right|_{r=R_B} \quad (2-3)$$

K_B = Thermal conductivity of bladder

In this work, at the boundary condition assume the interface temperature is known. Using only initial condition, therefore the above equation is not required.

NUMERICAL ANALYSIS OF THE HEAT TRANSFER MODEL

(Liang Xu and R.J. Crawford, 1992)

The approach taken to solve the parabolic partial differential heat transfer equations by a numerical method is to replace the partial derivatives by finite difference approximations. It was assumed that the body in which the flow of heat was taking place was subdivided into small finite cells by some regular series of intersecting planes, and each of these cells is at a uniform temperature which equals the average temperature of two adjacent nodes. The heat transfer is applied to each cell in turn. Instead of the differential equations, therefore, a number of very simple simultaneous algebraic equations are produced and these may, in principle, be solved by straight forward methods.

1. FINITE DIFFERENCE APPROXIMATIONS TO DERIVATIVES

Since, of derivatives the function of temperature T , are single-valued, finite and continuous functions of r , then by Taylor's theorem, one gets (Smith, G.D., 1985).

$$\begin{aligned}
 T(r+\Delta r) = & T(r) + (\Delta r)T'(r) + 1/2(\Delta r)^2 T''(r) \\
 & + 1/6(\Delta r)^3 T'''(r) + \dots
 \end{aligned}
 \tag{2-4}$$

and

$$T(r-\Delta r) = T(r) - (\Delta r)T'(r) + 1/2(\Delta r)^2 T''(r) - 1/6(\Delta r)^3 T'''(r) + \dots \quad (2-5)$$

Addition of eqn. (2-4) and (2-5) gives :

$$T(r+\Delta r)+T(r-\Delta r) = 2T(r) + (\Delta r)^2 T''(r) + O[(\Delta r)^4] \quad (2-6)$$

where $O[(\Delta r)^4]$ denotes terms containing fourth and higher powers of (Δr) . Assuming these are negligible in comparison with lower power of (Δr) , it follows that,

$$T''(r) = (d^2T/dr^2) = 1/(\Delta r)^2 * [T_{(r+\Delta r)} - 2T_{(r)} + T_{(r-\Delta r)}] \quad (2-7)$$

Subtraction eqn. (2-5) from eqn. (2-4) and neglecting terms of order $(\Delta r)^3$ and higher leads to :

$$T_{(r+\Delta r)} - T_{(r-\Delta r)} = 2(\Delta r) * T'(r) \quad (2-8)$$

Equation (2-8) clearly approximates the slope of the tangent at P by the slope of the chord AB, this is called a central - difference approximation (see Fig. 2.6)

