Energy-Saving Performance and Production Accuracy of the Direct-Pressure Tire Curing Technology with an Expandable Steel Internal Mold

Jinyun Zhang 1, Bogang Wang 2, Xiaoying Liu 2, Lisheng Cheng 1*, Hua Yan 1, Quanyong Ding 2, Jing Tan 1 and Weimin Yang 1,*

1 College of Mechanical and Electrical Engineering, Beijing University of Chemical Technology, Beijing 100029, China; zjy_luna@126.com (J.Z.); chengls@mail.buct.edu.cn (L.C.); yanhua999@vip.sina.com (H.Y.);
tanj@mail.buct.edu.cn (J.T.)
2 Triangle Tyre Co., Ltd., Weihai 264200, China; wangbogang@triangle.com.cn (B.W.);
liuxiaoying@triangle.com.cn (X.L.); dingquanyong@triangle.com.cn (Q.D.)
* Correspondence: yangwm@mail.buct.edu.cn

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Abstract: Due to the low thermal conductivity and low rigidity of the rubber bladder, the traditional tire curing process faces problems such as low efficiency, high energy consumption, and low production accuracy. To eliminate defects, this work presents a novel direct-pressure curing technology (DPCT) with a steel internal mold heated by electromagnetic induction. Special equipment featuring this novel technology was developed and used for trial-production of tire with a specific size. The energy consumption of sample tires was measured for comparison between the new technology and the traditional one. Nonuniformity and unbalance of tires are tested, meanwhile, physical properties of tread and sidewall parts of cured tires are tested. Furthermore, a finite element analysis (FEA) is carried out to investigate the heating rate of the new curing technology and to optimize the curing process. According to the results, with the new curing technology, the energy consumption per cure cycle is cut down by about 86%, while the curing efficiency and the tensile strength of sidewall part of the cured tire are improved by 22.5% and increased by 13.9%, respectively. In addition, the radial force variation (RFV), couple unbalance mass and curing temperature difference are also reduced by 16.8%, 37%, and 8 °C, respectively. These results suggest that DPCT has excellent energy-saving performance and production accuracy.

Keywords: curing; internal mold; energy consumption; electromagnetic induction heating; production accuracy

1. Introduction

As the final key process in tire production, vulcanization not only determines the manufacturing accuracy of the tire but also consumes the greatest amount of heat energy in the entire process of production. As shown in Figure 1, in the traditional curing process of tires, the uncured tire is heated by the saturated steam through the steel external mold and the rubber bladder, and a large amount of steam is dissipated in the pipelines from the boiler to the vulcanizer. In particular, after the steam is transferred to the vulcanizer, the green tire needs to obtain heat from the bladder. The low thermal conductivity of the bladder has significant impacts on curing efficiency. In addition, since the saturated steam pressure is interlocked with the temperature, the curing internal temperature is not freely adjustable, leading to a long curing cycle.
Many studies have been carried out to solve this problem. Guo et al. [1] presented a collaborative detection method with an artificial immune algorithm in which internal leakage of the steam trap was defined as non-self-antigens and the steam pressure differences between the steam pipe and steam rooms (or bladders) were extracted as epitopes of antigens and reduced steam waste. Wang et al. [2] presented finite element analysis (FEA) to evaluate the giant radial tire’s state of cure (SOC) and found the shortest time that there was no under-cured region and optimized the temperature to reduce the difference of SOC of tire constituents. As a result, the cure time changed from 9780s to 7680s. Gough [3] used FEA software MSC.Marc in conjunction with Python scripts to calculate the press times meeting criteria for adequate cure for a wide range of thicknesses of rubber pads, and simple equations were provided to estimate the cure time at any cure temperature. To minimize the temperature difference between the top and bottom points of the bladder and to find out the delay time in the tire curing process, Pandya et al. [4] carried out fluid flow analysis inside the bladder. Reduction of delay time and minimization of temperature difference can improve product quality and reduce utility costs. Su et al. [5] provided a combination method, in which the temperature history of surface points are obtained by thermocouples and inner points are predicted by the FEA method. The method was proved to be accurate and effective by the fact that maximum temperature error was not greater than 3 °C and the maximum SOC error was 5%. To cut the pressing time, radiation [6] and microwave technologies [7–9] were applied in the pre-curing of rubber components or green tire and to provide assistant heat, electromagnetic induction technology was tried to be applied in the tire curing process. Mitamura et al. [10] from Kobe Steel, Ltd. invented an apparatus comprising a heating coil and a high-frequency power supply. The apparatus is installed inside the bladder and generated heat to the steel cord and bead embedded in the deep position of the green tire. Okada et al. [11] invented a tire vulcanizer including mold, an induction heating unit, and a medium channel, which was connected to
the inner space of the bladder. The heating unit heated the channel through electromagnetic induction so as to heat the medium flowing through the channel to cure the raw tire. Although the above studies can promote efficiency and reduce the energy cost of the curing process, the traditional heating mode of tire curing has not been changed, where heat was supplied by steam for the raw tire through medium channel and the heat conductivity of the bladder is poor.

