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Structural design and experimental research of microwave radiation heater for asphalt pavements

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Abstract: In order to improve the efficiency of heating and the uniformity of temperature distribution in recycling asphalt mixtures, a pyramidal radiation heater is designed. The principles of designing horn surface size and antenna length are established according to the law of energy conservation and microwave antenna radiation theory. Modeling and simulation are carried out using IE3D software. The simulation results demonstrate that, with a fixed horn surface size, the shortened electric antenna length is the main factor leading to the improved heating uniformity. On the other hand, with a fixed antenna length and diminished surface size, the standing wave ratio decreases with the improved radiation efficiency. Furthermore, the efficiency of radiation drops with increased distance between the horn surface and the asphalt pavement. Microwave heating experiments are carried out using this type of heater. The temperature distribution of asphalt samples is obtained by the grid temperature measurement method, and Matlab simulation is performed. The experimental results are in good agreement with the simulation.
Key words: asphalt mixtures; microwave heating; temperature distribution; microwave radiation heater; structural design

In China, a maintenance period will enter corresponding to the increase in mileage and road-age of high-quality roads. However, due to semi-rigid base asphalt pavement structure types and the base strong bearing capacity, functional damages to the surface of asphalt pavements such as formation of cracks, potholes and portrait craze are inevitable over time. It is the most direct and most efficient method to restore pavement service function by using hot in-place recycling[1]. Microwave heating increases the temperature of heated objects through enhancing the movement of the molecules of the material. It is a type of volume heating which has the advantage of deep penetration, small thermal inertia and easiness to control[2]. The combination of microwaving heating and hot in-place recycling has currently become an important hot in-place recycling technology, and has attracted more and more attention.

A main issue in developing a microwave heating recycling system is the design of radiation antenna. The antenna should provide uniform radiation distribution to achieve uniform heating at the surface of asphalt mixtures and eliminate tangential hot-spots and cold-spots at the surface. This will increase the efficiency and quality of recycling, and meanwhile achieve optimal matching of impedance in order to maximally improve heating efficiency. In 1978, Boyko et al. [3] developed a microwave repairing engineering vehicle which could be mounted on the chassis of trucks. This vehicle used for the first time a multi-unit combination microwave source. Openings were made in the trough waveguide wall to create leaky waves for radiation heating. Afterwards, Thuéry[4] performed studies of heating equipment. Most of the equipment used high-power industrial magnetron-tubes which had complex structures. Specially designed protecting equipment such as circulators was necessary to protect magnetron-tubes from being damaged by microwave reflection. Overall, this type of equipment was not widely used due to the limited performance-cost ratio. In contrast, pyramidal horns have an increased opening surface size. The abrupt change in the characteristic impedance at the peristome was transformed into a gradual change which decreased the standing-wave ratio and increased the radiation efficiency and uniformity. This design has become more and more widely used in the microwave heating of asphalt pavements. In this paper, we describe a pyramidal horn type radiation heater. We design this heater based on the horn antenna radiation theory and the characteristics of common magnetron-tubes with a working frequency at 2. 45 GHz. We use IE3D for structural modeling simulation and perform experimental verification.

1 Structural Design of Radiation Heater

The microwave radiation heater stands above asphalt pavements, as shown in Fig. 1. D_1D_2 is the surface size of the horn, h is the height between the horn surface and the samples, H is the thickness of the samples, and z-direction is the microwave propagation direction. A coordinate system is established as shown in Fig. 1. The microwave, emitted by a magnetron-tube antenna and prompted by a prompting cavity, produces the required work pattern, comes into the horn radiation cavity[5], and then accomplishes hot-recycling through surface field radiation of the horn antenna.