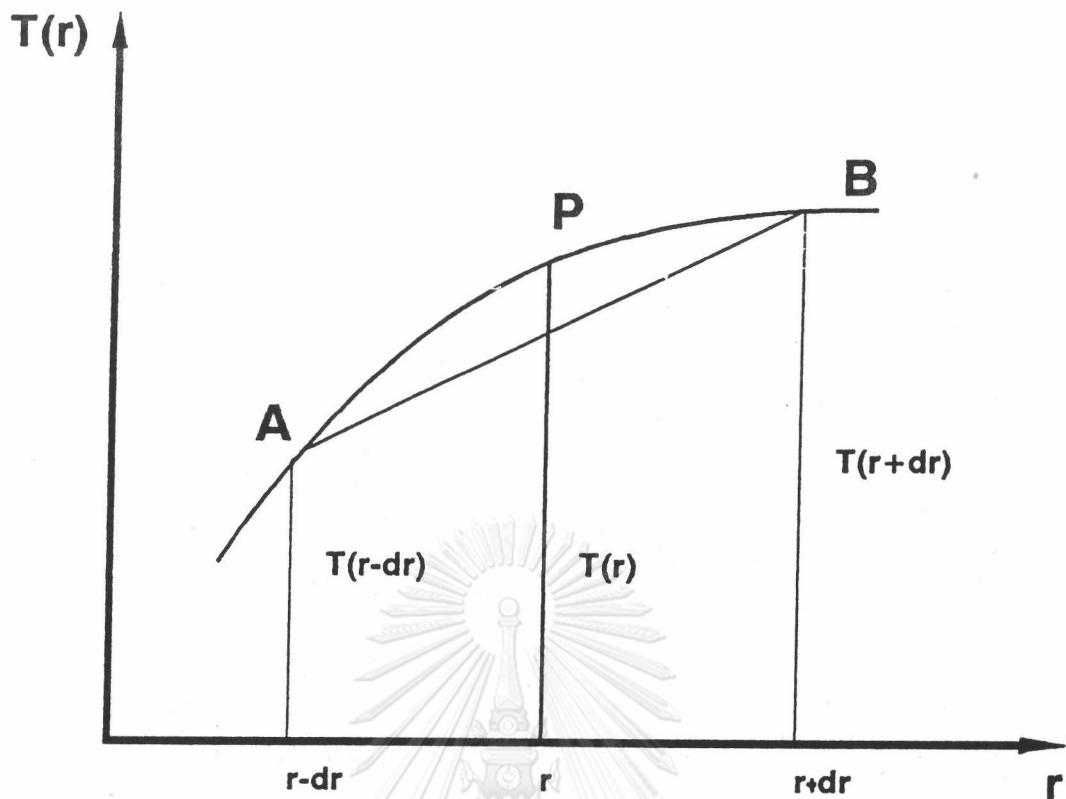


Figure 2.6 Approximation used in finite difference method.

The slope of the tangent at P can also be approximated by either the slope of the chord PB., giving the forward-difference formula :

$$T'(r) = 1/\Delta r [T_{(r+\Delta r)} - T_{(r)}] \quad (2-9)$$

Or the slope of the chord AP. giving the backward-difference formula :

$$T''(r) = 1/\Delta r [T_{(r)} - T_{(r-\Delta r)}] \quad (2-10)$$

Both eqn. (2-9) and eqn. (2-10) can be written down immediately from eqn. (2-4) and eqn. (2-5), respectively.

For a general heat transfer equation of the cylindrical model can be written as :

$$K(d^2T/dr^2) + K/r(dT/dr) = \rho C_p (dT/dt) \quad (2-11)$$

$$; D = K/\rho C_p$$

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The solutions of (d^2T/dr^2) , (dT/dr) can be approximated by eqn. (2-7) - (2-10) and by evaluating the time derivative (dT/dt) by a forward difference :

$$dT/dt = [T_{(t+\Delta t)} - T_{(t)}]/\Delta t \quad (2-12)$$

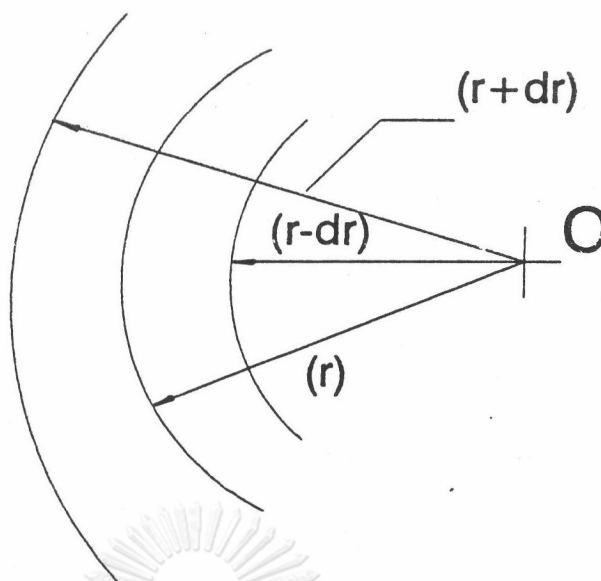


Figure 2.7 Corresponding radius at difference nodes.

