Transient Thermal Simulation Based Design of a Remote Temperature Measuring System for Tire Molds

H.M.S.C. Jayaweera
Department of Mechanical Engineering
University of Sri Jayewardenepura
Nugegoda, Sri Lanka
hmscjayaweera@gmail.com

C.D. Makavita
Department of Mechanical Engineering
University of Sri Jayewardenepura
Nugegoda, Sri Lanka
makavita@sjp.ac.lk

S. D. Bandara
Department of Mechanical Engineering
University of Sri Jayewardenepura
Nugegoda, Sri Lanka
sayurudilan@sjp.ac.lk

R. Y. Sampath
Department of Mechanical Engineering
University of Sri Jayewardenepura
Nugegoda, Sri Lanka
yasun@sjp.ac.lk

L. Balasooriya
Michelin Lanka (Pvt) Ltd.
Ekala Tyre Division ,
Ekala, Sri Lanka
lasitha.balasooriya@michelin.com

***Abstract*—The curing process of tires significantly impacts their quality, performance, and production cost. Therefore, temperature control is the most crucial aspect of the curing process. Temperature measurement of the mold that reflects the tire temperature is done with human involvement, which has an associated health risk. Hence, this study aimed to develop a remote temperature measuring approach to avoid direct human involvement. The temperature distribution of the tire mold during the curing process was simulated using the transient thermal analysis system in Ansys workbench by maintaining the boundary conditions fixed. The optimal temperature measuring locations were evaluated to determine the best location to insert the temperature measuring sensor. Boundary conditions were created according to the requirement to maintain the internal temperature of the mold at the curing temperature (140 °C). Resistance Temperature Detectors (RTD), a contact-type temperature measuring device were identified as the most suitable for this application based on their high accuracy and stability. After selecting the temperature sensor and determining the insertion point, a wireless communication method was developed based on the ATmega328 microcontroller, in which the communication between the transmitter and receiver circuits occurs via the NRF24L01 2.4 GHz transceiver module. Thus, this remote mold temperature measurement approach would help eliminate human involvement in temperature measurement while providing accurate measurements for the curing process.**

***Keywords*—Tire mold, Curing process, Remote temperature measurement, Transient thermal analysis, Temperature measuring**

I. INTRODUCTION

The tire manufacturing process is divided into five main processes listed below and the flow of the manufacturing process is shown in Fig. 1. [1],

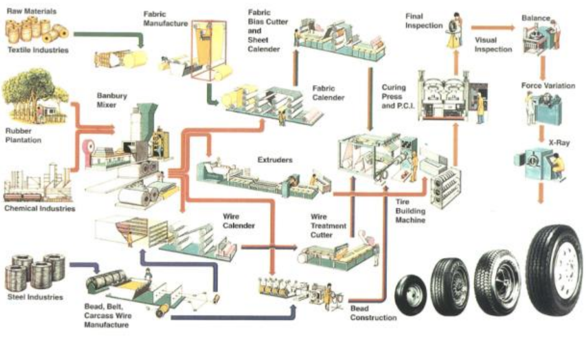


Fig. 1. Tire Manufacturing processes[2]

(1) Compounding and boundary mixing
(2) Milling
(3) Extruding and calendaring
(4) Curing and vulcanizing
(5) Inspection and finishing

The availability of each machine and its essential parts directly affects how well the manufacturing system works overall [1]. The ability to complete the goals in the tire manufacturing process is greatly impacted by the operation of the curing process. The curing process significantly impacts a rubber product's quality, performance, and production cost [4]. The three most important variables to control in the curing process are pressure, temperature, and time. Because even a small variation in temperature (2.6 °C) and pressure (1.5 Kg/cm^2) has a direct impact on the tire's quality [3]. When considering the temperature, low tire temperature results in minimal sulphur production and hence low wear resistance. Also, a high temperature causes the tire to produce too much sulphur, shortening the tire's lifespan [3],[5].

In the curing process, the rubber tire is heated in the mold during the initial phase. After that, the tire is de-molded and let to cool in the surrounding air temperature [4]. Tire curing process is a more energy-consuming process compared to other processes. Therefore, an accurate temperature monitoring system is important to reduce manufacturing costs, environmental impacts, and, energy waste. As well as increase the production quality of the tire.

