Effect of Dielectric Parameters and Frequency on Temperature Field of Microwave Curing of rubber compound

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Abstract. This paper aims to predict the heating behavior of rubber samples based on finite element methods using comsol multiphysics software. The effects of frequency and dielectric parameters on the temperature distribution of the stratified and non-layered models were investigated. The dielectric parameters mainly affect the temperature of the temperature field, and the influence on the temperature field distribution is relatively small. The temperature state of the tire surface distributed by different frequencies is not exactly the same. When further studying the influence of frequency on temperature distribution, the combined frequency of 915+2450MHz is selected in the double-waveguide cavity model, and the temperature field distribution is optimal. The power selected at this time is 1000w+1000w. The average temperature of the layered model is higher than that of the non-layered model, and the temperature difference is larger. The research results can provide reference for the research of heating rubber composites in microwave heating systems.

Key word: Temperature field; comsol Multiphysics; microwave heating.

1. Introduction
Curing is the last and most important step in the rubber processing process. The purpose is to optimize the physical and mechanical properties of the rubber parts. The traditional curing method is mainly the external heating method. The heat is transferred from the outside to the inside by heat conduction, the curing time is long, the curing is uneven and the energy waste is serious, and the microwave heating is a body heating mode, and the internal and external molecules move together under the action of electromagnetic waves. The mechanical energy is converted into heat energy, the curing time is short, the curing is uniform, and energy is saved. However, the curing process of rubber is complicated, and the research on the microwave curing of rubber has not been applied to the entire curing process. In the curing process of rubber, temperature is one of the three elements of curing. If the temperature setting is not suitable, the rubber is prone to sulphur or supersulfur, which seriously affects its performance. Therefore, it is important to study the temperature field during the rubber curing process.

At present, most of the research uses simulation to simulate the rubber microwave curing process. Although numerical simulation can provide some theoretical guidance for microwave curing, there are still some gaps with the actual heating process because many details are neglected in the simulation process. Although some scholars used the experimental method to preheat the tire blank, the microwave
was not applied in the whole process of curing, and the temperature field of the rubber in the microwave heating chamber was not studied.

This paper aims to study the temperature rise law of tire rubber compound in microwave heating chamber by combining electromagnetic field theory and rubber curing theory, and obtain the temperature field of film in the cavity, which provides basis for optimization of numerical simulation model, and also uniformity of tire microwave curing. The implementation of sexuality, rapidity and energy-saving is carried out in advance. In addition, some scholars only preheated the tire embryos, and did not conduct a practical study on the process conditions of the tire matrix curing process. In this paper, microwave curing was prepared by power time combination method, and the microwave curing process parameters of tire rubber compound were obtained, which laid a foundation for the research of tire microwave curing process.

2. Establishment of numerical simulation model

2.1. Model simplification

Make reasonable assumptions about the model as follows:

- Assumption 1. The rubber compound constituting the sample (tire) is uniform and isotropic.
- Assumption 2. The initial temperature of the sample (tire) and air is uniform.
- Assumption 3. The mass transfer process is ignored.
- Assumption 4. The convective heat transfer between the air and the sample (tire) is ignored.
- Assumption 5. The dielectric loss of air is ignored.
- Assumption 6. The waveguide and cavity are made of copper.
- Assumption 7. Heat transfer in the air is ignored.
- Assumption 8. The sample (tire) boundary is completely insulated.
- Assumption 9. The port is excited by a transverse electromagnetic standing wave field in the Y direction.

2.2. Physical Model

Figure 1 shows the outline of the 7.50R20 inner support tire. The 7.50R20 inner support tire is simplified into 5 layers, which are the tread rubber, shoulder rubber, sidewall soft rubber, belt layer and apex. The layered contour is shown in Figure 2.

![Fig.1 The outline of the tire](image-url)
2.3. Grid quality
Use the physics control grid to build the entire geometry. The grid cell size is set to super-fine. In order to get accurate results, the largest grid cell size is fine to one tenth of the wavelength of the microwave. We validate the Grid-independent of the model. Figure 3 shows the temperature field of the non-hierarchical model and hierarchical model at the same frequency. It can be seen from the figure that when the unit size is set above the coarsening, the accuracy is set. The increase of accuracy and the increase in the number of grids have negligible effects on the temperature field during the simulation.
In this simulation, non-hierarchical model and hierarchical model are uniformly selected for ultra-fine refinement. The final grid number is 10336 and 47332 respectively. At this time, the average unit mass of the two models is 0.8188 and 0.8578 respectively, when the average unit mass value is greater than 0.6, the results of this simulation are reliable.