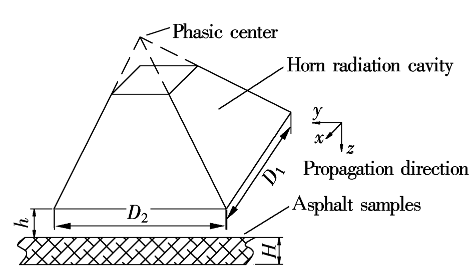

Fig. 1 Schematic of microwave heating recycling

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1.1 Principles of opening surface design

The design of the opening surface of a radiation heater is based on the following hypotheses: 1) Magnetron-tube output power as an internal heat source is completely absorbed by asphalt mixtures; 2) The opening size of asphalt mixtures is an adiabatic condition; 3) The asphalt mixture sample with a thickness of H cm is heated in t s to achieve a bulk temperature increase of ΔT and reach the recycling temperature of asphalt mixtures; 4) Physical parameters such as specific heat capacity and dielectric constants do not change with temperature variation.

The mechanism of microwave heating is that the intrinsic polar molecules of asphalt mixtures become polarized under the influence of an external electromagnetic field. During this process, the microwave power is dissipated in the form of heat within the mixture which results in a temperature increase of the asphalt mixture[6]. Based on the hypothesis, the magnetron-tube output power is completely absorbed by the asphalt mixture leading to the increase in temperature. Based on the law of energy conservation,

$$Q/t = P,\ Q = C_p M(T - T_0) = C_p V\rho\Delta T \tag{1}$$

where Q is the absorbed heat by the asphalt mixture(J), P is the power of microwave radiation(W), and t is the heating time(s). C_p and ρ are the specific heat capacity and the density of the asphalt mixture, respectively. $C_p = 0.889\,6$ J/(g · ℃), and $\rho = 2\,435$ kg/m^3[7]. V is the volume of heated material, and $V = HD_1D_2$; ΔT is the temperature increase in the material(℃).

For a magnetron-tube with an input power of P_0, if we assume that its output power is between P_1 and P_2(W) and use Eq. (1), the surface size (m^2) can be described as

$$4.61\times10^{-7}t\frac{P_1}{H\Delta T}\leqslant D_1D_2\leqslant4.61\times10^{-7}t\frac{P_2}{H\Delta T} \tag{2}$$

If the standing wave ratio and other heat loss are taken into account, the actual value of the opening size based on Eq. (2) will decrease.

When a pyramidal horn is used as a microwave antenna, the higher the directivity and the gain, the narrower the beam of the antenna. In turn, the electromagnetic energy of the antenna radiation will be more focused and directed, and better fulfill the design requirements[8]. However, the width of the beam should not be too narrow in order to decrease the horizontal temperature gradient of the asphalt pavements and improve the uniformity of heating. Otherwise, the distribution of the electromagnetic field will be overly concentrated rather than being uniform, leading to uneven distribution of the thermal field in the heated area. Therefore, the design of the radiation heating device should not be too demanding on the directivity and gain of the antenna. Nonetheless, when considering the combination of multiple radiation heaters, the width of the beam should not be too wide. Otherwise, the mutual coupling of neighboring antennas will be enhanced causing decreased efficiency[9].

The width of the beam is defined as the width of a major valve $2\theta_{0.5}$. The width of the major lobe is expressed as the angle between the two half-power points on the sides of the maximal radiation direction; i. e. when the power decreases to one-half of the maximum, the field intensity will decrease to $1/\sqrt{2}$ of the maximum or 3 dB less than the maximum. Based on antenna radiation theory, for a pyramidal horn, with a fixed working frequency and opening size, the width of major valves $2\theta_{0.5E}$ and $2\theta_{0.5H}$ are also set. The relationship can be expressed as

$$\frac{1+\cos\theta_{0.5E}}{2}\frac{\sin\psi_2}{\psi_2}=\frac{1}{\sqrt{2}},\ \frac{1+\cos\theta_{0.5H}}{2}\frac{\cos\psi_1}{1-(2\psi_1/\pi)}=\frac{1}{\sqrt{2}} \tag{3}$$

where $\psi_{1,2}=\frac{1}{2}\kappa D_{1,2}\sin\theta_{0.5H,0.5E}$, $\kappa=\frac{2\pi}{\lambda}$, and λ is the working wavelength.

According to Eq. (3), if the main lobe beam width $2\theta_{0.5}$ of the horn antenna is known, the size of the horn surface can be obtained. By comparison with Eq. (2), the size of the horn surface can be determined finally by comparison with Eq. (2) with modification.