Hence, temperature control is a most crucial aspect of the tire manufacturing industry. However, due to the high pressure inside the mold, directly measuring the tire's temperature is not feasible. Therefore, the temperature of the tire mold, which closely reflects the tire's temperature, is measured and it is important to identify the correct point for measuring the temperature. Additionally, determining the number of readings to be taken is crucial.

When selecting the type of temperature measuring device, operating conditions and accuracy of the device should be considered. As well as the temperature-measuring device insertion into the mold is done with human involvement. That task is risky due to the environment in the oven is very hot. Therefore, the insertion process of the temperature measuring device into the tire mold should be improved to avoid human involvement. To address this problem, the wireless temperature measuring system was developed using Arduino technology.

II. METHODOLOGY

A. Problem Definition and Objectives

The objectives were designed to address the identified problems and align with industrial needs and potential applications.

1. Analyse the temperature distribution of the mold during the tire curing process.
2. Evaluate the optimal temperature measuring locations on the mold, determining the minimum number of locations necessary for accurate readings.
3. Select the most suitable temperature measuring method (contact/non-contact) and the appropriate device (thermocouples, RTD, IR sensors) to measure the temperature of the tire mold.
4. Develop the remote temperature measuring system to eliminate human involvement in mold temperature measuring.

B. 3D Model Development in SolidWorks

SolidWorks 2020 was utilized to design and develop a detailed 3D model of the tire mold. This tire mold is used to produce B4-type solid tires. These solid tires are generally designed for heavy-duty applications.

(a) (b)

Fig. 2. (a) B4 mold with locking devices, (b) B4 mold without locking devices

TABLE 1. DETAILS OF THE B4 TIRE MOLD

Product code of the tire	9.374.11993
Tire size	21 in x 8.9 in
Thread pattern	mag
Heel pattern	Quick
Rim size	6 in
Brand	Solideal Magnum
Casing	B4-X-053

C. Transient Thermal Analysis in Ansys

Transient thermal analysis was carried out using Ansys 2021 R2 software. In this study, the temperature distribution of the mold varies with time. Therefore, this analysis is done using the Ansys transient thermal analysis system. In this study, the boundary conditions are fixed, therefore, the time to reach a steady state temperature can be evaluated through this study. Then, this study helps to determine the time required to preheat the mold which is equal to the time taken to reach the steady state temperature of the mold. However, the main goal of this analysis is to identify the most suitable temperature-measuring locations that are in close proximity to the temperature of the curing tire.

Transient thermal analysis system in Ansys Workbench was set up to simulate the temperature distribution of the tire mold during the curing process. Then realistic boundary conditions were applied including heat flow, convection, and temperature. Material properties were extracted from the material data sheet and literature [7],[8].

There are some assumptions made for conducting this thermal simulation.

- The total heat generated by the heating elements is transferred to the mold.
- The temperature of the air inside the oven is equal to the curing temperature.
- There is no heat loss during heat transfer.
- The temperature of all surfaces inside the mold is equal to the curing temperature of the tire.

Material Properties Assignment

The next consideration is the material of the mold. The mold is manufactured using 42CrMo4 high-quality steel. This material has a good combination of strength and toughness in the quenched and tempered condition. Therefore, it can withstand the temperature and pressure experienced during the curing process of the tire. The details of the material 42CrMo4 are listed in Table 2.

TABLE 2. MATERIAL DETAILS OF 42CRMO4 STEEL[8]

Material	42CrMo4
Material Number	1.7225
Density	7720 kg/m^3

During this process, it's important to note that the thermal properties of 42CrMo4, including specific heat capacity and thermal conductivity, will vary with the heating temperature. Specific heat transfer coefficient values and thermal conductivity of the material 42CrMo4 are outlined in Table 3. The variation of the specific heat transfer coefficient values of the 42CrMo4 with the temperature is shown by the graph in Fig. 3. Thermal conductivity also needs to be considered for its temperature-dependent variation [7],[9]. The variation of the thermal conductivity of the 42CrMo4 with the temperature is shown by the graph in Fig. 4.