![Fig.4 Grid unit](image)

3. Simulation of non-hierarchical two-dimensional model

3.1. Influence of dielectric parameters on temperature field of tire model

In order to study the influence of dielectric parameters on the temperature field in the tire model, the real part of the complex permittivity is set as a variable, and the simulation is performed at a microwave excitation frequency of 915 MHz. At this time, the mode of the microwave cavity is set to TE10, and the output is set. The total power is 10KW, that is, the single waveguide power is 5KW, the initial temperature of the heated tire model is 20 °C, and the microwave heating time is 4000S.

![Fig.5 The profiles of temperature distribution of tire at 4000s](image)
According to Fig. 4, when the microwave excitation frequency is the same 915 MHz, the tire model of the tread rubber is the same in the main heating part of the resonant cavity by the comparison of the temperature distribution map. In tire sidewall part of the tire model, the positions where the highest temperature and the lowest temperature appear are approximately the same. At the same time, when the loss tangent is constant, the average temperature of the model increases by about 4.4 °C and the maximum value increases by about 3.8 °C when the real part of the complex permittivity increases by 0.1. At the same time, the minimum value increases by 3.4 °C and the temperature difference increases by 0.5 °C.

**Tab.1** The different result of the simulation of the real part of complex permittivity

| the real part of complex permittivity | the loss tangent | the average temperature | the maximum value | the minimum value | the temperature difference |
|--------------------------------------|-----------------|------------------------|------------------|------------------|----------------------------|
| 4.5                                  | 0.04            | 93.7                   | 115.2            | 67.4             | 47.8                       |
| 4.6                                  | 0.04            | 98.1                   | 119.1            | 70.8             | 48.3                       |
| 4.7                                  | 0.04            | 102.4                  | 122.9            | 74.2             | 48.7                       |

The loss tangent is a variable, and the simulation is performed at a microwave excitation frequency of 915 MHz. At this time, the mode of the microwave cavity is set to TE10, and the output power is always 10 KW, that is, the single waveguide power is 5 KW, and the initial temperature of the heated tire model is 20 °C. The microwave heating time is 4000 s.

**Fig.6** The profiles of temperature distribution of tire at 4000 s

Note: (a)(b)(c) are the temperature distribution values of the loss tangent values 0.03, 0.04, and 0.05 respectively.

It can be seen from Figure 5 that, in the case where the loss tangent changes, the tire model of the tread rubber is the same in the main heating part of the cavity by the comparison of the temperature profile, which is the part of the sidewall tire, the tire model. The positions where the highest temperature and the lowest temperature appear are approximately the same. At the same time, when the real part of the complex permittivity is constant, the average temperature of the model decreases as the loss tangent
increases, and the loss tangent increases from 0.03 to 0.04. The average temperature increase is changed from 21.7 °C to 17.3 °C, and the increments of the maximum, minimum, and temperature difference are reduced.

**Tab.2** The different result of the simulation of the loss tangent

| the real part of complex permittivity | the loss tangent | the average temperature | the maximum value | the minimum value | the temperature difference |
|---------------------------------------|------------------|-------------------------|------------------|------------------|---------------------------|
| 4.6                                   | 0.03             | 76.4                    | 93.8             | 53.4             | 40.4                      |
| 4.6                                   | 0.04             | 98.1                    | 119.1            | 70.8             | 48.3                      |
| 4.6                                   | 0.05             | 115.4                   | 142.4            | 86.8             | 55.6                      |

It can be seen from the simulation that the change of the dielectric parameters of the rubber compound mainly affects the temperature value of the temperature field. In the dielectric parameters of the rubber compound, the real part increases linearly, and the temperature value in the simulation also increases linearly. In terms of loss tangent, as its value increases, the temperature value in the simulation decreases. By comparing the temperature in two cases, the small change in the loss tangent has a greater influence on the temperature and a less influence on the temperature distribution in the temperature field.

