Guide and control of thermal conduction with isotropic thermodynamic parameters based on a rotary-concentrating device

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A rotary-concentrating device for thermal conduction is constructed to control and guide thermal energy transmitting in elastic plates. The designed device has the ability of concentrating for thermal conduction and controlling the processes of thermal diffusion in a plate. The multilayered isotropic material properties of the rotary-concentrating device are derived based on the transformation and rotary medium method and a rotation parameter to control the thermal diffusion process is introduced. The efficiency of the rotary-concentrating device for thermal conduction is verified. Stability of temperature fields in a plate with the rotary-concentrating device is analyzed to study the performance of rotary-concentrating. Numerical examples show that the constructed rotary-concentrating device for thermal conduction can effectively rotate and focus on the thermal energy into the device for a wide range of diffusion temperatures, which can enhance the thermal conduction. Therefore, this study can provide a theoretical support for potential applications in fields of energy harvesting and thermal conduction control.

Keywords: rotary-concentrating, thermal conduction, isotropic thermodynamic parameters, control of thermal conduction process

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1. Introduction

In 2006, Pendry *et al.*[1] and Leonhardt[2] proposed the transformation optics theory almost simultaneously and independently. In this theory, according to the form invariance of Maxwell equation on coordinate transformation, one can design the corresponding coordinate transformation functions according to the application needs, and then use the spatial coordinate relationship to calculate the corresponding dielectric parameter distribution, so as to realize the electromagnetic functional devices that meet the requirements. The application of transformation optics theory is far from limited to the cloak.[3,4] Scholars have successively designed a series of novel functional devices, such as field concentrator,[5,6] field rotator,[7] super-lens,[8] high directional antenna.[9,10]

The device of rotator can change and control the incident wave direction and lead to high-efficiency reception for different types of waves.[11] The idea of concentrating also has potential applications in the design of high-efficiency receiving energy because it can improve the incident wave energy density.[12] Therefore, there are many researches concentrating on these two devices, including regular and irregular shape designs, development of two-dimensional structure to three-dimensional structure, simplification of device parameters, and so on.[13–15] Chen and Chan[16] proposed a function of rotation to design the rotating device for control of the electromagnetic wave. Jiang *et al.*[17] constructed a metamaterial for acoustic wave rotator and accomplished experimental validation. Yang *et al.*[18] used the transformation method to design a concentrator for acoustic wave with polygonal cross-section. Liu *et al.*[19] designed a new multifunctional electromagnetic device with performance of rotary-concentrating based on the theory of transformation optics. Wang *et al.*[20] designed a multilayered concentrator for acoustic waves, which can guide propagating trajectory of acoustic waves and realize concentrating of acoustic wave energy. Lu *et al.*[21] constructed an elastic wave concentrator based on the fractional Fourier transform and studied scattering effect of wave trajectories control. The device can guide and rotate the propagation trajectory of the electromagnetic wave and elastic wave at a specified angle in the core area of the device, which realizes the concentrating of electromagnetic and elastic wave energy to the core area.

The idea of transformation medium for concentrating wave energy has received great attention. Wang *et al.*[22] used a linear transformation function to design an acoustic wave rotary-concentrating device with homogeneous materials, which would be provided a theoretical support in fields of communication and acoustic sensing. Fakheri *et al.*[23] adopted the transformation acoustic theory to design an arbitrary shaped acoustic concentrator with natural homogeneous materials by effective medium theory. An omnidirectional concentrator for broadband low-frequency elastic wave is designed to realization of energy attenuation based on the transformation method.[24] Huang[25] provided a review of thermal metamaterials that includes basic theory of thermodynamics, historical contributions, and future study topics. Fan *et al.*[26] constructed shaped graded materials in which thermal

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conduction can be guided from the cold to hot, which is an abnormal behavior. Fujii and Akimoto[27] studied a concentrator for heat flux based a topology optimization approach and realized cloaking and concentrating. Xu and Huang[28] designed a thermal metamaterial to actively tune and control the thermal wave conduction. Mao *et al.*[29] constructed a cylindrical concentrator for thermal waves and realized thermal conduction concentrating based on a coordinate transformation method, while the rotary function was not exhibited. Li and Zhang[30] studied concentration and rotation functions and designed a rotary-concentrating device, whose performances are compared with the traditional counterpart. Sun *et al.*[31] designed a device with interconnected structure can realize cloaking and concentrating for thermal conduction. Yang *et al.*[32] given a review of thermal metamaterials that contains theoretical developments, engineering applications, and experimental studies. Material parameters of most of traditional rotary-concentrating devices for thermal conduction are anisotropic and inhomogeneous, which are difficult to apply in engineering structures.