TABLE 3. SPECIFIC HEAT CAPACITY AND THERMAL CONDUCTIVITY OF 42CRMO4 STEEL [7]

Temperature (°C)	**Specific heat transfer coefficient (J/kgK)**	**Thermal conductivity (W/mK)**
25	460.43	58.682
100	485.32	70.708
200	514.61	48.112
300	570.14	45.689
400	585.73	41.718

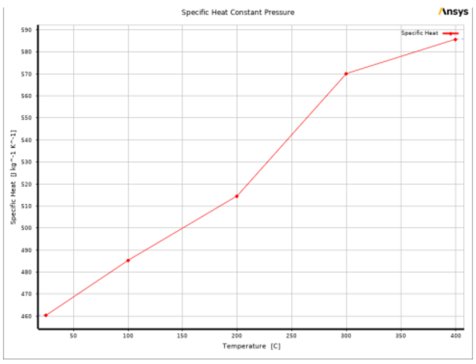


Fig. 3. Specific heat transfer coefficient Vs temperature

This mold is heated by the heating elements. Heating elements have been installed on the inside of the oven door and the bottom of the oven. There are 4 heating elements on each aforementioned side of this oven. However, the number of heating elements and their positions vary with the type of mold. The heat generated by one heating element is 2000 W. Considering the above-discussed conditions, the heat flow supplied by heating elements is used to make the boundary conditions.

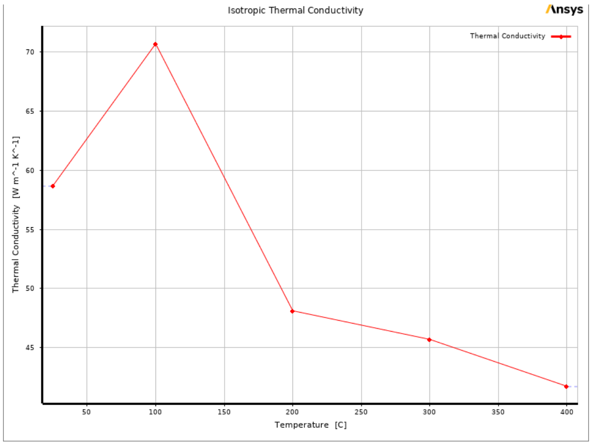


Fig. 4. Thermal conductivity Vs temperature

Boundary conditions for the analysis

Boundary conditions have been created according to the requirements for the curing cycle and based on assumptions. The primary requirement is to maintain the internal temperature of the mold at the curing temperature. The curing temperature can vary between 135°C and 145°C. This variation depends on the temperature of the green tire. As well as, the curing cycle time may slightly change with the temperature measured in the oven, and based on the temperature of the green tire. However, in this analysis, the internal temperature is considered as 140°C.

In this curing process, the main heat transfer method is conduction. Additionally, heat is transferred to the mold via convection from the surrounding air inside the oven and through the radiation. The ambient temperature inside the oven is considered to be 140°C, as the internal temperature of the mold is maintained at 140°C. The emissivity coefficient of the material is 0.95 [10]. Fig. 4 shows the boundary conditions used for the thermal analysis.

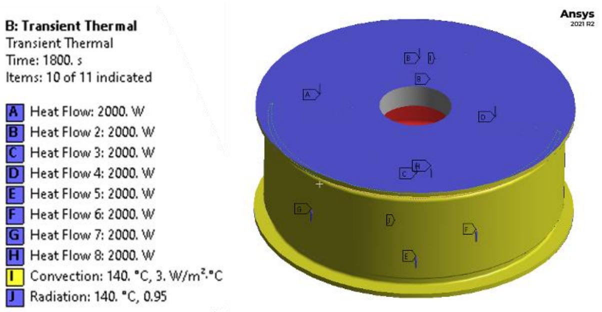


Fig. 5. Boundary conditions of the analysis

The initial temperature inside the oven is considered as 27 ˚C. The convection heat transfer coefficient which varies with temperature is shown in Table 4 and Fig. 6.