1.2 Principle of heating chamber of pyramidal horn design

In reality, the average distance between the opening of the horn and the surface of the asphalt pavement is less than 10 $(\lambda/2\pi)$, which can be considered as near field radiation. Based on the analysis above, the requirement for the directivity of the antenna is not high as long as the main lobe beam width appropriately increases. The splitting of the main lobe can paradoxically improve heating uniformity within the heated region. Therefore, as long as the maximal phase deviation at the horn opening is within the permissible range, the design of the horn length can be resolved.

A pyramidal horn surface coordinate system can be established as shown in Fig. 2. The center of the pyramidal horn surface is set as phase zero. The horn surface field can be expressed as

$$E_s = E_0\cos\left(\frac{\pi x_s}{D_1}\right)e^{-j\frac{\pi}{\lambda}\left(\frac{x_s^2}{R_1}+\frac{y_s^2}{R_2}\right)} \tag{4}$$

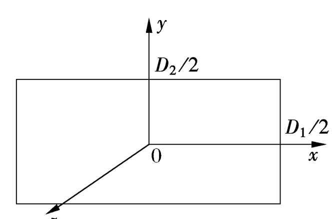

Fig. 2 Coordinate of the pyramidal horn surface

Based on the above equation, the amplitude of the pyramidal horn surface is in cosine distribution along x_s and uniform distribution along y_s. Phase shifting along x_s and y_s will occur and be distributed as square law phase

$$\varphi=\frac{\pi}{\lambda}\left(\frac{x_s^2}{R_1}+\frac{y_s^2}{R_2}\right) \tag{5}$$

At the rim of the horn surface, $x_s = D_1/2$. The maximal phase deviation within the H plane is

$$\varphi_{2mh}=\frac{\pi D_1^2}{4\lambda R_1} \tag{6}$$

Considering cosine amplitude and square law phase distribution within the H plane, based on the directivity of a pyramidal horn, when $\varphi_{2mh} \leqslant \pi$, the directivity has no apparent deterioration. However, when $\varphi_{2mh} \geqslant 3\pi/2$, the directivity will deteriorate significantly. Therefore, when

$$\frac{3}{4}\pi < \varphi_{2mh} = \frac{\pi D_1^2}{4\lambda R_1} \leqslant \frac{3}{2}\pi \tag{7}$$

the requirements for the directivity and the beam width of the horn radiation heating can be met.

For a pyramidal horn, the size of the input end must fit the size of the waveguide feed. Based on Fig. 3,

$$\frac{R_1 - C}{a} = \frac{R_1}{D_1}, \quad \frac{R_2 - C}{b} = \frac{R_2}{D_2} \tag{8}$$

The solution of Eq. (8) leads to

$$R_1\left(1 - \frac{a}{D_1}\right) = R_2\left(1 - \frac{b}{D_2}\right) \tag{9}$$

The antenna length R_1 and R_2 can be deduced via a combination of Eqs. (7) and (9).

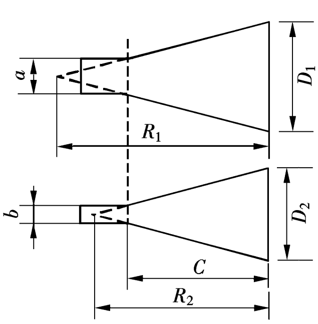

Fig. 3 Geometrical structure size of a pyramidal horn

1. 3 Structure of microwave heater

When magnetron-tubes are used for heating of asphalt pavements, the antenna of the magnetron-tube as a mono-polar antenna can induce excitation within the excitation chamber. The excitation chamber actually forms an ab-sized rectangular waveguide. When the chamber is designed as a rectangular waveguide, we have

$$\frac{\lambda}{2} < a < \lambda, \quad b \leqslant \frac{a}{2} \tag{10}$$

It can transform the TEM wave emitted from the magnetron-tube antenna into TE_{10} transmission. Based on the structure of the magnetron-tube and setting requirements, the axis of the magnetron-tube antenna is vertical to the surface of asphalt pavements. According to the antenna radiation theory, radiation has directivity. Radiation intensity reaches its maximum along the directions of vertical-to-the-axis of the antenna. Therefore, the excitation chamber can be designed as an E-plane biaxial conjunction transition structure. A transition waveguide with a length of L can be added in between both ends of the waveguide plane as shown in Fig. 4. In order to have reflection waves from both ends of the waveguide set off each other completely, L should be equal to an odd number of the times of the waveguide wavelength, i. e.