In this paper, multilayered isotropic material properties of the rotary-concentrating device are designed based on the transformation and rotary medium method and a rotation parameter is introduced to control the thermal diffusion process. The aim of this study is to construct a good rotary-concentrating device for thermal conduction in plates and to enrich the study of thermal conduction rotary-concentrating device.

This paper is organized as follows. After a brief introduction, a method to construct the rotary-concentrating device for thermal conduction in plates is proposed in Section 2. Effectiveness and performance of the current rotary-concentrating device for thermal conduction in plates are calculated in Section 3. Finally, some conclusions are presented in Section 4.

2. Design of rotary-concentrating device for thermal conduction

In this section, the coordinate transformation theory is applied to design the rotating and concentrating structure for thermal conduction in plates. There are two steps to construct the coordinate transformation expressions for rotating and concentrating of thermal conduction. Figure 1 shows the process of two coordinate transformations. In Fig. 1, a, b, and c are radii of three concentric cylinders. The first step is to compress the original spaces I and II in Fig. 1(a) to physical space I in Fig. 1(b), so that the device can focus the incident thermal energy to space I. The second step is to expand the remaining part of the original space, and to realize the spatial rotation of the region. The current rotator and concentrate device can be realized by two components r and θ independently transformed, which can be used to guide and tune thermal conduction in plates.

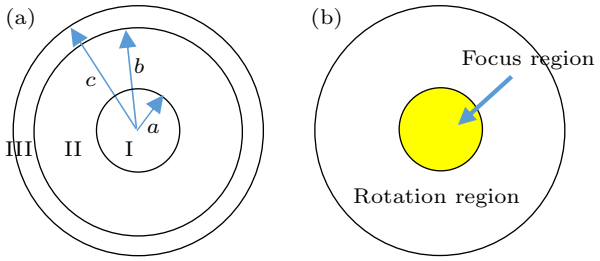


Fig. 1. Schematic diagram of a rotary-concentrating device: (a) before transformation and (b) after transformation.

Figure 1(b) shows how to compress regions I and II of the original space into region I in the transformation space, and the corresponding coordinate transformation equation is

$$\begin{cases} \tilde{r} = \dfrac{a}{b} r, \\ \tilde{\theta} = \theta, \end{cases} \tag{1}$$

where r and $\tilde{r}$ are radial components of polar coordinates in original and physical spaces, respectively. $\tilde{\theta}$ and θ are angular components of polar coordinates in original and physical spaces, respectively. The govern equation of thermal conduction for a plate in original space is

$$\rho_0 c_0 \frac{\partial T}{\partial t} = \nabla \cdot (\kappa_0 \cdot \nabla T), \tag{2}$$

where $Q_0 = \rho_0 c_0$ is heat capacity, in which c_0 and ρ_0 are the specific heat capacity distribution and the mass density distribution, respectively. T is the temperature field distribution and κ_0 is the thermal conductivity distribution. According to the principle of coordinate transformation[2] and by using of Eq. (1), the heat capacity and thermal conductivity distribution of compressed space can be calculated as

$$\kappa_{\mathrm{p}} = \kappa_{\mathrm{o}}, \tag{3}$$

$$\rho_{\mathrm{p}} c_{\mathrm{p}} = \rho_0 c_0 \left(\frac{b}{a}\right)^2, \tag{4}$$

where κ_{p}, ρ_{p}, and c_{p} are thermal conductivity distribution, mass density, and specific heat capacity distribution of compressed space, respectively. Figure 1(b) shows how to rotate region III of the original space by a rotation angle reflected in the transformation space, and the corresponding rotation coordinate transformation equation is