On the other hand, the traditional tire curing technology has the defect that accuracy of the produced tire is low. Firstly, variations in geometry and material often occur during components preparation and the raw tire building. When raw tire is moved to the curing process, due to a lack of sufficient rigidity, it is difficult for the high-elastic bladder that expands relying on steam to correct the uneven raw tire. What is more, the bladder itself is often asymmetric because of incomplete expansion, aging, adhesion, or unreasonable design, aggravating the problem. These situations would result in the unbalance and non-uniformity of the tire, which seriously affect its operation and driving safety [12–14]. Secondly, when the nitrogen gas with a pressure of 2.4–2.6 MPa is injected into the bladder through the inlet following the steam, the saturated steam with a pressure of about 1.8 MPa would naturally accumulate in the upper part of the bladder, because it has a lower density than the nitrogen. This accumulation of steam would consequently result in temperature difference between the top and bottom parts of the bladder. Due to heat exchange, the temperature difference increases as the condensate water deposited at the bottom of the bladder increases, leading to the inconsistency of SOC of the left and right sidewall, which affects the tire quality.

Facing the drawback of the traditional curing method, this work presents a novel direct-pressure curing technology (DPCT) [15,16] and develops a set of special equipment utilizing a radially expandable steel internal mold to replace the bladder. The internal mold generates heat through electromagnetic induction in conjunction with the external mold instead of steam and pipelines. Sample tires were trial-produced with the DPCT equipment. The energy-saving performance and high-precision characteristics of the new technology are also discussed.

2. Development of Direct-Pressure Vulcanization Equipment

2.1. Steel Internal Mold

The internal mold is a primary part of direct-pressure curing equipment. Since it has higher roundness and rigidity than the elastic bladder, geometry and material distribution of the cured tire is more symmetric and more even, thereby improving balance and uniformity of the tire. The main design difficulty of the internal mold is that a large expansion ratio $\lambda$ should be obtained, in order to meet the motion of the tire shaping and unloading, the expansion is defined as:

$$\lambda = \frac{d}{d'}$$

where $d$ is the diameter of the cured tire cavity, $d'$ is the diameter of the bead toe of the cured tire.

As shown in Figure 2, the physical prototype of the internal mold for a selected size of tire is composed of seven groups each of large- and small-segment radially driving mechanisms. When fully expanded, the mold has an outer shape according to the surface of the finished tire cavity, and the gap between adjacent segments should be small enough to prevent the rubber compound from leaking during curing. The finite element method was applied to optimize the design of the internal mold, and the strength of the mold was checked to ensure that the mold structure could remain stable without deformation under high curing temperatures and pressures. Furthermore, to enable the mold’s easy separation from the cured tire, the surface roughness of the segment should not be too low and the venting lines should be opened on the surface of the segment.
2.2. Electromagnetic Induction Heating System

The induction heating system is another key part of the DPCT equipment. The high-frequency current flowing into the coil winding generates a high-frequency alternating magnetic field, and the magnetic line of force passes through the metal mold to form a closed-loop circuit, causing an eddy current on the mold surface. Due to the thermal effect of the eddy current, the mold can emit heat at high speed, thereby improving energy utilization efficiency and reducing energy consumption in vulcanization. To note that since the polymer matrix is in a solid state, the fillers in the rubber are not likely to orient with the magnetic field.