TABLE 4. CONVECTION HEAT TRANSFER COEFFICIENT OF 42CRMO4 [7]

Temperature (˚C)	Convection heat transfer coefficient (W/m^2˚C)
0	2.5
25	2.66
60	3.5
100	5
200	13.85
300	10
400	3

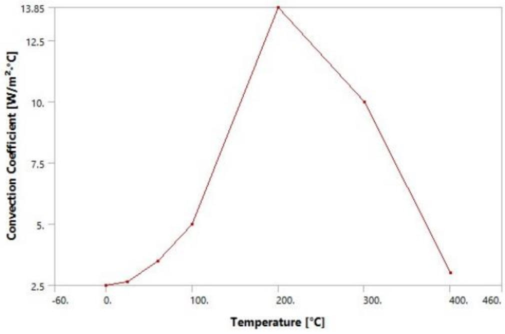


Fig. 6. Convection heat transfer coefficient Vs temperature

Mesh generation and result evaluation

This is the final step of thermal analysis. When considering the mesh size of the mold, the results of the analysis depend on it. Therefore, to get results more accurately, a mesh-independent test should be carried out. When doing the mesh independent test, analysis has to be run until the results of the analysis do not vary with mesh size. So, in that case, the analysis has to be run using very small mesh sizes. When the mesh size is small, high-performance computers are required to run the analysis. Due to the unavailability of high-performance computers, this analysis was carried out using the default mesh size. After mesh generation, setup was run to get the results and the results have been discussed in detail under the results and discussion.

D. Suitable Temperature Measuring Device Selection

When considering the application of the temperature measuring device, the temperature measuring device should be mounted inside the oven and the temperature of the inner mold surface should be measured. Therefore, the type of temperature-measuring device should be selected according to the aforementioned requirements. When considering the non-contact type temperature measuring devices, the main disadvantage of non-contact sensors is that they are not as precise as contact type temperature measuring devices. Additionally, they are subjected to errors due to background radiation, and their usable temperature is 85 ˚C typically [11], [12]. Moreover, the temperature at the point of the inner surface of the mold is difficult to measure more accurately using non-contact type temperature measuring devices due to their temperature measuring mechanism. Since non-contact type temperature measuring devices use the signal transmission pattern to measure the temperature, measuring the inner surface temperature of the mold is difficult. So, when considering all the factors, contact-type temperature measuring devices are most suitable for this application.

Contact temperature sensors measure temperature by coming into direct contact with the object of interest. They are the most common type of temperature sensors and are used in various industrial applications. Contact sensors work by measuring the heat energy that is transferred from the object to the sensor. The most common types of contact-type temperature sensors are thermocouples and resistance temperature detectors (RTD) [12]. When selecting the most suitable temperature-measuring device between them, the accuracy of the device is the most important point. The temperature of the tire should be measured with an accuracy of ± 2 ˚C. Because the variation in temperature (±2.6 °C) has a direct impact on the tire's quality [3]. The comparison between thermocouple and resistance temperature detectors is shown in Table 5.

TABLE 5. COMPARISON BETWEEN THERMOCOUPLE AND RESISTANCE TEMPERATURE DETECTORS

	Thermocouple	RTD
Temperature range	Up to 2500 ˚C	Up to 400 ˚C
Accuracy	±1˚C - ±2 ˚C	±0.1 ˚C
Sensitivity	3x	x
Linearity	S-type relationship temperature to voltage	Linear relationship temperature to resistance
Stability	Thermocouple readings tend to drift	Stay stable and repeatable for a long time
Cost	Cheaper	Two or three times more expensive than thermocouples

Thermocouple and RTD, both are in the required temperature range. But the RTD has higher accuracy than thermocouples and it is in the required accuracy range and the stability of the RTD is higher than thermocouples. Therefore, even though RTDs are expensive, it is the most suitable temperature sensor to measure the tire mold temperature. Furthermore, its minimum storage temperature is 200 ˚C. The PT100 sensor is the most common type of RTD. These sensors are a well-liked choice in many industries, mainly laboratories and industrial processes. The main reason for their use is due to their stability and accuracy [13].

E. Remote Temperature Measuring System Development

Using the wireless method or automatic method, a remote temperature measuring system can be developed to eliminate human involvement in mold temperature measuring. When considering the automatic method, it is very complex and due to the limited space inside the oven, it is difficult to operate. Therefore, the wireless method is most suited for this application. In the wireless connection method, the two circuits have to be developed. Those circuits are called transceiver and receiver circuits. To make the connection between these two circuits, Bluetooth signals, Wi-Fi signals, or radio signals can be used. The data transmission has to be chosen based on the application. When considering the application, the data should be transferred through the oven walls. Also, the signal should be transferred to the correct circuit without any interference and entanglement. Therefore, the radio signals have been selected as a data transmission medium to fulfill the above-mentioned requirements. The NRF24L01 module is the most common wireless data transfer module used in ATmega328p microcontroller projects. This module uses 2.4GHz radio signals to transmit the data wirelessly.