$$\begin{cases} \tilde{r} = \dfrac{c-a}{c-b} r + \dfrac{b-a}{b-c} c, \\ \tilde{\theta} = \theta + \dfrac{c-r}{c-b} \theta_0, \end{cases} \tag{5}$$

where θ_0 is the rotation angle and the value of angle that reflects deflection degree of thermal conduction transmitting trajectories. The Jacobian matrix has the following expression

$$\boldsymbol{B} = \begin{bmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{bmatrix}, \tag{6}$$

in which

$$B_{11} = \frac{c-a}{c-b} \cos\tilde{\theta} \cos\theta + \frac{\tilde{r}}{r} \sin\tilde{\theta} \sin\theta + \frac{\theta_0}{c-b} \tilde{r} \cos\theta \sin\tilde{\theta}, \tag{7a}$$

$$B_{12}=\frac{c-a}{c-b}\cos\tilde{\theta}\sin\theta-\frac{\tilde{r}}{r}\sin\tilde{\theta}\cos\theta+\frac{\theta_0}{c-b}\tilde{r}\sin\theta\sin\tilde{\theta}, \quad (7b)$$

$$B_{21}=\frac{c-a}{c-b}\sin\tilde{\theta}\cos\theta-\frac{\tilde{r}}{r}\cos\tilde{\theta}\sin\theta-\frac{\theta_0}{c-b}\tilde{r}\cos\theta\cos\tilde{\theta}, \quad (7c)$$

$$B_{22}=\frac{c-a}{c-b}\sin\tilde{\theta}\sin\theta+\frac{\tilde{r}}{r}\cos\tilde{\theta}\cos\theta-\frac{\theta_0}{c-b}\tilde{r}\sin\theta\cos\tilde{\theta}. \quad (7d)$$

The determinant of the matrix $\boldsymbol{B}$ is

$$\det(\boldsymbol{B})=\frac{c-a}{c-b}\frac{\tilde{r}}{r}. \quad (8)$$

In the Cartesian coordinates, the expressions of each component of the thermal conductivity distribution and mass density of the cylindrical rotary concentrating device can be obtained by applying the principle of transformation optics, yield

$$\kappa_{11}^{(\mathrm{p})}=\frac{1}{\det(\boldsymbol{B})}\left[\frac{\theta_0^2\tilde{r}^2}{(c-b)^2}+\left(\frac{c-a}{c-b}\right)^2\right]\cos^2(\tilde{\theta}+\varphi)+\frac{1}{\det(\boldsymbol{B})}\left(\frac{\tilde{r}}{r}\right)^2\sin^2\tilde{\theta}, \quad (9)$$

$$\kappa_{12}^{(\mathrm{p})}=\frac{1}{\det(\boldsymbol{B})}\left(\frac{\theta_0^2\tilde{r}^2}{(c-b)^2}+\left(\frac{c-a}{c-b}\right)^2-\left(\frac{\tilde{r}}{r}\right)^2\right)\sin\tilde{\theta}\cos\tilde{\theta}, \quad (10)$$

$$\kappa_{21}^{(\mathrm{p})}=\kappa_{11}^{(\mathrm{p})}, \quad (11)$$

$$\kappa_{22}^{(\mathrm{p})}=\frac{1}{\det(\boldsymbol{B})}\left[\frac{\theta_0^2\tilde{r}^2}{(c-b)^2}+\left(\frac{c-a}{c-b}\right)^2\right]\cos^2(\tilde{\theta}+\varphi_1)+\frac{1}{\det(\boldsymbol{B})}\left(\frac{\tilde{r}}{r}\right)^2\cos^2\tilde{\theta}, \quad (12)$$

where

$$\varphi=\arctan\frac{c-a}{\theta_0\tilde{r}}-\frac{\pi}{2},\quad \varphi_1=\arctan\frac{\theta_0\tilde{r}}{c-a}.$$