The design of the induction heating system of the internal mold is more challenging than that of the external mold. The internal mold is made of metal and composed of irregularly shaped segments, making it difficult to achieve a uniform temperature of a single segment and of all segments. Figure 3 shows the design scheme adopted in this study. Each internal mold segment is independently configured with one induction heating unit. To make the temperature uniform in each segment, each winding contains two series-coils symmetrically arranged on the two sides of the carrier. The magnetizer controls the direction of the magnetic flux so that the temperature at the end of the segment rises rapidly, thereby ensuring that the temperature of each segment in the axial direction of the segment rises synchronously, so that the tire can be uniformly vulcanized. Moreover, the magnetizer can shield parts excluding segments to prevent their being heated through the magnetic flux that escapes from the magnetic field, which not only increases energy consumption but may also hinder the part’s normal operation due to lengthy overheating. Table 1 shows the main parameters of the electromagnetic induction heating system. The controller in the electromagnetic induction heating system can use half-bridge or full-bridge modes. The full-bridge mode has greater circuit efficiency than the half-bridge one in general. According to the data listed in Table 1, the half-bridge mode is adequate for the low power and the small inductance, and full-bridge mode is adequate for the high power and the big inductance.

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**Table 1. Parameters of induction heating system.**

|                  | Internal Mold | External Mold |              |              |              |
|------------------|---------------|---------------|--------------|--------------|--------------|
| **AC Power supply** | 380 V/50 Hz   | 380 V/50 Hz   | 380 V/50 Hz  | 380 V/50 Hz  |
| **Max. Power of Controller (KW)** | 3            | 15            | 15           | 15           | 15           |
| **Number of Controllers** | 7            | 1             | 1            | 1            | 2            |
| **Resonance Mode** | Half-bridge   | Full-bridge   | Full-bridge  | Full-bridge  |
| **Inductance (µH)** | 90            | 150           | 150          | 150          |
| **Frequency (KHz)** | 18–22         | 18–22         | 18–22        | 18–22        |

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**Figure 2.** The schematic of the working principle of internal mold: design of the mold in (a) contraction and (b) expansion states.
2.3. Process Validation

Krupp 48” hydraulic Bag-o-Matic curing press was selected to be configured with the internal mold and induction heating system for process validation. More than 200 sample tires were prepared both by using the DPC and traditional technologies with the outer and inner temperatures fixed at 178 °C and 185 °C, respectively. The curing energy consumption of two batches of samples tires was measured by a watt-hour meter and flow meter, respectively. To investigate production accuracy of the DPCT, all sample tires were tested for non-uniformity and unbalance by the dynamic balancing machine, and physical properties of tread and sidewall parts of cured tires are also tested.

3. Finite Element Analysis of the Process

The study of simulation in determining the optimal condition of the tire curing process is systematical and deep now, which shows significant advantages in reducing the development cost and shortening the development period. A comparison of efficiency between traditional curing and DPCT at the same temperature was made in this article. Cure pressure and temperature are interlocked tightly in the traditional curing; on the contrary, DPCT temperature can be regulated freely. On this basis, cure times under six different temperatures were worded out and the optimal cure temperature was determined. For the finite element (FE) model, the temperature-varying thermophysical properties of raw rubber components, the anisotropy of heat transfer properties of composite materials, the heat generation were taken into account, in addition, a tire model with not only longitudinal grooves but also transversal, sloping grooves was created. These settings of the simulation were derived from the actual curing process.

3.1. Material Characterization

The heat transfer mechanisms and curing reaction kinetics provide a theoretical basis and foundation in the tire-curing process [17]. Heat transfer of tire curing can be described by the following second-order parabolic partial differential equation:

$$\frac{k_1}{\partial^2 T/\partial x^2} + \frac{k_2}{\partial^2 T/\partial y^2} + \frac{k_3}{\partial^2 T/\partial z^2} + \dot{q} = \rho c \frac{\partial T}{\partial t},$$  

(2)

where \(k_1\), \(k_2\), and \(k_3\) are thermal conductivities in the \(x\), \(y\), and \(z\) directions, respectively, \(\dot{q}\), is the rate of heat generation, \("\rho"\) is the material density, and \("c"\) is the specific heat capacity [18].