Therefore, to build the wireless connection between the transceiver side and the receiver side, the NRF24L01 2.4GHz Wireless Transceiver Module can be considered the most suitable option. Since the RTD sensor gives analog output, it needs to be converted to a digital signal before being sent to the Arduino board. So, to do this job, the MAX31865 RTD to digital convertor has been selected.

TABLE 6. BASIC COMPONENTS OF RECEIVER AND TRANSCEIVER CIRCUITS

	Item No	**Transceiver circuit**	**Item No**	**Receiver circuit**
o	01	Arduino Nano Development Board	01	Arduino Nano Development Board
	02	NRF24L01 2.4GHz Wireless Transceiver Module	02	NRF24L01 2.4GHz Wireless Transceiver Module
	03	MAX31865 RTD to digital convertor	04	SSD1306 128×64 Mono 0.96 Inch I2C OLED Display
	05	PT100 RTD Sensor		-

Table 6 shows the components used in each transceiver and receiver circuit and Fig. 7 and Fig. 8 show each circuit diagram.

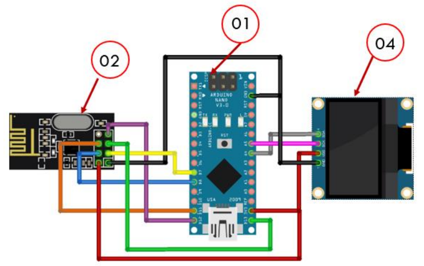


Fig. 7. Receiver Circuit

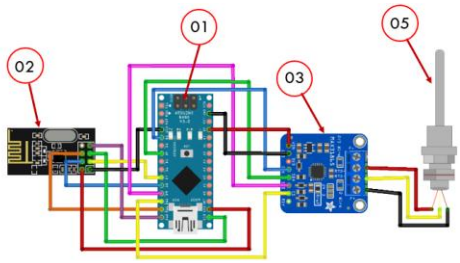


Fig. 8. Transceiver Circuit

III. RESULTS AND DISCUSSION

This study was carried out based on the aforementioned objectives. The main goal of the transient thermal analysis was to evaluate the optimal temperature-measuring locations. According to the temperature distribution results of the mold obtained through the simulation, the region suitable for inserting the temperature sensor to measure the temperature inside the mold was identified. The simulation results are shown in Fig. 9 through Fig. 12.