$$L = \frac{(2n+1)\lambda_g}{4} \qquad n = 0, 1, 2, \ldots \tag{11}$$

where λ_g is the waveguide wavelength. For a single mode transmission waveguide, $\lambda_g = 2a\lambda / \sqrt{4a^2 - \lambda^2}$, where λ is the working wavelength and $\lambda \approx 12.2$ cm.

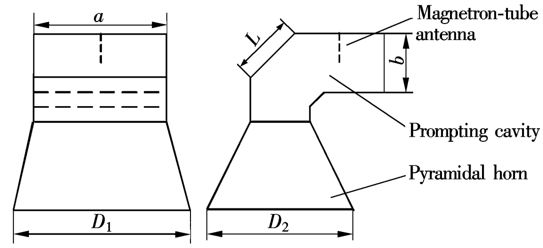

Fig. 4 Sketch of pyramidal horn heater structure

2 Modeling and Simulation

2. 1 Conditions of model construction

We use Zeland IE3D software to perform modeling and simulation, the conditions of the model construction can be ensured as follows:

1) A magnetron-tube cylinder antenna is replaced by a thin strip antenna. According to Zeland User's manual[10], there is a minimal difference between the simulation results from the two methods.

2) The distance between the feed end and the grounded layer is 1 mm, and the actual measured length of the magnetron-tube antenna is 22 mm.

3) The relative dielectric constant of the asphalt mixture $\varepsilon_r' = 5.8$, $\tan\delta = 0.0344$. The thickness is set as 60 mm. The material is semi-infinite flat media. Air is filled outwards along the direction of radiation.

4) The starting radiation frequency is 2. 4 GHz and the end frequency is 2. 5 GHz. The simulation frequency step size is 0. 01 GHz and the number of the simulation frequency dots is 11.

5) The highest frequency of the discrete parameter is 2. 6 GHz. Each wavelength has 10 unit numbers.

6) The initial distance between the horn surface and the asphalt mixture sample is $h = 30$ mm.

The structural model of the pyramidal horn heater is shown in Fig. 5.

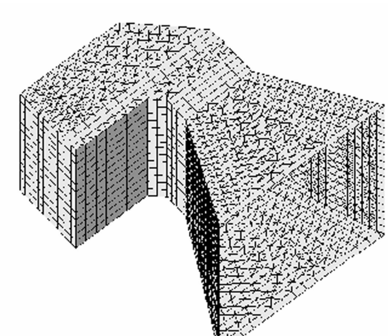

Fig. 5 Structural model of the pyramidal horn heater

2. 2 Simulation results and analysis

Based on the design principles, one size heater is selected as the basic type. Simulation is performed for different horn lengths, surface sizes and different distances between the horn surface and asphalt pavements. The results are shown in Tab. 1.

Tab. 1 Properties of radiation heater under four conditions at 2 450 MHz

Pattern parameters	Horn antenna in different structures					
	When horn length is shortened	When surface size is reduced	Basic type			
			$h=0$ mm	$h=30$ mm	$h=60$ mm	$h=120$ mm
Incident power/mW	10. 0	10. 0	10. 0	10. 0	10. 0	10. 0
Input power/mW	9. 24	6. 57	5. 82	5. 58	3. 64	2. 41
Radiated power/mW	6. 92	5. 76	5. 82	5. 58	3. 64	2. 41
Radiation efficiency/%	74. 9	87. 7	100	100	100	100
Antenna efficiency/%	69. 2	57. 6	58. 2	55. 8	36. 5	24. 1
Linear gain/dBi	8. 13	5. 05	9. 02	3. 19	4. 39	2. 37
Linear directivity/dBi	9. 72	7. 45	11. 40	9. 35	8. 78	8. 54
3 dB beam width/(°)	(43. 2, 60. 7)	(29. 1, 64. 9)	(17. 6, 61. 8)	(17. 5, 66. 4)	(23. 9, 64. 1)	(13. 7, 45. 4)