Thus, the radial and angular distribution of anisotropic thermal conductivity distribution and mass density of the rotary-concentrating device in the polar coordinates approximately can be expressed as

$$\kappa_{\mathrm{r}}=\left[1+\frac{\theta_0^2\tilde{r}^2}{(c-a)^2}\right]\left(1-\frac{(b-a)c}{(b-c)\tilde{r}}\right), \quad (13)$$

$$\kappa_\theta=\frac{(b-c)\tilde{r}}{(b-c)\tilde{r}-(b-a)c}, \quad (14)$$

$$\rho=\rho_0\left(\frac{c-b}{c-a}\right)^2\left(1-\frac{(b-a)c}{(b-c)\tilde{r}}\right). \quad (15)$$

The rotary-concentrating device designed by the approach of transformation has anisotropic thermodynamics parameters, which are unfavorable to engineering application. The effective medium theory is used in this paper to realize homogenization of materials. As shown in Fig. 2(b), materials 1 and 2 periodic arrangement constitutes a unit cell of the rotary-concentrating device. Thicknesses of materials 1 and 2 are l_1 and l_2. The rotary-concentrating device with alternating materials 1 and 2 has the following expressions:

$$\frac{1}{\kappa_{\mathrm{r}}}=\frac{1}{1+\varepsilon}\left(\frac{1}{\kappa_1}+\frac{\varepsilon}{\kappa_2}\right), \quad (16)$$

$$\kappa_\theta=\frac{\kappa_1+\varepsilon\kappa_2}{1+\varepsilon},\quad \rho=\frac{\rho_1+\varepsilon\rho_2}{1+\varepsilon}, \quad (17)$$

where $\varepsilon=l_2/l_1$ is the thickness ratio of layers 2 and 1, κ_1 and ρ_1 are stiffness tensor and mass density of material 1, and D_2 and ρ_2 are stiffness tensor and mass density of material 2. In this study, by using $\varepsilon=1$, material parameters of the rotary-concentrating device can be obtained as

$$\kappa_1(r)=\kappa_\theta+\sqrt{\kappa_\theta^2-\kappa_{\mathrm{r}}\kappa_\theta}=\frac{c-b}{c-a}\left(\frac{\tilde{r}}{r}+\sqrt{\left(\frac{\tilde{r}}{r}\right)^2-\frac{\theta_0^2\tilde{r}^2}{(c-b)^2}-\left(\frac{c-a}{c-b}\right)^2}\right), \quad (18)$$

$$\kappa_2(r)=\kappa_\theta-\sqrt{\kappa_\theta^2-\kappa_{\mathrm{r}}\kappa_\theta}=\frac{c-b}{c-a}\left(\frac{\tilde{r}}{r}-\sqrt{\left(\frac{\tilde{r}}{r}\right)^2-\frac{\theta_0^2\tilde{r}^2}{(c-b)^2}-\left(\frac{c-a}{c-b}\right)^2}\right), \quad (19)$$

$$\rho_1=\rho_2=\rho_0\frac{c-b}{c-a}\frac{r}{\tilde{r}}. \quad (20)$$

Many rules are adopted to evaluate concentrating quality of a rotary-concentrating device. Value of temperature variation ST[33] can reflect degree of thermal diffusion cloaking, which is also used in this paper to evaluate quality of a rotary-concentrating device:

$$ST=\sqrt{\sum_1^n(T_i-T_i^{\mathrm{o}})^2}, \quad (21)$$

where n is the total number of the points, T_i^{o} is the values of temperature in the plate with no rotary-concentrating device and inside medium, and T_i is values of temperature in the plate with a rotary-concentrating device contained an inside medium. The second parameter evaluates quality of the thermal concentrating, which can be expressed as

$$\zeta=\frac{\lfloor T_9-T_{10}\rfloor}{\lfloor T_1^{\mathrm{o}}-T_5^{\mathrm{o}}\rfloor}, \quad (22)$$

where T_9 and T_{10} denote values of temperature of points 9 and 10, respectively. T_1^{o} and T_5^{o} are values of temperature of points 1 and 5, respectively.

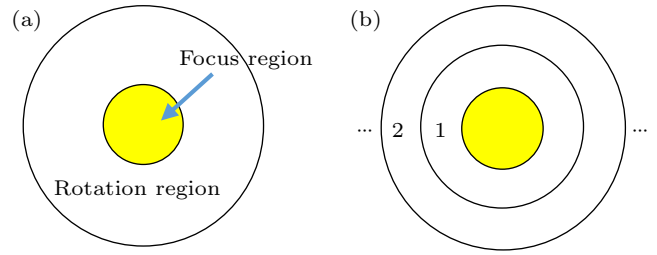


Fig. 2. (a) Computational schematic diagram of the rotary-concentrating device for thermal conduction in a plate. (b) Materials 1 and 2 periodic arrangement constitutes a unit cell of the rotary-concentrating device.