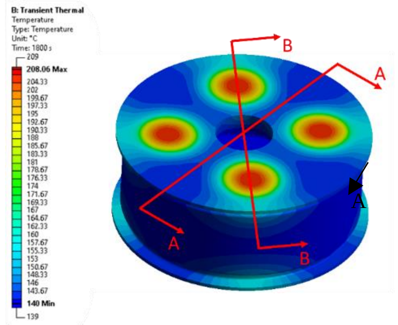


Fig. 9. Temperature distribution of the mold

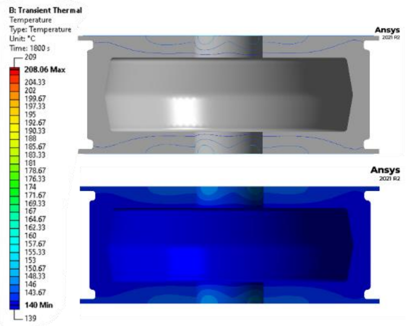


Fig. 10. Temperature distribution of the mold – Section view A-A

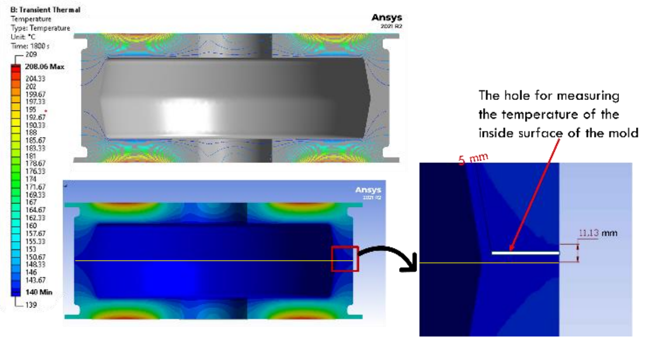


Fig. 11. Temperature distribution of the mold – Section view B-B

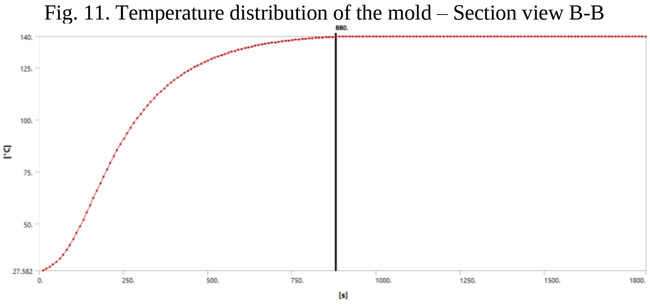


Fig. 12. Temperature variation of the mold with respect to time

These results demonstrate how the temperature of the mold varies. According to the results, tire mold takes 880 seconds to reach a steady state. That time can be used to preheat the mold.

Because the temperature measuring point in the mold can vary (rotate) with respect to the position of the heating elements since the mold is not placed such that the temperature measuring point is at the same position with respect to heating elements every single time a tire is cured. The minimum temperature distribution is obtained when the temperature measuring point is positioned in the middle of two adjacent heating elements (section A-A) whereas the maximum temperature distribution is obtained when the temperature measuring point is positioned along the vertical axis of two heating elements on either side of the mold (section B-B). According to the maximum and minimum temperature distributions obtained from the simulation, it is observed that the minimum temperature of 140°C is recorded close to the horizontal axis of the mold. Further, it is also observed that the curing temperature can be recorded within the zone of 11.13mm to either side of the horizontal axis of the mold along the outer circumference of the mold as shown in Fig. 11.

In the simulation, it was assumed that the minimum temperature at the outer surface of the mold was 140°C and there is no effect from the ambient temperature. However, in practice, the temperature of the outer surface of the mold can vary depending on the ambient temperature at the time of measurement. Therefore, to obtain an accurate reading the temperature measuring device/sensor should be placed within the mold rather than on the outer surface, as close as possible to the tire surface and within the aforementioned zone of 11.13mm from the horizontal axis of the mold. Hence, the temperature measuring point should be positioned within 11.13mm from the horizontal axis of the mold and it shall be positioned at any half (top or bottom) of the mold. According to the thermal distribution of the mold, one temperature measuring point is enough to get an accurate reading.

After evaluating the temperature sensor and insertion point, a wireless method was developed based on Arduino to eliminate human involvement in temperature measurement. The wireless communication between the transceiver and receiver circuits occurs via the NRF24L01 2.4GHz transceiver module, which has a communication range of 100 meters. Therefore, this transceiver module is very suited for this application.

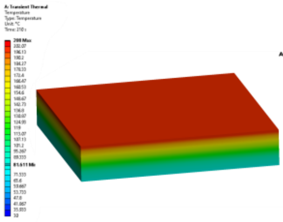
The transceiver circuit should be mounted on the tire mold, while the receiver circuit should be positioned outside the oven. Since the transceiver circuit operates within the oven during the curing cycle, its operational temperature must exceed the curing temperature (140°C). However, the Arduino board and other circuit components typically have an operating temperature range of -40°C to 85°C [14]. But, the recommended temperature range is -25°C to 70°C. Therefore, maintaining the Arduino circuits within this recommended temperature range is more suitable. To address this, the transceiver circuit should be insulated.

To insulate the transceiver circuit, it can be stored in the insulation box. To fabricate the insulation box, cellular glass was selected as a material. Cellular glass is a lightweight, rigid material made from glass that has been foamed to create a cellular structure. It is typically produced in the form of boards, blocks, or pipe insulation. Cellular glass insulation offers excellent thermal insulation properties. Therefore, it is commonly used in various industrial and commercial applications where high thermal efficiency and durability are required. Additionally, cellular glass is non-combustible and does not emit harmful gases, making it a safe choice for insulation applications [15]. Therefore, the selected material is very suited for this application.