Inserting the above difference equations eqn. (2-7,10,12) into the partial heat transfer equations converts the mathematical heat transfer model for the tire curing process into a number of simultaneous algebraic equations. These equations were then solved using a computer.

2. NUMERICAL ANALYSIS OF THE HEAT TRANSFER MODEL IN THE METAL MOULD WALL AND IN THE GREEN TIRE

A numerical method has been used to solve the heat transfer equations and is discussed in detail below :

To simplify the program for the analysis within the metal mould wall, in the green tire and bladder (hot water inside) a general heat transfer equation for a cylindrical mould eqn. (2-11)

$$K[(d^2T/dr^2) + 1/r(dT/dr)] = \rho C_p(dT/dt) \quad (2-13)$$

Inserting the developed finite - difference approximation equations into the above equation results is :

$$\begin{aligned} K[(T_{(r+\Delta r)} - 2T_{(r)} + T_{(r-\Delta r)})/(\Delta r)^2] + K/r[(T_{(r+\Delta r)} - T_{(r-\Delta r)})/2\Delta r] = \\ = \rho C_p[(T_{(t+\Delta t)} - T_{(t)})/\Delta t] \end{aligned} \quad (2-14)$$

OR

$$\begin{aligned} [T_{(t+\Delta t)} - T_{(t)}]/\Delta t = K/\rho C_p [(T_{(r+\Delta r)} - 2T_{(r)} + T_{(r-\Delta r)})/(\Delta r)^2] \\ + K/\rho C_p * 1/r[(T_{(r+\Delta r)} - T_{(r-\Delta r)})/2(\Delta r)] \end{aligned} \quad (2-14)$$

Eqn. (2-14) multiplied by (Δt) and rearrange to dimensionless term as following :-

$$\begin{aligned} [T_{(t+\Delta t)} - T_{(t)}] = (K/\rho C_p) * (\Delta t/\Delta r^2) [T_{(r+\Delta r)} - 2T_{(r)} + T_{(r-\Delta r)}] \\ + (K/\rho C_p) * \Delta t/r * \Delta r/\Delta r [(T_{(r+\Delta r)} - T_{(r)})/\Delta r] \end{aligned} \quad (2-15)$$

$$F_o = (K/\rho C_p) * (\Delta t/\Delta r^2) , \text{ Fourier's number}$$

Definition

$F_o = (K/\rho C_p) * (\Delta t / \Delta r^2)$ is the Fourier's number, a dimensionless group which has been defined to assist in the representation of transient heat flow calculations. The Fourier's number gives an indication of the speed at which a body will respond to a temperature change. Low value of F_o imply that a long period of time is required to heat the body. (D.Hands and A. Hamilton, 1988)

$$\begin{aligned}
 T_{(t+\Delta t)} - T_{(t)} &= F_o [T_{(r+\Delta r)} - 2T_{(r)} + T_{(r-\Delta r)}] \\
 &+ F_o * \Delta r / r [T_{(r+\Delta r)} - T_{(r)}] \quad (2-16) \\
 &= F_o T_{(r+\Delta r)} (1+\Delta r/r) - F_o T_{(r)} (2+\Delta r/r) + F_o T_{(r-\Delta r)}
 \end{aligned}$$

Since at time $(t+\Delta t)$, $T_{(t+\Delta t)}$ is the simulation results, calculated by :

$$T_{(t+\Delta t)} = F_o [T_{r+\Delta r} * (1+\Delta r/r) - T_{r} * (2+\Delta r/r) + T_{r-\Delta r}] + T_{(t)} \quad (2-17)$$