3. Rotary-concentrating performance of thermal conduction

A simulation example is first considered to verify reliability of the rotary-concentrating structure for thermal conduction. As shown in Fig. 3, an isotropic iron plate embedded with the current cylinder rotary-concentrating structure is constructed to control and guide thermal conduction; geometric parameters of the current device are $a = 0.01$ m, $b = 0.019$ m, $c = 0.02$ m, and $\theta_0 = \pi/6$. The rotary-concentrating device consists of 30 concentric cylinder whose material parameters can be calculated by Eqs. (18)–(20). Different heat diffusions are exerted on left and right boundaries of the computational domain to study performance of rotary-concentrating for the current device. In this study, the software COMSOL Multiphysics has been adopted to simulate the thermal conduction in elastic plates.

In order to demonstrate validity of the current device for manipulating thermal diffusion in elastic plates, one numerical case is considered. Processes of thermal conduction in the rotary-concentrating device calculated with different rotation angles and results shown in Fig. 4. As shown in Fig. 4, the current device is flexibility in guiding thermal diffusion in elastic plates by changing the value of rotation angles. Thus, the current method for thermal conduction can be effectively used to design rotary-concentrating device in elastic plates.

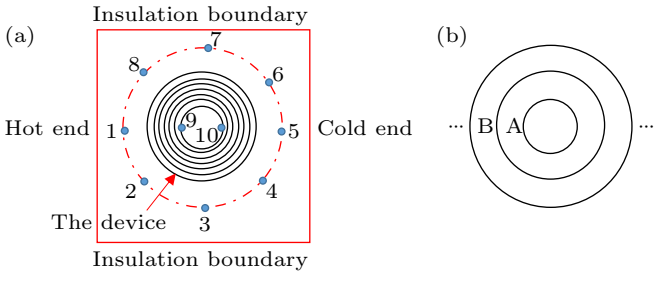


Fig. 3. (a) Computational schematic diagram of the thermal rotary-concentrating device. (b) A cell of the current device in panel (a) is consisted of two layers of materials A and B.

Distributions of temperature field for the plate are calculated with the rotary-concentrating device exerted by heat diffusion from the left boundary to right boundary of the iron plate and results shown in Fig. 5(a), where temperatures of cold and hot boundaries are 300 K and 650 K, respectively and material parameters of the iron plate are $\rho_o = 7850$ kg/m^3, heat capacity $c_0 = 0.46 \times 10^3$ J/(kg·K) and thermal conductivity $\kappa_0 = 80$ W/(m·K). Distributions of temperature field for the plate are calculated with the rotary-concentrating device exerted by heat diffusion from the left and upper boundaries to right and lower boundaries of the iron plate and results shown in Fig. 5(c). Temperature field distribution of the iron plate without the rotary-concentrating device also be calculated by a purpose of comparison with results shown in Figs. 5(b) and 5(d). As shown in Fig. 4, the current device can realize the cloaking performance and shield heat conduction from outside the rotary-concentrating device. One can also find that heat diffusion into the rotary-concentrating device from the surrounding area under different conditions of heat diffusion. This property possessed by the current device that can be used to focus heat diffusion, so that realize heat harvesting in a plate. Furthermore, the diffusion process of heat in rotary area in the current device can be controlled and tuned by varying the value of rotary angle.

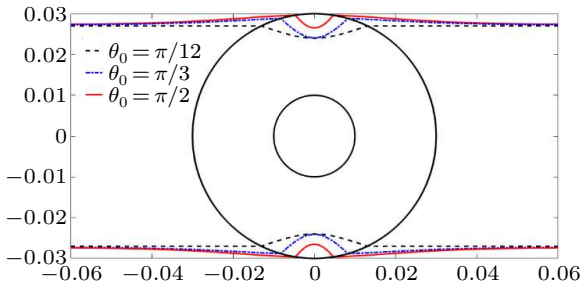


Fig. 4. The processes of the thermal conduction in the cylindrical rotary-concentrating device with different rotation angles.