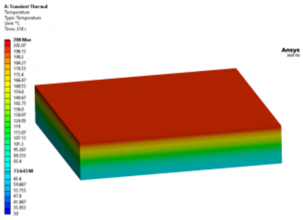
To fabricate the insulation box, the wall thickness of the insulation box should be determined. Ansys Transient thermal analysis was run to find the required minimum wall thickness of the insulation box. The maximum temperature that can be maintained inside the insulation box without damage to the Arduino circuits is 70 ˚C. When the inside temperature of the insulated box is equal to the recommended maximum temperature (70 ˚C) of the Arduino components, the required minimum wall thickness can be found. Therefore, to determine the required minimum wall thickness of the insulation box, transient thermal analysis was carried out for a wall of the insulated box which is mating with the tire mold. Since the maximum heat transfer happens through that wall, it was selected for the analysis. Then, the analysis was carried out to determine the required minimum wall thickness of the insulated box by changing the thickness of the wall. The obtained results are outlined in Fig. 13 and Table 7.

TABLE 7. TEMPERATURE CAN BE MAINTAINED INSIDE THE INSULATED BOX WITH THE THICKNESS OF THE WALL

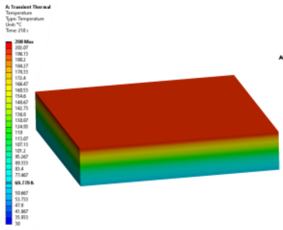
The wall thickness of the insulated box (mm)	**Temperature can be maintained inside the insulated box (˚C)**
20	81.611
21	73.643
21.5	69.779
22	66.096
25	48.500
30	32.412



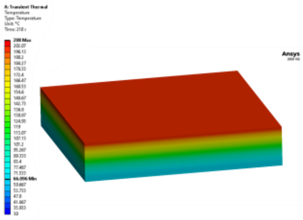
(a) Thickness = 20 mm



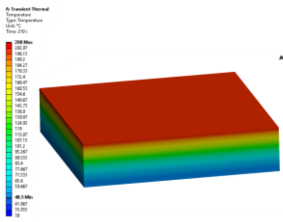
(b) Thickness = 21 mm



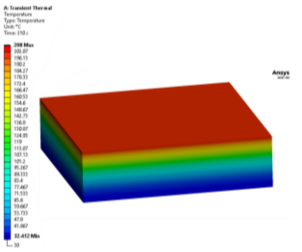
(c) Thickness = 21.5 mm



(d) Thickness = 22 mm



(e) Thickness = 25 mm



(f) Thickness = 30 mm

Fig. 13. Analysis results for the wall of the insulated box

According to the results of the analysis, the wall thickness of the insulated box should be at least 21.5 mm thick. Otherwise, the inside temperature of the insulated box can't be maintained at healthy temperatures for the Arduino circuit throughout the curing cycle of 90 minutes.

After considering the transceiver circuit dimensions and wall thickness of the insulation box, the insulation box was designed as per Fig. 14 and the insulation box mounting position on the tire mold is shown in Fig. 15.

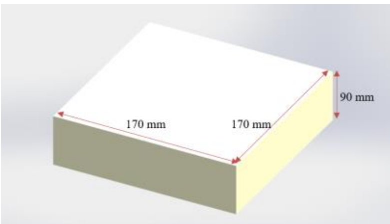


Fig. 14. Transceiver circuit installation

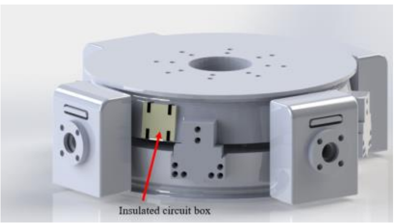


Fig. 15. Transceiver circuit installation

IV. CONCLUSIONS

The curing process is the most important process among tire manufacturing processes. Because the tire curing process gives the final shape and tread pattern to the tire. This process mainly affects the quality of the tire. To increase the quality of the tire, pressure, temperature, and, time of the curing process should be monitored accurately. If there is any mistake in temperature measurement, the entire product can be rejected in the final inspection stage. Hence, this study was carried out by conducting the transient thermal analysis as the initial step to get an idea of the temperature distribution of the mold. Then according to the result of that simulation, the number of temperature measuring points and optimal temperature measuring locations of the mold was identified. After that, a wireless temperature measurement system was developed based on the ATmega328 microcontroller and the NRF24L01 module. Since the transceiver circuit is attached to the mold, an insulation box was developed using cellular glass material. The required minimum wall thickness to fabricate the insulation box is 21.5 mm.

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