Figure 3. The heating unit of the segment.
The curing process needs to be discretized into several isothermal steps because of its temperature-varying nature. The Arrhenius law [19] is used to calculate the optimum cure time \( \tau \) at the selected temperature \( T \):

\[
\tau = \tau_0 \times e^{\frac{E}{R} \left( \frac{1}{T} - \frac{1}{T_0} \right)},
\]

where \( \tau_0 \) is a measured cure time at temperature \( T_0 \), \( E \) is the activation energy, and \( R \) is a gas constant. Accordingly, the state of cure can be obtained during the non-isothermal curing process as:

\[
D = \int_0^1 e^{\frac{E}{R} \left( \frac{1}{\tau} - \frac{1}{\tau_0} \right)} dt/\tau_0.
\]

The influence of reaction heat on vulcanization technology cannot be neglected. In this study, the thermal flow-time curve was measured using the differential scanning calorimeter (DSC) thermal analysis method, and then the heat flow-temperature curve was obtained and linearly fitted according to the temperature-time curve. The fitting results were substituted in the computational model by means of the ABAQUS user subroutine written in Fortran.

### 3.1.1. Thermal Conductivity Test

The thermal conductivity of rubber changes with temperature during vulcanization. The thermal diffusivity and specific heat capacity of the rubber compound of each component at different temperatures were measured by an LFA447 laser flashing thermal conductivity meter to obtain the thermal conductivity-temperature curve. Taking the tread component as an example, the thermal conductivity-temperature curve and specific heat capacity versus temperature are shown in Figure 4.

Figure 4. Relations of (a) thermal diffusivity versus temperature and (b) specific heat capacity versus temperature.

### 3.1.2. Thermal Conductivity of Core-Rubber Composite Material

The orthotropic core-rubber composite belt layer, as well as ply, overlay, and chipper, are shown in Figure 5a, where \( e \) is the distance between two cords; 1-direction, along the cords; 2-direction, transverse to the cords; and 3-direction, transverse to the layer. The thermal conductivity of composite material depends on the directions above. The blackened area is shown in Figure 5a is a representative volume element as shown in Figure 5b, where \( h \) denotes ply thickness and \( a \) is the effective length of cord circle. Thermal conduction in the material is closely correlated with the current flow conduction in the circuitry, so the thermal resistance is represented by electric resistance. In addition, thermal conduction in rubber and steel/fiber cord are completely independent, so in the 1-direction, the effective composite conductivity is represented by the rule of mixtures as [19]

\[
K_1 = K_c \times V_c + K_r \times V_r = \frac{a^2 \times k_c}{a^2 + h/4e} + \frac{(h/4e) \times k_r}{a^2 + h/4e},
\]
where \( k_c \) and \( k_r \) are the thermal conductivity of cord and rubber, respectively.

\[
R_{th} = L/(A \times k),
\]

where \( L \) is the length of the heat flow, \( A \) is the cross-sectional area, and \( k \) is the thermal conductivity. Thus, the effective conductivity in the 3-direction is

\[
K_3 = \frac{L}{A \times R} = \frac{1}{eh} \left( \frac{1}{R_2} + \frac{1}{R_1 + R_c} \right) = \left( \frac{\frac{1}{2e} - a}{eh^2/2} \right) + 1 \left( \frac{eh}{K_c} + \frac{h/2 - a}{ehk_r} \right).
\]

where \( R_c, R_{r1}, R_{r2} \) are thermal resistances of three parts shown in Figure 5b. \( R_c \) is the thermal resistance of the square shadow cord region, \( R_{r1} \) is the thermal resistance of the up rectangle rubber region, and \( R_{r2} \) is the thermal resistance of the right rectangle rubber region. \( R_{r1} \) and \( R_{r2} \) are different because of the width and length differences of the two rubber regions. The effective conductivity in the 2-direction can be calculated as well. After determining the effective conductivities, the heating rate can be calculated based on Equation (2) in the tire-curing process. The discrete local CS of every element in belt 1 is shown in Figure 5d. Effective conductivities \( k_1, k_2, \) and \( k_3 \) are assigned to each element in the three directions of the discrete local CS.