The simulation results in Tab. 1 show that with a fixed size of the pyramidal horn, decreased antenna length is a main factor leading to decreased gain, increased beam width and improved uniformity of heating. When the horn surface size decreases while the antenna length remains unchanged, the standing wave ratio will increase with the improved radiation efficiency. Under the same condition, the decreased antenna length provides better effects compared with decreasing horn surface area. When the distance between the horn surface and asphalt pavements increases, the radiated power will decrease.

3 Experimental Results and Discussion

Experiments are carried out under four conditions. A 2M210F magnetron-tube with a working frequency of 2 455 MHz and a maximal output power of 875 W is used as the source of microwave. The experimental device is shown in Fig. 6. For the safety of operators during the experiment, a metal web hood is made to shield them from the radiation. An AV3941 radiometer is placed at 0. 5 m from the device to measure microwave leaking at the periphery of the device. The maximal leaking is 212 $\mu W/cm^2$, indicating that the environment is safe.

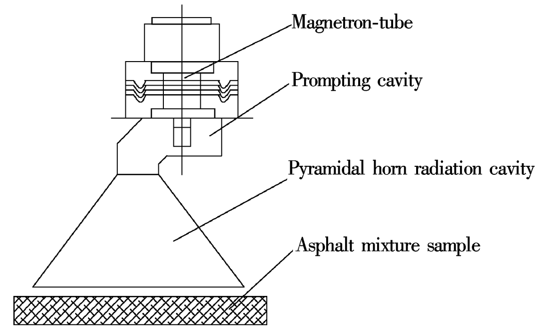

Fig. 6 Microwave heating experiment device

The initial experimental conditions are as follows: thickness H is 8 cm; AC-13 sample is selected with the asphalt-aggregate ratio of 5. 3%; the composition of materials includes mole-seed-tablet 30% (diorite), little pebble(25%), stone-chip (40%), and slag-powder (5%).

The dielectric properties are the same as in condition 3) of the model construction. A grid template is made for measuring the temperature of the sample. The surface of the sample is divided into an 8×10 grid. After heating 15 min, the temperatures are measured using an infrared thermometer[11]. The corresponding data are shown in Tabs. 2 to 5.

Tab. 2 Surface temperature(8×10 grid) of asphalt mixtures for the basic type horn ℃

Surface temperature of sample(ambient temperature is 11. 4 ℃, initial temperature is 8. 2 ℃)										Average increased temperature
53. 8	65. 6	79. 4	83. 6	92. 6	77. 8	73. 2	71. 6	67. 0	32. 8	62. 3
72. 4	86. 0	101. 2	103. 4	105. 0	92. 8	94. 8	85. 8	82. 2	52. 0	
75. 8	100. 2	111. 4	113. 2	110. 0	107. 4	109. 8	109. 8	98. 0	53. 0	
69. 2	93. 4	101. 4	106. 4	107. 6	111. 4	109. 2	109. 4	94. 8	60. 2	
55. 4	78. 2	89. 6	93. 6	96. 6	95. 4	97. 2	94. 2	80. 4	54. 4	
41. 2	53. 0	66. 2	71. 6	67. 2	76. 8	74. 0	69. 6	53. 2	38. 2	
32. 2	39. 0	50. 2	56. 0	57. 8	55. 4	43. 8	43. 2	36. 2	21. 2	
20. 4	24. 8	28. 2	28. 0	28. 4	27. 6	25. 2	20. 4	15. 8	12. 6	

Tab. 3 Surface temperature(8×10 grid) of asphalt mixtures for the shortened horn length ℃