### 3.2. The effect of frequency on the temperature field of tire microwave curing

Section 2.1 studies the effects of dielectric parameters on the temperature field. The change of dielectric parameters at the same frequency has little effect on the temperature distribution of the temperature field, which mainly affects the temperature value of the temperature field. In order to further study the relevant process parameters for microwaves, the influence of the curing temperature field is simulated on the tread rubber tire model at the excitation frequency of 915 MHz and the temperature at 2450 MHz. The required data are the dielectric parameter frequencies of the tread rubber at 915 MHz and 2450 MHz, respectively. Table 3 It indicates that the mode of the microwave cavity is TE10, the output power is 10KW, the initial temperature of the heated tire model is 20 °C, and the microwave heating time is 4000s. The numerical simulation of the tire microwave curing process in the double waveguide cavity of the above two different syntax frequencies, and the temperature profile of the final tire.

**Tab.3** Tread dielectric parameters at 915MHz and 2450MHz

| Microwave frequency | the real part of complex permittivity | the imaginary part of complex permittivity | the loss tangent |
|---------------------|--------------------------------------|------------------------------------------|-----------------|
| 915MHz              | 4.6                                  | 0.18                                     | 0.04            |
| 2450MHz             | 12.2                                 | 3.91                                     | 0.32            |

**Fig.7** The profiles of temperature distribution of Tread at 4000s at 915MHz and 2450MHz

It can be seen from the above figure that the main heating points of the microwave curing of the tire are different due to the different excitation frequencies of the resonant cavity, and the uniformity is also different. When the excitation frequency is 2450MHz, the main heating part of the tire in the double-waveguide cavity is close to the shoulder portion; when the excitation frequency is 915MHz, the main
heating part of the tire in the double-waveguide cavity is lower than the middle side of the sidewall A little part.

In the same heating time of 4000s, the average temperature of the two-dimensional tire model is higher when the excitation power is 2450MHz, but the difference between the minimum temperature and the maximum temperature of the model is very close to 100 °C, that is, the temperature distribution is very uneven; Although the average body temperature at 915 MHz is not as high as the average body temperature of the tire model at 2450 MHz, the simulated microwave heating uniformity is better at this frequency, and the temperature difference is relatively small, and the value is 48.3 °C.

Tab.4 Simulation Temperature of Tread Rubber at 915MHz and 2450MHz

| Microwave frequency | Average temperature | minimum temperature | maximum temperature | temperature difference |
|---------------------|---------------------|---------------------|---------------------|------------------------|
| 915MHz              | 98.1                | 70.8                | 119.1               | 48.3                   |
| 2450MHz             | 100.3               | 64.0                | 170.7               | 106.7                  |

By observing the temperature distribution diagram 7 during the 4000s process, it is found that the highest temperature absorbs the most heat at the highest temperature. From the temperature rise curve, heating at a frequency of 2450 MHz, the temperature of the part increased by about 40 °C during the first 500 s, while the other positions rose by an average of 10 °C and about less than 1400 s, The temperature has reached 100 °C, at which time the average temperature is about 50 °C. The rate at which the temperature rises during the heating at a higher temperature is much faster than the rate at which the average surface temperature rises and the rate at which the minimum surface temperature rises, although the overall rate of temperature rise is reduced there. For the process of heating at 915MHz, the temperature rise is about 100 °C at about 3000s, and the average temperature is 75 °C.

The frequency bands that can be used without permission are mainly 915 ± 25MHz and 2450 ± 50MHz in the industry. The frequency between these two frequencies is generally less common for some reasons, in order to further understand the frequency to the tire model temperature. In the case of distribution, several frequencies are selected between 915MHz and 2450MHz, which are 1000MHz, 1250MHz, 1500MHz, 1725MHz, 2000MHz, 2250MHz. The following table shows the relevant values of the corresponding dielectric parameters at different frequencies of the tread rubber:

Tab.5 Tread dielectric parameters at different frequency

| frequency /MHz | the real part of the complex permittivity | the imaginary part of the complex permittivity | loss tangent |
|----------------|------------------------------------------|-----------------------------------------------|--------------|
| 1000           | 4.65                                     | 0.18                                          | 0.041        |
| 1250           | 4.93                                     | 0.21                                          | 0.044        |
| 1500           | 5.45                                     | 0.27                                          | 0.049        |
| 1750           | 7.4                                      | 0.64                                          | 0.08         |
| 2000           | 13.3                                     | 2.8                                           | 0.21         |
| 2250           | 22.32                                    | 46.8                                          | 2.10         |