### 3.2. Finite Element Model

The FE model was built according to a commercially available high-performance passenger car tire (PCR): 255/30R22 TB596 with the following procedures: First, create a 2D mesh of smooth tire, shown in Figure 6a. Second, create a 3D mesh of tread pattern, shown in Figure 6b. Third, combine a 3D mesh of smooth tire spanning from the 2D mesh with the 3D mesh of pattern and we get the 3D hexahedral tire, shown in Figure 6c.
Figure 6. Finite element (FE) models: (a) 2D smooth model, (b) half pitch of pattern, and (c) 3D patterned tire.

The scale is reduced by about 82% compared to a tetrahedral model. It requires far fewer iterations and far less CPU time, and results in greatly improved accuracy. Further development of the software HYPERMESH based on TCL is made to mesh efficiently, accurately and automatically. Accordingly, the time was reduced from 120 min to 10 min to mesh the 2D smooth tire section and the half-pitch hexahedral pattern model can automatically expand, pitch by pitch, to obtain a finite element (FE) model of the whole patterned tire. The main originality of this model is as follows: firstly, 3D pattern model consists of the longitudinal, transversal even sloping grooves, comparatively, 2D or 3D longitudinal-grooved model were used in the previous studies; secondly, hexahedra rather than tetrahedral pattern was used in this article; thirdly, we got a 2D smooth mesh (Figure 6a) and pattern pitch (Figure 6b) array automatically with an important programming development. Model structure detail and sophisticated element make it of supreme accuracy. Element type selection significantly reduced the element number and this brought about far fewer iterations and far less CPU time. We proposed an efficient modeling tool up to the mustard of industry application by further development.

3.3. Model Verification

To obtain temperature versus time and SOC versus time curves, we selected eleven points (Nodes 2, 5, and 7–11) for our numerical validation as shown in Figure 7. In the experiments, the temperatures of these points were measured with a thermocouple embedded in the tire. Nodes 2, 8, and 10 were the critical points, which were used to monitor whether the press time was adequate to meet cure criteria and to verify the accuracy of the FEA model. The temperature of Nodes 1, 3, 4, and 6 on the surface of the tire also needed to be measured by the thermocouple since they were taken as the boundary conditions of the FE model. Since the thermocouples embedded in the inner positions of the tire are difficult to be pinpointed and it is inevitable to introduce artifacts. However, such artifacts should be ignorable.
was generally 5 mm. The thermal conductivity of the internal mold made up by steel was about 46 \text{ w/mk}. The skin effect of electromagnetic induction could cause a rapid increase in the surface temperature of the internal mold, so thickness of heat transmission tended to be zero, therefore, the thermal resistance had a significant influence on curing efficiency. In the conventional process, the thermal conductivity of the bladder was about 0.09 \text{ w/mk} and the thickness of heat transmission was generally 5 mm. The thermal conductivity of the internal mold made up by steel was about 46 \text{ w/mk}. The skin effect of electromagnetic induction could cause a rapid increase in the surface temperature of the internal mold, so thickness of heat transmission tended to be zero, therefore, the thermal resistance had a significant influence on curing efficiency.

As shown in Figure 8, the simulated data was in good agreement with the test data, and the maximum error in the initial stage of vulcanization was caused by the simulated temperature boundary error. Conventionally, SOC at the critical point required as high as 50% when the tire was removed from being pressed and this period was called $t_{50}$ of the critical point or the curing time in mold. Table 2 compares the simulated and test values of Node 2, 8 and 10 in terms of temperature and $t_{50}$ differences. Results show that the maximum errors of the three points were all less than 5%, indicating the reliability of the simulation model. The effectiveness of this method was proved not only on the passenger car tire but also on the off-the-road-tire (OTR) 27R49_TB526.

![Figure 8](image-url)  
Figure 8. Relation of (a) temperature versus time and (b) state of cure (SOC) versus time at Node 10.