Boundary condition are :

$$\begin{aligned}
 T_{r+\Delta r} &= \text{The mould surface temperature} \\
 T_{r-\Delta r} &= \text{The bladder surface temperature} \\
 &\text{Or band ply temperature}
 \end{aligned}$$

$$T(r,t) \Big|_{t=0} = T(r,0) = T_o$$

THEMOPHYSICAL CHARACTERIZATION OF RUBBER COMPOUND
AND DETERMINATION

1. DETERMINATION OF DENSITY :

The methods of determination are described in ISO 2781. Method A (Buoyancy method) calculates the density from the mass of the sample in the air and in a test liquid, generally water, and from the density of this liquid. Common analytical balances with special equipment can be used to achieve this. The disadvantage of this method is that air inclusions in the sample and air bubbles on the surface can both distort these measurement. Although wetting agents are used to prevent air bubbles on the sample surface, they pass over into the test liquid during the measurement, thus quickly changing its density (Brabender OHG, Tire Technology international, 1994).

Method B is based upon the principle of liquid displacement by the sample. The reasons for error described for method A cannot be excluded with this method either. If more precise density measurements are needed, a "Density column", as standardized for testing rubber compound, can be used. This method require only very small sample weights, but it takes more than 10 minutes just to reach an equilibrium of the sample particles within the column.

In this work, the measuring method was modified from the density column method. The density of solution (density gradient) was prepared by changing of Zinc chloride concentration. The density gradient was measured by Hydrometer. The small sample was submersed into the solution. This submersion should be done sequentially from lower to higher density. During the sample submersed, the equilibrium of sample within the solution was obtained when the sample was at steady position. The density of rubber compound was equal to density of ZnCl-solution.

1.1. Density versus temperature measurement.

In general, vulcanization of rubber compound occurs during heat transfer through the rubber article. Rubber changes from paste or elastic to melt and then to solid or harden. Thus the density of the rubber compound changes with temperature. But this changing occurs inside mould cavity during moulding process. It means that it is occurring at constant volume, so that the density changes slightly. To measure these changes a special test was developed using thermomechanical analysis (TMA) equipment and Dilatometer accessory. The principle of operation of this method is that the dimensional changes of the sample can be measured as temperature of the specimen is raised. The schematic diagram of this analyser is shown in fig. 2.8

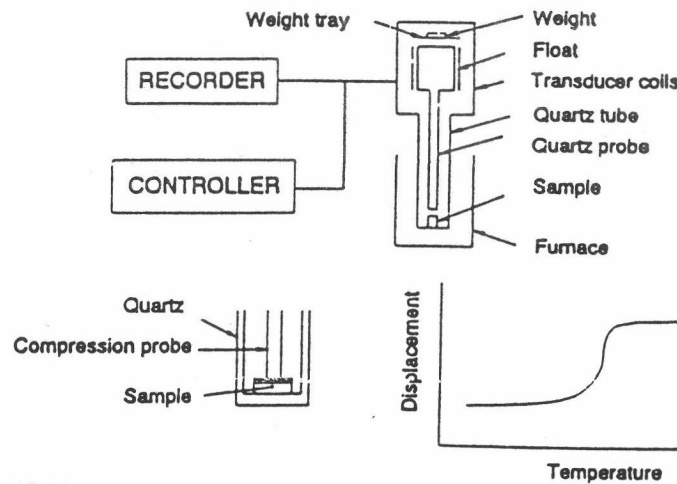


Figure 2.8 Schematic diagram of TMA. and the measuring data.

A linear variable differential transducer is used in conjunction with fused quartz probe which is in contact with Dilatometer accessory. The basic principle of this test is that the movement of quartz probe which can be raised because the specimen and filler filled inside Dilatometer accessory changing of dimensional.

2. SPECIFIC HEAT VERSUS TEMPERATURE MEASUREMENT :

The specific heat is the amount of heat required to raise the temperature of a 1 Kg mass through 1 °C at a constant pressure. The heat added causes a change in the internal energy (U) and in the enthalpy (H) of the material. (Bird, Stewart and Lighfoot, 1960)

$$C_p = [d(U+PV)]/dT = [dH]/dT \quad (\text{J/Kg}^\circ\text{C}) \quad (2-18)$$

In this work, the changing of specific heat with temperature of rubber compound material were measured by a Differential Scanning Calorimetry (DSC.) test.