Surface temperature of sample(ambient temperature is 20. 4 ℃, initial temperature is 18. 8 ℃)										Average increased temperature
68. 6	70. 0	68. 2	64. 4	68. 8	60. 0	55. 4	54. 2	44. 4	31. 2	65. 4
97. 6	118. 2	127. 2	123. 2	116. 8	99. 4	86. 0	76. 8	62. 6	43. 0	
118. 8	126. 8	128. 6	125. 2	121. 4	117. 2	100. 6	90. 8	78. 2	58. 4	
123. 6	129. 6	130. 0	129. 2	123. 8	121. 2	116. 8	98. 8	82. 4	60. 8	
117. 2	123. 6	126. 2	123. 4	119. 8	110. 2	102. 6	90. 4	76. 8	55. 4	
106. 6	118. 6	117. 8	116. 6	113. 8	99. 4	89. 2	73. 8	61. 6	46. 6	
75. 4	86. 4	89. 8	85. 4	79. 2	68. 4	64. 8	49. 2	44. 8	35. 8	
31. 2	36. 4	37. 2	38. 2	40. 2	39. 2	33. 4	31. 6	30. 4	29. 2	

Tab. 4 Surface temperature (8 × 10 grid) of asphalt mixtures for the diminished surface size ℃

Surface temperature of sample (ambient temperature 9.9 ℃, initial temperature 7.6 ℃)										Average increased temperature
43.0	53.4	68.2	70.4	74.0	56.6	54.8	55.2	45.2	38.4	
72.0	95.4	102.2	100.2	91.4	73.2	68.2	79.2	70.2	47.6	
104.8	131.2	138.4	129.2	117.8	94.4	95.2	92.0	87.2	57.4	
108.6	130.4	139.0	130.4	117.0	102.8	105.6	106.0	103.2	57.2	63.2
96.8	113.6	123.6	115.8	108.0	98.8	104.8	98.6	89.4	53.2	
73.6	85.4	94.8	92.8	90.2	89.2	87.2	78.8	68.8	43.2	
46.8	57.8	66.2	69.0	69.2	68.2	64.6	63.2	50.6	33.4	
32.2	37.4	38.2	38.8	39.8	49.2	48.8	36.2	31.6	21.2	

Tab. 5 Surface temperature (8 × 10 grid) of asphalt mixtures for the extended distance between surface and sample ℃

Surface temperature of sample (ambient temperature 20.4 ℃, initial temperature 18.8 ℃)										Average increased temperature
52.6	63.8	71.4	77.2	79.6	71.8	70.6	61.4	57.4	45.8	
72.4	83.6	86.4	88.6	86.8	79.8	75.8	72.4	74.2	62.2	
82.2	92.0	94.4	91.4	85.8	83.8	84.8	87.2	84.8	68.6	
81.2	91.4	92.4	89.2	84.8	82.6	84.8	87.8	87.4	76.2	50.2
69.2	79.4	82.6	84.2	83.4	80.2	82.2	81.8	75.4	63.8	
57.2	64.8	71.6	74.2	75.6	74.4	76.2	70.2	65.8	51.0	
46.8	52.6	56.8	61.2	63.2	62.2	61.8	56.2	47.8	35.8	
33.4	35.0	39.2	39.4	43.4	37.8	37.4	39.2	31.2	25.2	

By using Matlab software, each temperature field is fitted and every fitting surface is shown in Fig. 7. According to the temperature field fitting results shown in Tabs. 2 to 5 and Fig. 7 and compared with the basic type of pyramidal horn heating, the shortening of the horn length resulted in a smoother temperature distribution curved surface of asphalt mixtures. The temperature at the periphery of the horn surface slightly decreases with no apparent temperature ladder and with good uniformity. By contrast, the average temperature of asphalt mixtures increases when the horn surface size decreases. This is associated with more temperature variation and an apparent temperature ladder. A region with higher temperature appears in the left-middle portion with a rapid decrease in temperature when moving away from this area. On the other hand, the right side of the horn surface is minimally heated with significant temperature variation. When the distance between the horn surface and the asphalt sample increases, the heating efficiency decreases but with good uniformity. The experimental results are essentially consistent with the simulation results.