### Table 2. Differences between the simulation and experimental results.

| Location | Maximum Difference | Maximum Error |
|----------|--------------------|---------------|
|          | Temperature $t_{50}$ | Temperature $t_{50}$ |
| Node 2   | 7 °C 23 s 3.78%     | 3.58%         |
| Node 8   | 5 °C 17 s 2.70%     | 2.64%         |
| Node 10  | 6 °C 36 s 3.24%     | 5.55%         |

4. Characteristics of Direct-Pressure Vulcanization Technology

4.1. Energy-Saving Performance

4.1.1. Vulcanization Efficiency

The thermal resistance had a significant influence on curing efficiency. In the conventional process, the thermal conductivity of the bladder was about 0.09 \text{ w/mk} and the thickness of heat transmission was generally 5 mm. The thermal conductivity of the internal mold made up by steel was about 46 \text{ w/mk}. The skin effect of electromagnetic induction could cause a rapid increase in the surface temperature of the internal mold, so thickness of heat transmission tended to be zero, therefore, the...
internal mold had essentially no thermal resistance. Accordingly the thermal resistance of the bladder was much higher than one of internal mold. Furthermore, the process steps differed between the new and traditional technologies. As shown in Figure 9a, in the traditional process, the bladder was first injected with 0.03–0.08 MPa of nitrogen for shaping tire before closing the mold until raw tire was expanded to the diameter of $D'$ (step 1), which satisfies

$$D - D' = h,$$

where $h$ is the pattern depth, and $D$ is the overall diameter of the cured tire. Then the mold was closed (step 2). Next, the bladder was filled with saturated steam (step 3) and the diameter of the raw tire continued to expand to $D$. In another word, once the in-mold vulcanization started, the raw tire had not immediately contacted the external mold. In addition, the temperature of bladder needs to rise slowly repeatedly from lower than $80^\circ C$ at the start of curing cycle since it is vacuumed at the end of the previous cycle to unload tire. Therefore the temperature rise of the raw tire would lag behind the start of the curing cycle to some extent.

With direct-pressure vulcanization technology, as shown in Figure 9b, when the tire was shaped by the internal mold before closing mold by step 1, the diameter of the raw tire directly expanded to the maximum diameter $D$. Then the raw tire immediately contacted the external mold when the mold was closed in step 2. Moreover, the internal and external molds were kept at a constant temperature throughout the entire curing cycle. Therefore, when the curing cycle was started, the inner and outer surface of the raw tire was heated without delay.

The changes in the internal heat-conduction mode and process steps directly affect the temperature field of the tire. The apex, shoulder, and tread of the tire are generally difficult to be cured in traditional curing process, as shown in Figure 10a–c, however, these positions are heated up more rapidly with direct-pressure vulcanization technology. According to Table 3, in the condition of the same curing temperature, the press time per curing cycle estimated by FEA was 723 s (Node 10) for the traditional process, the press time of DPCT was 643 s and the vulcanization efficiency was increased by 11.07% with the new technology.
On the other hand, neither can the impact of the saturated steam on the cycle time of the traditional curing process be ignored. Due to the correlation of the temperature and pressure of the saturated steam, the internal temperature of the bladder cannot be set too high, for the higher the temperature the greater the pressure. The combination of high pressure and temperature will cause the thermal degradation of the rubber compounds and damage the crosslinked structure. Therefore, the proper degree of curing was obtained through prolonging the press time at the lower internal temperature in the traditional curing.

In the new method, the interlocking relation between the internal temperature and pressure was decoupled, realizing their free adjustment. For this characteristic, six internal temperatures were picked up for FEA, in order to cut down the press time. The certain external temperature of traditional curing process was still adopted in consideration of the appearance quality of outer surface of the finished tire being sensitive to the high temperature. According to simulation results shown in Figure 11, the temperature of rubber compound, which is usually difficult to be cured in the traditional curing process, rose more rapidly and higher process temperatures were obtained. As a result, it was earlier to reach $T_{50}$. However, excessive temperature would cause degradation of rubber parts and appearance defects on the tire, such as trapped air. Thus, the optimized internal temperature was 205 °C. $T_{50}$ was calculated by FEA for various cure temperatures and is listed in Table 4. The curing cycle of the proposed technology was shortened by 162.6 s compared with that of the traditional curing method.

### Figure 10. Relations of temperature evolution at different times at (a) Node 2, (b) Node 8, and (c) Node 10 obtained by finite element analysis (FEA).