The simulated frequency output power is 10 KW, the initial temperature of the heated tire model is 20 °C, and the microwave heating time is 4000 s. The numerical simulation of the tire microwave curing process in the double-waveguide resonator with different excitation frequencies mentioned above is carried out. The temperature distribution of the final tire when the average temperature is about 100 degrees is as follows:
It can be seen from the figure that at different excitation frequencies, as the temperature of the tread rubber model increases, the temperature profile of the tire can be clearly distinguished when the final body reaches an average of about 100℃. At a frequency of 1000MHz, the tire model of a single material is mainly heated on the shoulder side of the cavity, compared to the 915MHz heating zone, and the position of the tire is relatively upward; at a frequency of 1250MHz, the tire model of a single material is The main heating zone of the cavity appears in the tread, the sidewall and the lowermost corner respectively. There is a distinct high temperature zone. At a frequency of 1500MHz, the tire model of a single material is similar to the region of 1250MHz in the main heating zone of the cavity,
but Compared with 1500MHz at 1250MHz, when the average temperature reaches 100°C, the high temperature region is more concentrated than the heating region at 915MHz, and the position of the tire is relatively upward; at the frequency of 1750MHz, the high temperature region completely moves to the lower part of the tire section. It can be seen from the figure that from 1750MHz, 2000MHz and 2250MHz, the tire model of a single material is in the cavity as long as the heating part is in the next section of the tire. As the frequency increases, the area of the high temperature area gradually decreases.

In the simulation results, the microwave heating time and the maximum temperature difference in the double-waveguide cylindrical cavity are obtained when the average temperature of the tire body is about 100°C, and the relevant data are counted in the table, as shown in Table 6.

### Tab. 6 Microwave heating time and maximum temperature difference when the average temperature is about 100°C

| frequency | Average temperature | Microwave heating time | minimum temperature | maximum temperature | temperature difference |
|-----------|---------------------|------------------------|---------------------|---------------------|------------------------|
| 1000      | 94.7                | 3720                   | 72.6                | 130                 | 57.4                   |
| 1250      | 96.4                | 3180                   | 65.2                | 137.8               | 72.6                   |
| 1500      | 101                 | 750                    | 52                  | 150                 | 98                     |
| 1750      | 99.77               | 2300                   | 70.2                | 140.9               | 70.7                   |
| 2000      | 95.49               | 900                    | 40                  | 192                 | 152                    |
| 2250      | 105.18              | 700                    | 37.6                | 234.8               | 197.4                  |

Based on a comprehensive summary chart, it is found that in the frequency range from 915MHz to 1500MHz, when the surface average is 100°C, as the frequency increases, the microwave heating time decreases, the surface minimum value decreases, and the maximum value increases, and the corresponding difference is also increased; 1750MHz is an inflection point, when the microwave heating time is longer than 1500MHz, the minimum value increases, the maximum value decreases, and the difference is also reduced compared to 1500MHz; from 1750MHz to 2250MHz, on the surface average when the surface average value is 100°C, the microwave heating time is shortened, the surface minimum value is decreased, the maximum value is increased, and the corresponding difference is also increased.

Comparing the temperature distribution map, it is found that the time required for heating, the maximum temperature, the minimum value of the temperature, and the variation of the difference can correspond to the high temperature distribution pattern of the temperature distribution map. It can be found that the temperature distribution of the cloud map can be regarded as one in the range of 1000MHz-1500MHz. The pattern of distribution, 1750MH-2250MH can also be seen as a pattern of temperature distribution.

### 3.3. Temperature distribution of the tire model at the combined frequency

Through the study in Section 2.2, it is found that the temperature distribution of the two-dimensional tire model by different frequencies is regular, that is, after heating at different frequencies, the highest temperature on the tire model also appears in different places, in order to heat the tire model. More uniform and more efficient, try to use COMSOL finite element analysis software to numerically simulate the tire model microwave curing process at combined frequency. The microwave power is 5kW, first use the combination of 915MH and 2450MHz commonly used in industry. In the COMSOL simulation software, add the second study, and in the study of the second setting, you can study it in tandem. After the first phase of the study-one calculation is completed, the relevant parameters can be set in the second study.

The first case of combining analog frequencies is selected, the total time is 4000s, and the time distributions of the two frequencies are the same, respectively 2000s, in which case the simulation is performed. In the case of time halving, it is divided into the case of 915MHz and then 2450MHz, first in the case of 2450MHz and then 915MHz. The results of the two cases after the simulation are completed are as follows:
Working condition 1                     Working condition 2

Fig.9 Combination frequency temperature profile

Note: Working condition 1 is the combination of 915+2450MHz, and the combination of working condition 2 bits 2450+915MHz.