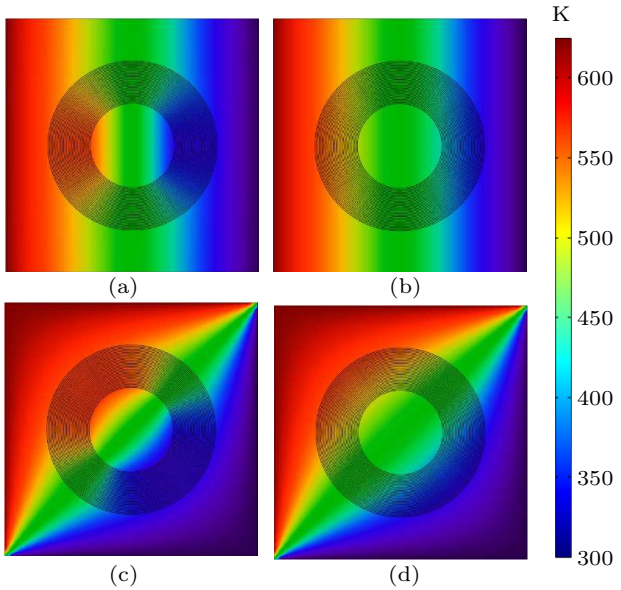


Fig. 5. Temperature field distributions of the plate exerted by diffusion from left to right: (a) with the current rotary-concentrating device, (b) without rotary-concentrating device; from left and upper to right and lower boundaries (c) with the current rotary-concentrating device, and (d) without current rotary-concentrating device, respectively.

The value of temperature variation *ST* is adopted to appraise quality of the rotary-concentrating device and its val-

ues with and without the current rotary-concentrating device are shown in Fig. 6. As the temperature T of thermal diffusion of the hot boundary increases in Fig. 6, the value of temperature variation ST for the plate with the current rotary-concentrating device is much lower than that without the device, which demonstrates that there is much less thermal energy radiation outside the current rotary-concentrating device. A good rotary-concentrating device has much less thermal energy scattering outside the concentrating region over a broad range of diffusion temperatures. The value of ζ is adopted to appraise quality of concentrating and its values with the current rotary-concentrating device are shown in Fig. 7. As shown in Fig. 7, the concentrating efficiency of the current device almost remains 90% as the temperature T of the thermal diffusion of the hot boundary increases. Thus, the proposed rotary-concentrating device for thermal conduction in the plate can shield thermal wave detection from outside background and also concentrating thermal energy into the device.

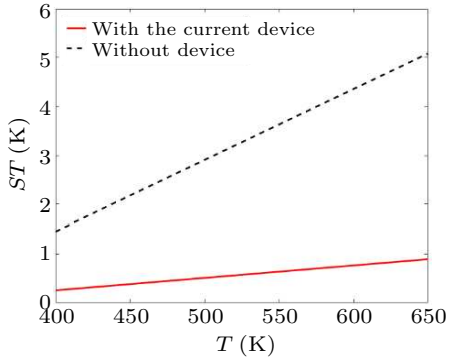


Fig. 6. The parameter ST of the iron plate with and without the current rotary-concentrating device under different thermal diffusion temperatures.

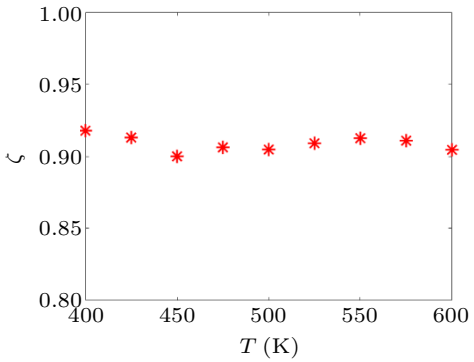


Fig. 7. The parameter ζ of the iron plate with the current rotary-concentrating device under different thermal diffusion temperatures.