### Table 3. Comparison of $T_{50}$ of different components of the tire calculated by FEA.

| Component     | Chafer Node 1 | Shoulder Node 10 | Apex Node 2 | Tread Node 8 | Belt Node 7 | Liner Node 3 |
|---------------|---------------|------------------|-------------|--------------|-------------|--------------|
| Traditional  | 388           | 723              | 446         | 604          | 473         | 492          |
| DPCT(s)       | 315           | 643              | 328         | 615          | 538         | 489          |

### Figure 11. A comparison of (a) temperature and (b) SOC of point located at Node 10 at different temperatures.
Table 4. $T_{50}$ calculated by FEA at different process temperatures with the new technology.

| Cure Temperature ($^\circ$C) | 185 | 190 | 195 | 200 | 205 | 210 |
|------------------------------|-----|-----|-----|-----|-----|-----|
| $T_{50}$ (s)                 | 643 | 621 | 600 | 579 | 560.4 | 543.6 |

4.1.2. Energy Consumption

According to previous studies [1,20,21], in the conventional curing process, a vulcanizer with leakage of steam trap will consume two to three times more steams, the leaked steam reached about 15% of the total consumption every year. In this work, the improvement was only with respect to the steam heating process. Since different processes and conditions are usually used during the curing of tire, we did not compare our results with those of other companies or researchers. Instead, we compared the results with the traditional steam heating process, which is extensively adopted in the industry. In the new method, no heating mediums and pipelines are needed. The internal and external mold rapidly heats up by cutting the magnetic line of force, and the generated heat energy is directly sent to the raw tire.

According to measured results, the average energy cost of each tire with two technologies was 3.72 KWh and 26.5 Kg, respectively. According to The Norm of Energy Consumption for per Unit Product of Tire (GB29449-2012), two energy types were converted into a standard coal equivalent calculated in terms of the equal value. As shown in Table 5, it is observed that energy consumption per cure cycle was cut down by about 86%. Due to the reduced energy consumption, the cost per tire product with the mold was estimated to be only 50% of that with the bladder according to our production data.

Table 5. Energy consumption per curing cycle.

| Method          | Internal Heating (Kgce) | External Heating (Kgce) | Total (Kgce) |
|-----------------|-------------------------|-------------------------|--------------|
| Steam           | 1.36                    | 2.04                    | 3.4          |
| Induction heating | 0.184                   | 0.276                   | 0.46         |

4.2. Production Accuracy

4.2.1. Non-Uniformity and Unbalance

Uneven mass distribution, geometric asymmetry, and variations in rigidity or force of the finished tire usually come from component preparation or the green tire building process, because component deformation or wrinkle, and uneven splice distribution often occur in these processes. However, with the traditional curing technology, the low rigidity of the bladders makes it difficult to eliminate or improve defects accumulated in the previous processes. Additionally, the bladder itself is often asymmetric because of incomplete expansion, aging, adhesion or unreasonable design, which would aggravate the problem of non-uniformity and unbalance.

Table 6 lists the test results of key items for evaluating tire nonuniformity and unbalance. According to the results, the new technology improved product accuracy significantly. The radial force variation (RFV) was reduced by 16.8%. The lateral force variation (LFV) and couple unbalance mass was reduced by 24% and 37%, indicating that the internal mold was more effective in eliminating the defects caused by the hemispherical or serpentine distortion of the tread, sidewalls, and other components. Furthermore, the service life of traditional bladder was only 200–250 times in general, and the frequent replacement made the produced tires of low repeat accuracy. Table 6 compares the nonuniformity and unbalance of the tire cured with the traditional and proposed solutions. To note that the results listed in the table were obtained by testing for 200 samples. The relative standard deviation (RSD) of the items with the DPCT were smaller than that with the traditional technology, indicating that the repeat accuracy of tires were improved relying on structure stability of the internal mold.
### Table 6. Nonuniformity and unbalance of cured tire.