3. THERMAL CONDUCTIVITY VERSUS TEMPERATURE MEASUREMENT

Thermal conductivity (K) is the quantity of heat transfer per unit time, area with a unit temperature gradient acting. It is a transport property of the material. The Fourier's equation is the defining equation for thermal conductivity. (Bird and Lighthfoot, 1960)

$$q = -KA \frac{dT}{dX} \quad (2-19)$$

; K = Thermal conductivity

A = Area

q = Heat flux

T = Temperature

X = distance

This equation illustrates that the rate of heat flow in one dimension is proportional to the product of the area flow and the temperature gradient. The negative sign results from the convention of defining a positive heat flow in the direction of a negative temperature gradient. The main methods for measuring

thermal conductivity are (D.Hands and A.Hamilton,1988) :

- 1). Guarded hot - plate method (ASTM C177-85)
- 2). Unguarded hot - plate method
- 3). Hot wire method
- 4). Differential scanning calorimetry (DSC. test)

Units

A variety of units have been used for thermal properties which is difficult when different sets of results have to be compared. The two most common units for conductivity are the cal./cm.sec. $^{\circ}$ C and the BTU.in/(ft²hr. $^{\circ}$ F). There are two units of length in the imperial unit, because area is measured in square feet and thickness in inches. A self-consistent conductivity unit BTU/ft.hr. $^{\circ}$ F, is obtained if the temperature gradient is measured in $^{\circ}$ F/ft. instead of $^{\circ}$ F/in., but this is not as common. For the S.I. unit of conductivity is the W/m $^{\circ}$ K. (see Table 2.1 shown the conversion factors for some of the thermal conductivity units.)(D.Hands and A. Hamilton,1988)

Table 2.1 The conversion factors for some of the thermal conductivity units

	W/mK	cal/cm.sec. °C	W/cm°C	kcal/m.hr. °C	Btu in/ft ³ hr. °F
W/mK	1	0.00239	0.01	0.86	6.93
cal/cm.sec. °C	419	1	4.19	360	2900
W/cm°C	100	0.239	1	86	693
kcal/m.hr. °C	1.16	0.00278	0.0116	1	8.06
Btu in/ft ³ hr. °F	0.144	0.000345	0.00144	0.124	1

4. THERMAL DIFFUSIVITY

Thermal diffusivity (D) is defined as the ratio of thermal conductivity to the heat capacity per unit volume:

$D = K/\rho C_p$ It determines the rate at which a non-uniform temperature distribution approaches equilibrium conditions in area per time (sq.m/sec.). Typical thermal property values for common materials are given in Table 2.2

The most common method used for thermal diffusivity measurement is the Guarded hot-plate method. (Parrott and Stukes, 1975).

TABLE 2.2 Conductivity and Diffusivity values for some materials

(Liang Xu & R.J. Crawford, 1994), (Kirk-Othmer, 1982)

Material	Thermal conductivity (W / m °C)	Thermal diffusivity (sq.m / sec.)
Copper	400	13.0×10^{-3}
Aluminium	230	7.7×10^{-3}
Steel	46	1.1×10^{-3}
Concrete	0.92	-
HDPE	0.50	-
LDPE	0.33	0.9×10^{-7} (20-190 C)
Nylon	0.31	1.3×10^{-7} (20-285 C)
PP	0.17 - 0.24	0.9×10^{-7} (20-230 C)
Polystyrene	0.03	-
Gum Natural Rubber	-	1.00×10^{-7}
NR Tread stock	-	1.62×10^{-8} - 1.40×10^{-7}
Butyl Rubber	-	8.98×10^{-7}