To verify effectiveness of the current rotary-concentrating device for different rotation angles, isothermal diagrams of the plates are calculated with the rotary-concentrating device exerted by a heat diffusion from the left boundary to right boundary with different rotation angles $\theta_0 = \pi/12$, $\pi/6$, $\pi/3$, and $\pi/2$ and results are shown in Fig. 8. The geometric and material parameters used here are the same as the above. As shown in Fig. 8, the current rotary-concentrating device also can be realized control of the process of thermal conduction in a plate and concentrating of thermal wave energy under different thermal diffusions. Thus, the current method can be used to design a rotary-concentrating device for thermal conduction in a plate.

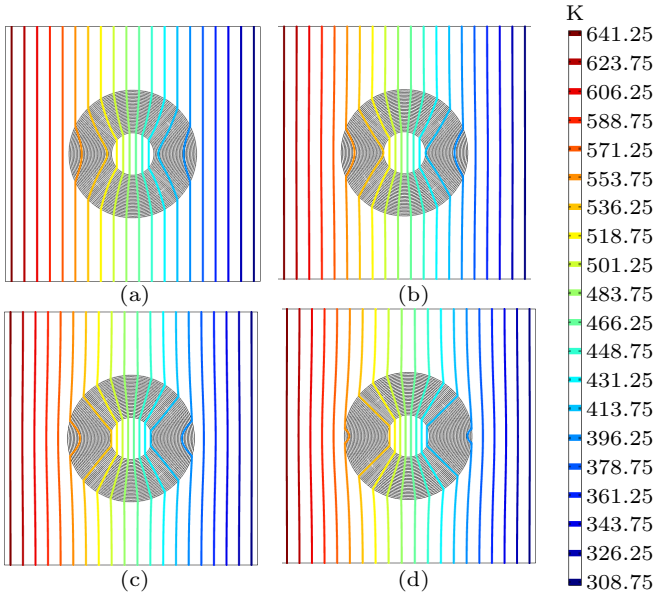


Fig. 8. Contours of temperature field distributions for the rotary-concentrating device with (a) $\theta_0 = \pi/12$, (b) $\theta_0 = \pi/6$, (c) $\theta_0 = \pi/3$, and (d) $\theta_0 = \pi/2$, respectively.

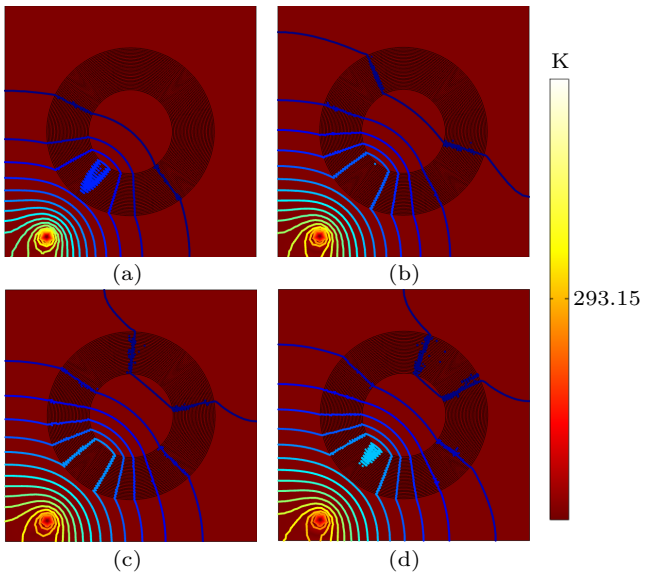


Fig. 9. Isothermal diagrams of the plates with the rotary-concentrating device at different time scales: (a) $T = 10$ s, (b) $T = 20$ s, (c) $T = 30$ s, and (d) $T = 40$ s.

Studies about thermal conduction above is carried out in steady state, that is, the temperature distribution of the structure is going a period of time. However, the thermal conduction is transient and eventually reaches a stable state over time. Isothermal diagrams of the plates with the current rotary-concentrating device exerted by a point thermal diffusion at $(-0.02$ m, -0.025 m) are calculated at different time scales and shown in Figs. 9(a)–9(d). Geometric and material parameters of the plate are the same as those in Fig. 4. As shown in

Fig. 9, the current rotary-concentrating device can also effective to realize rotary and concentrating for thermal conduction under a point thermal diffusion.