Tab. 7 Temperature conditions of two combined frequencies

| Combination method | Average temperature | minimum temperature | maximum temperature | temperature difference |
|--------------------|----------------------|----------------------|---------------------|------------------------|
| 1                  | 98.5                 | 74.5                 | 116.6               | 42.1                   |
| 2                  | 100.1                | 61.5                 | 148.8               | 87.3                   |

The distribution of different temperature fields affected by different frequencies is different. Therefore, after changing the frequency, the heating position in the simulation is different. The temperature of the original high temperature is slowed down at the new frequency, and the original low temperature is at the new frequency. The temperature rise is more obvious when it is lower.

From the temperature profile and the data in the table, for the 2450MHz, during the first 2000s of heating, the maximum temperature on the upper part of the tire has reached 122 °C, and the rate of temperature rise after the frequency is changed. The original frequency is low, so the final temperature reached is lower than in the case of 2450MHz. At the same time, at 2450MHz, the part with lower temperature, the frequency change becomes the heat absorption, and the temperature rises relatively quickly. It can be seen that the area of the high temperature area with respect to 2450MHz becomes larger, the combination frequency of 2450MHz+915MHz improves the temperature distribution at 2450MHz. For the combined frequency of 915MHz+2450MHz, the maximum temperature of the model is 78°C during the first 2000s of heating. When the frequency is changed, the main heating part changes. During the simulation, the heat is more uniform. Compared with the single 915MHz case, the average temperature finally reached is better, and the temperature difference is relatively reduced.

In order to further study the influence of the combined frequency on the temperature distribution and temperature rise of the tire model, the 915MHz+2450MHz combination is selected. The two frequencies are simulated in two cases at a total time of 4000s. In the first case, the frequency of 915MHz is used. The 1000s simulation is performed, and then 3000s is performed at 2450MHz. In the second case, the 3000s simulation is performed using the frequency of 915MHz, and the 1000s is performed at 2450MHz, and the difference between the final temperature value and the temperature distribution in the two cases is compared.
Fig.10 The profiles of temperature distribution of Tread at 4000s at 915MHz and 2450MHz

It can be seen from the temperature distribution diagram that under the combination of 915MHz+2450MHz, the temperature distribution of 3000s+1000s is better than that of 1000s+3000s, and the overall temperature distribution is relatively uniform, but the overall situation is not as good; Good. According to the above situation, in the case of 915MHZ+2450MHz combination, the average distribution time, the heating effect is better, and the temperature distribution is more uniform when the total time is constant.

Tab.8 Different allocation times of Tread at 4000s at 915MHz and 2450MHz

| Combination method | Average temperature | minimum temperature | maximum temperature | temperature difference |
|--------------------|---------------------|---------------------|---------------------|------------------------|
| 3000:1000          | 99.5                | 75.0                | 131.4               | 56.4                   |
| 2000:2000          | 98.5                | 74.5                | 116.6               | 42.1                   |
| 1000:3000          | 102.3               | 70.6                | 146.4               | 75.8                   |

3.4. Influence of power on tire microwave curing temperature field

In Section 2.3, it is concluded that in the combined frequency, the total time is 4000s, the excitation frequency is 915+2450MH, and the heating effect is the best, but the temperature difference still does not meet the ideal requirement. In order to continue to optimize the simulation, the influence of the waveguide power on the temperature field is studied under the condition that the combined frequency is optimal. The previous research of the research group has discussed that the average power distribution of the waveguide power is best when the upper and lower double waveguides are heated, and the proper waveguide power can optimize the uniformity of the temperature distribution of the microwave heating. The power set at the beginning of this section is 10KW, and the two waveguides are each 5KW. Therefore, the simulation is carried out by selecting the total power of 2KW, 4KW, 6KW and 8KW.
According to the simulation results, when the power is reduced, the average temperature of the body and the maximum temperature and the minimum temperature are simultaneously reduced, and the relative temperature difference is also reduced. From the table, it can be seen that the power is from 1000W to 5000W, and the average temperature increases by 2000W. The increase is 7 ℃; at the same time, the increase in the minimum temperature and the maximum temperature becomes large, and the temperature difference becomes large.