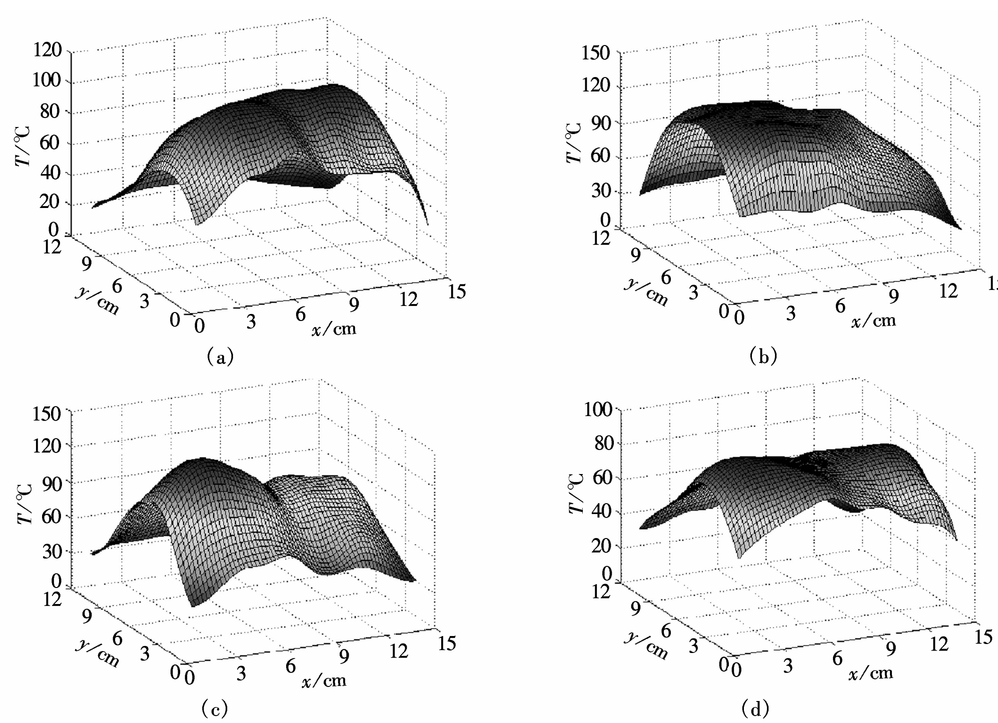

Fig. 7 Temperature field fitting of four conditions. (a) Temperature field fitting of the basic type horn; (b) Temperature field fitting when the horn length is shortened; (c) Temperature field fitting when the surface size is diminished; (d) Temperature field fitting when the distance is extended

4 Conclusion

A pyramidal horn type microwave radiation heater is designed. Based on the structural characteristics and setting requirements, feed wave is designed as an *E*-plane biaxial conjunction transition structure type. According to the law of energy conservation and the principles of microwave antenna radiation, we establish general principles in designing the horn surface area and the length of the antenna. Based on these principles, we perform structural modeling and simulation calculations under four conditions. The uniformity of heating and radiation efficiency is also compared. Heating experiments are carried out on asphalt mixtures under the four conditions. The results are consistent with those obtained from simulation, indicating the validity of our study. Our work provides a practical guidance for designing the horn structure. Due to the limitations of our experimental conditions, the simulation was performed on an asphalt mixture with one type of dielectric property. In future, asphalt mixtures with different dielectric properties will be tested. The structural design of the heater should enhance the radiation capability with wider beam and higher efficiency in order to broaden its applications on different pavements.

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沥青路面微波辐射加热器结构设计与实验研究

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摘要:为了提高微波加热沥青混合料的效率和温度分布的均匀性,设计了一种角锥喇叭辐射型加热器. 运用能量守恒定律和天线辐射原理,建立了喇叭口面尺寸和天线长度设计原则. 采用 IE3D 进行了结构建模和仿真运算,结果表明在喇叭口面尺寸一定的前提下,天线长度缩短是改善加热均匀性的主要因素;当天线长度不变而口面尺寸减小时,其驻波比减小,辐射效率提高;口面离沥青路面距离增加时,辐射效率下降. 对这种结构加热器进行了实验,采用网格测温法测出了沥青试样表面温度分布并进行了 Matlab 模拟,实验结果与仿真具有较好的一致性.

关键词:沥青混合料;微波加热;温度分布;微波辐射加热器;结构设计

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