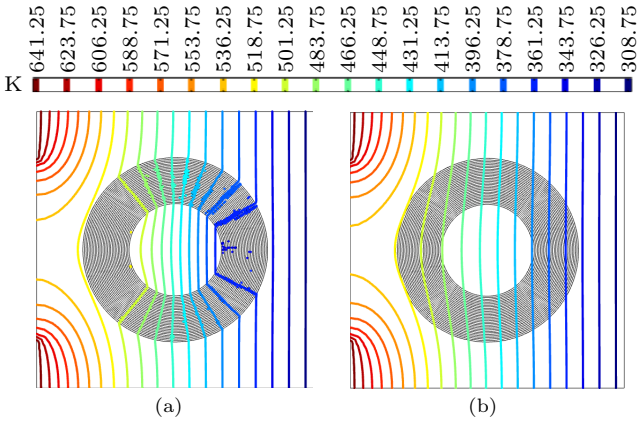


Fig. 10. Temperature fields of the plate exerted by two line thermal diffusion sources (a) with and (b) without the rotary-concentrating device.

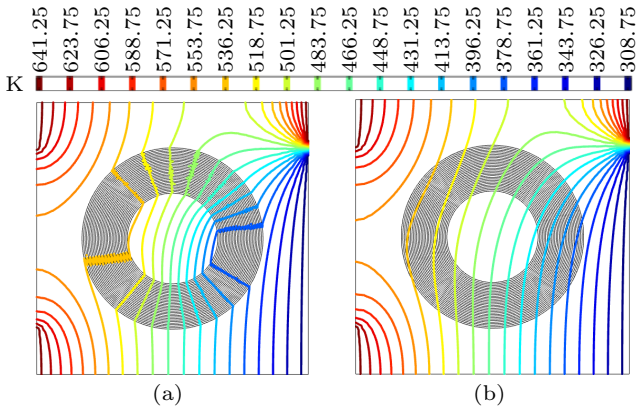


Fig. 11. Temperature fields of the plate exerted by three line thermal diffusion sources (a) with and (b) without the rotary-concentrating device.

Temperature field distributions of the plate with rotary-concentrating device exerted by two or three independent line thermal diffusion resources are computed to study stability of the current rotary-concentrating device for thermal conduction. The line thermal diffusion sources are located at ($x = -0.03$ m, 0.02 m $\leq y \leq 0.03$ m), ($x = -0.03$ m, -0.03 m $\leq y \leq -0.02$ m), and ($x = 0.03$ m, 0.02 m $\leq y \leq 0.03$ m), where temperatures of cold and hot boundaries are 300 K and 650 K. The other geometric and material parameters are the same with Fig. 4. In Fig. 10, temperature fields of external area of the rotary-concentrating device are the same with that of without the current device, which demonstrates that the rotary-concentrating device can realize cloaking of thermal conduction. Furthermore, temperature fields inside the rotary-concentrating device are rotated and concentrated, which demonstrates that the rotary-concentrating device can realize rotary and concentrating of thermal conduction. Such behaviors can also be observed in Fig. 11. Therefore, temperature fields in the plate with the current rotary-concentrating device are stability encounter interference of different types of thermal diffusion, which obtains an excellent rotary and concentrating effect for thermal conduction.

4. Conclusion

A rotary-concentrating device is constructed to control and guide processes of thermal conduction in elastic plates. The anisotropic thermodynamic parameters of the rotary-concentrating device are homogenized to multilayered isotropic materials based on the transformation and rotary medium method and a rotation parameter is introduced to guide processes of thermal conduction. Results shown that the current rotary-concentrating device exhibits on both rotation and concentrating properties. For different interference forms, temperature fields of the plate with the rotary-concentrating device are undisturbed, which demonstrates that a good rotary-concentrating device for thermal conduction is constructed. Accurate guide of thermal conduction processes in plates under different types of thermal diffusion sources inside the rotary-concentrating device is confirmed. Our approach provides an alternative means for rotating and concentrating thermal conduction, which has potential applications in fields of energy harvesting and thermal conduction control.

Acknowledgments

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