| power     | Average temperature | minimum temperature | maximum temperature | temperature difference |
|-----------|----------------------|----------------------|----------------------|------------------------|
| 1000W+1000W | 70.8                 | 65.5                 | 78.5                 | 13.0                   |
| 2000W+2000W | 77.5                 | 67.3                 | 83.7                 | 16.4                   |
| 3000W+3000W | 84.1                 | 69.4                 | 90.1                 | 22.7                   |
| 4000W+4000W | 91.8                 | 71.8                 | 101.5                | 29.7                   |
| 5000W+5000W | 98.5                 | 74.5                 | 116.6                | 42.1                   |

According to the ideal requirements, it is hoped that the temperature difference is within 20℃, the total power of 2KW and 4KW under 4000s simulation can meet the temperature difference requirement, but the average temperature of 77.5 ℃ and 84.1 ℃ is relatively low, in order to meet the actual requirements, the following two the working conditions extend the simulation time. Simulate the time of the two operating conditions separately:
Tab.10 The profiles of Tread at 1000W+1000W

| Time  | Average temperature | Minimum temperature | Maximum temperature | Temperature difference |
|-------|---------------------|---------------------|---------------------|-----------------------|
| 4500s | 75.4                | 69                  | 83.5                | 14.5                  |
| 5000s | 81.2                | 72.5                | 87.5                | 16.0                  |
| 5500s | 87.6                | 76.0                | 94.3                | 18.3                  |
| 6000s | 93.8                | 80.1                | 100.6               | 20.5                  |

Tab.11 The profiles of Tread at 2000W+2000W

| Time  | Average temperature | Minimum temperature | Maximum temperature | Temperature difference |
|-------|---------------------|---------------------|---------------------|-----------------------|
| 4500s | 83.4                | 70.2                | 89.8                | 19.5                  |
| 5000s | 88.2                | 76.5                | 99.5                | 23.0                  |

According to the table data, it is found that the lower power is used, and the heating time is longer to improve the temperature distribution of rubber curing. At this time, the average temperature can reach 93.8 °C, and the temperature difference can reach 20.5 °C.

4. Related simulation of layered model

4.1. Effect of frequency on temperature distribution of layered model

There is still a certain gap between the simulation of the tire model of a single material and the actual situation of microwave heating of the tire. In order to reduce the simulation gap, this section uses a two-dimensional model of the layered tire to simulate the case where the excitation frequency is different, the effect of frequency on the temperature field distribution.

The frequency of the 915MHz and 2450MHz commonly used in industrial production is used as the excitation frequency of the model. The mode of the microwave cavity is TE10, the output power is 10KW, the initial temperature of the heated tire model is 20 °C, and the microwave heating time is 2000s.

![Fig.12 The profiles of temperature distribution of Tread at 4000s at 915MHz and 2450MHz](image)

In the case of the same simulation time, it can be seen from the temperature profile and the temperature diagram 4-7 that at a frequency of 915 MHz, the temperature distribution of the model of the layered model and the single material does not differ much, but at the temperature value, The overall temperature rises and the temperature difference becomes larger; Compared with the layered model of 2450MHz and the non-layered model, the overall temperature rises and the temperature difference becomes larger. However, unlike the low frequency, there are some differences in the temperature distribution, and two symmetrical high temperature distributions are added. The above two simulations show that at low frequencies, the stratification of the rubber compound has no obvious response to the propagation of microwaves in the electromagnetic field; as the frequency increases, the different
dielectric parameters of different rubber compounds have an effect on the microwave propagation of the electromagnetic field. Therefore, the difference in temperature distribution between the layered model and the non-layered model at 2450 MHz is caused.

Tab.12 Simulation Temperature of Rubber at 915MHz and 2450MHz for 4000s

| frequency  | Average temperature | minimum temperature | maximum temperature | temperature difference |
|------------|---------------------|---------------------|---------------------|------------------------|
| 915MHz     | 154                 | 112                 | 189                 | 77                     |
| 2450MHz    | 170                 | 127                 | 238                 | 111                    |

Further simulating the influence of other frequencies on the temperature field, it is found that the temperature distribution changes in the non-layered model also show a certain regularity. Starting from 915MHz, it appears in the high temperature position on both sides of the tire, and moves to the tread as the frequency increases; from 1250MHz, the high temperature is at the tread, and a new high temperature appears at the sidewall; at 1750MHz, the high temperature is reached. The position changes significantly and appears in the lower part of the sidewall. As the frequency increases, the high temperature becomes concentrated upwards, and the sub-high temperature occurs at the shoulder.