| Items                        | Traditional | DCPT      |
|------------------------------|-------------|-----------|
|                              | Mean   | RSD (%) | Mean   | RSD (%) |
| Nonuniformity                |         |         |         |         |
| RFV (N)                      | 11.13  | 22.06   | 9.26   | 18.6    |
| LFV (N)                      | 9.05   | 20.89   | 6.9    | 18.04   |
| RFV1H (N)                    | 5.87   | 22.48   | 4.66   | 17.34   |
| Conicity (CON; N)            | 1.55   | 18.09   | 1.48   | 18.9    |
| Unbalance                    |         |         |         |         |
| Static unbalance value (g cm) | 1058.51 | 21      | 946.72 | 17.75   |
| Couple unbalance mass (g)    | 13.72  | 23.4    | 8.64   | 19.21   |
| Upper side compensating      | 22.72  | 25.65   | 17.33  | 17.63   |
| unbalance mass (Upper; g)    |         |         |         |         |
| Lower side compensating      | 26.25  | 23.3    | 22.27  | 18.32   |
| unbalance mass (Lower; g)    |         |         |         |         |
| Upper + Lower (g)            | 48.97  | 24.39   | 39.6   | 18.02   |

4.2.2. Uniformity of SOC

We conducted thermocouple measurements to obtain temperature versus time curves of the points located at the inner surface of the sidewalls. As shown in Figure 12, temperature difference existed at the very beginning of the traditional cure process due to the adiabatic compression of saturated steam. With the passage of vulcanization time, more and more condensed water was deposited at the bottom of the bladder due to heat exchange, and the temperature difference continued to increase, which eventually reached to about 11 °C, leading to serious uneven degree of curing between the left and right sides.

![Figure 12. Temperature difference between outer surfaces of upper and lower sidewalls.](image)

The temperature difference dropped to 3 °C when electromagnetic induction heating method was used. As for electromagnetic induction heating, due to the symmetry of the heating unit attached to the internal mold, the magnetic field strength was also symmetric. So, that the eddy current density around the two ends of the segment was the same, which ensures the consistency of the degree of curing of the left and right sidewalls.

4.2.3. Physical Properties

A tire is a composite of various rubber parts, the physical properties of the rubber parts determine tire overall performance. According to the Table 7, Physical properties of tread changed slightly, on the contrary, those of sidewall changed significantly. Tensile strength of sidewall part of the cured tire was increased by 13.9%. It is likely that although under the same pressing force, the pressure exerted by the internal mold on the sidewall was greater, which made the compounds more compact and of higher crosslinking density.
Table 7. Physical properties of rubber parts of the cured tire.

| Items                              | Tread   | DPCT    | Sidewall | DPCT   |
|------------------------------------|---------|---------|----------|--------|
| Density (g/cm³)                    | 1.154   | 1.159   | 1.110    | 1.101  |
| Hardness (shore A)                 | 58      | 59      | 47       | 52     |
| Tensile strength (TS; MPa)         | 16.3    | 17.7    | 13.7     | 15.6   |
| Elongation at break (Eb; %)        | 460     | 455     | 649      | 580    |
| Stress at 100% Elongation (MPa)    | 2.3     | 2.3     | 1.3      | 1.3    |
| Stress at 200% Elongation (MPa)    | 5.5     | 5.5     | 2.4      | 2.8    |
| Stress at 300% Elongation (MPa)    | 9.9     | 10      | 4.4      | 5.3    |

5. Conclusions

To solve problems in traditional tire vulcanization technology, e.g., high energy consumption, low vulcanization efficiency, and poor manufacturing accuracy, this work proposed a direct-pressure vulcanization technology with the steel internal mold heated by electromagnetic induction heating. Through simulation and trial-production of a certain tire size, the following conclusions can be drawn.

1. Based on the same process temperature, the new technology reduced vulcanization energy consumption by 86%.
2. The new technology breaks the interlocking of internal temperature and pressure. Through finite element simulation, the traditional process was improved and curing efficiency was increased by 22.5%, with the internal temperature of vulcanization raised from 185 to 205 °C.
3. The uniformity and balance of the tire was improved, with both RFV and couple unbalance mass reduced.
4. The temperature difference between the upper and lower sidewall of the raw tire was reduced from 11 to 3 °C, and the uniformity of degree of curing of sidewalls was clearly improved.
5. Physical properties of the rubber parts of the finished tire were improved, which was especially significant for the sidewalls.

The current internal mold structure was suitable for tires with an expansion ratio smaller than 0.45. Further development is needed to expand the size series, which have a larger radial expansion ratio. Moreover, the influence of internal pressure generated from the internal mold on the vulcanization quality of tires remains to be extensively studied.

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