Fig.13 The profiles of temperature distribution of Tread at 4000s at different frequency
4.2. Influence of combined frequency on temperature distribution of layered model

In the previous section, it was found through simulation that the temperature distribution of the two-dimensional layered model with different frequencies is regular, and the law is similar to the law of non-layering. In order to further study the influence of the combined frequency on the temperature distribution of the layered model, the total simulation time is set to 2000s, and the time distributions of the two frequencies are the same, respectively, 1000s, in which case the simulation is performed. In the case of time division, it is divided into the case of 915MHz and then 2450MHz, which is first 2450MHz and then 915MHz. The results of the two cases after the simulation is completed are as follows:

![Combination frequency temperature profile](image)

It can be seen from the figure that the simulation is performed in the manner of combining frequency 915+2450, and the results are compared. At 915MHz and at 2450MHz, the temperature distribution is more uniform, the temperature difference is relatively small, but the average temperature is also reduced. The simulation is performed in the form of a combined frequency of 2450+915. The result is better in temperature distribution and the temperature difference is reduced in the case of 2450 MHz, but the temperature difference is compared with the simulation of 915 MHz, and the temperature difference is not small at 915 MHz alone. This law is similar to the simulation law of non-stratification, and the values are different. In summary, when the frequency is 915+2450, the time is evenly distributed, and the simulated heating is best.

| Combination method | Average temperature | minimum temperature | maximum temperature | temperature difference |
|--------------------|---------------------|---------------------|---------------------|------------------------|
| 915+2450           | 135                 | 107                 | 165                 | 58                     |
| 2450+915           | 160                 | 114                 | 197                 | 83                     |

5. Conclusion

This chapter has carried out related research on frequency and dielectric parameters, mainly using numerical simulation method, in the double-waveguide cavity model pass frequency table and the dielectric parameters that should be changed, the following conclusions are obtained:

(1) The dielectric parameters mainly affect the temperature of the temperature field, and the influence on the temperature field distribution is relatively small. When other dielectric parameters are constant, the linear constant change of the complex permittivity, the temperature of the model also changes linearly; When other parameters are fixed, the influence of the loss tangent on the temperature is relatively large. The variation of the temperature field temperature value in the simulation increases with the loss angle, and the temperature value increases. The size of the electrical parameters can be used to determine the different rubber compounds. The highest value of the temperature distribution and the general case of the final average temperature at the same time of heating.
(2) In the microwave curing simulation process of a fixed-size double-waveguide (upper and lower-distribution) resonant cavity tire model with different frequencies between 915MHz and 245MHz, different frequencies eventually result in different temperature states distributed on the tire surface. For example, at 915MHz, the main heating part of the microwave is the middle part of the sidewall. As the frequency increases to 1500MHz, the highest temperature distribution moves to the tread. At 1750MHz, there is a distribution change law from 1750MHz to 2250MHz. The highest temperature of the temperature distribution is located at the most corner of the sidewall, and as the frequency increases, the maximum value increases while the area of the highest temperature decreases.

(3) The frequency combination of the 915MHz and 2450MHz analog heating simulation, in the combination of (2450 + 915 average) MHz, the final effect is better than the 2450MHz microwave heating effect, but still can not match the effect of 915MHz alone. At a combination of (915 + 2450 averaging) MHz, the temperature distribution is better than the 915 MHz simulation alone, while the relative temperature difference is reduced.

(4) Select the optimal setting of 915+2450MHz combined frequency, and change the power to study the simulation. Under the condition of certain simulation time, the smaller the power, the lower the average temperature and the smaller the temperature difference. Select 1000W+ The power condition of 1000W was simulated, and finally the optimization of the average temperature of 93℃ and the temperature difference of 20℃ was obtained.

(5) For the layered model, the temperature distribution of the non-layered model is similar at the same frequency, but the average temperature is higher than that of the non-layered model, the temperature difference is larger, and the 915MHz and 2450MHz are performed. In the frequency combination simulation heating simulation, a law similar to that in the non-layered simulation was also found. Whether it is a layered model or a non-hierarchical model, at a combined frequency of 915 + 2450, the two frequencies have the best distribution when the total time is constant.

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