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Thermal expander

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ABSTRACT

One type of thermal device, named as thermal expander, is proposed and verified through both simulation and experiment. The thermal expander performs an efficient way to expand a heat flow of line-shape front. Moreover, the thermal expander shows an advantage in rectifying a heat flow from crooked front to line-shape front, which indicates that the thermal expander could act as an efficient point-to-line heat source convertor. We suggest that the thermal expander would be of help to energy saving and emission reduction, especially in thermal circuits and thermal management.

1. Introduction

As one of the fundamental energy transport phenomena in nature, heat flow automatically balances the thermal distribution around us [1]. Unfortunately, although people have realized that the ability to precisely control heat conduction will lead to an abundant wealth of applications (for example, thermal computation [2] and thermal memory [3]), heat flow management is still in its infancy [4–6]. To date, many interesting thermal devices (such as thermal rectifiers [6,7], thermal diodes [8–12], thermal cloaks [12–23], and so on [2,20,24–29]) have been proposed for the purpose of taming heat flow.

In experiments, these thermal devices are usually demonstrated with large scale heat flows of line-shape front (described by the shape of isothermal line) [12,15–18,20]. In order to realize a large heat flow of line-shape front, a heat source which is much larger than the sample size is always adopted [12,15,16]. Obviously, this method is not so efficient for the purpose of energy saving and emission reduction. Then comes a question: could we efficiently realize a large heat flow of line-shape front with a small heat source (heat flow) or even a point heat source?

Here, we propose a two-component thermal device, named as thermal expander. The thermal expander is realized by matching the thermal conductivities and geometries of two materials with a constraint condition. The thermal expander performs an efficient way to expand the heat flow of line-shape front, which is demonstrated through both simulation and experiment. Moreover, the thermal expander shows an advantage in rectifying a heat flow from crooked front to line-shape front, which is also verified by simulation and experiment. We suggest that the thermal expander would be of help to energy saving and emission reduction, especially in thermal circuits and thermal management.

2. Theory

The thermal expander, schematically illustrated by red dashed lines in Fig. 1a, is composed of two symmetrical quarter rings (Material I) with the same inner radius R_1 and outer radius R_2 and with the thermal conductivity of κ_1. The thermal conductivity of the connection (Material II) area between two quarter rings is κ_2.

The condition for the efficient expanding effect of thermal expander on a heat flow of line-shape front is easy to figure out as: the front of heat flow on the end-position of the thermal expander (as indicated by red-arrow in Fig. 1b and 1c, respectively) must still be line-shape. To satisfy this condition, the front of heat flow in the area of Material II is kept to be line-shape (as shown in Fig. 1b). Therefore, the conduction equation should hold the form as the one dimensional Laplace equation (temperature distributions is a linear function of positions), that is, the shape of the material must have no effect on temperature distribution. Without loss of generality, for a polar coordinate system (r, θ), considering two-dimensional thermal conduction equation for the steady state without the heat source and suppose all the materials involved are homogenous and isotropic, the dominant equation can be written as

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 T}{\partial \theta^2} = 0, \tag{1}$$

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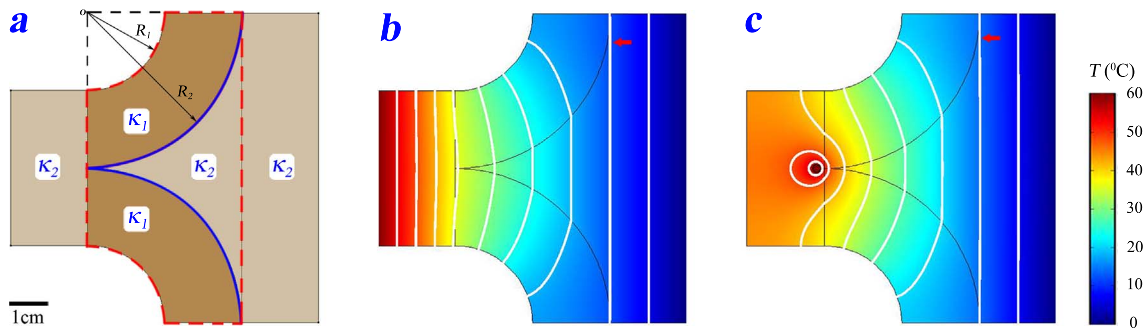

Fig. 1. (a) Schematic diagram of a thermal expander (area depicted by red dashed curves). Blue curves denote the boundaries between regions with thermal conductivities κ_1 and κ_2 (respectively). (b) Simulated expanding effect of thermal expander on a heat flow of line-shape front. (c) Simulated result of a heat flow of crooked front rectified to be of line-shape front by thermal expander. The point heat source is of diameter 2.2 mm. The black curves in (b) and (c) depict the structure and location of thermal expander. The white curves are isothermal lines (with steps of 6 °C for (b) and 6.9 °C for (c)) corresponding to the color legend. Each isothermal line arrowed describes the shape of flow front on the end-position of thermal expander. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

where, T is the temperature distributions in the space. Since the upper and lower parts of the thermal expander are symmetric, the general solutions can be obtained as

$$T_i = \sum_{n=1}^{\infty} [A_{2n-1}^{i} r^{2n-1} + B_{2n-1}^{i} r^{-(2n-1)}]\cos(2n-1)\theta, \tag{2}$$

where, A_{2n-1}^{i} and B_{2n-1}^{i} are constants determined by the boundary conditions, and T_i is the temperature potential in different regions (i = 1, 2). As to the thermal expander shown in Fig. 1a, i = 1 denotes the quarter ring areas ($R_1 < r < R_2$), and i = 2 denotes the connection area ($r > R_2$). Taking account of the continuities of the temperature potential and heat flow across the different interfaces, the boundary conditions are listed as

$$T_1|_{r=R_2} = T_2|_{r=R_2},$$
$$\kappa_1 \frac{\partial T_1}{\partial r}\bigg|_{r=R_2} = \kappa_2 \frac{\partial T_2}{\partial r}\bigg|_{r=R_2},$$
$$\kappa_1 \frac{\partial T_1}{\partial r}\bigg|_{r=R_1} = 0. \tag{3}$$

Moreover, without being specified, the outer boundaries of the whole system are all set as insulated.

In order to eliminate the distortion caused by the shape of the device, only the first order factors in solutions are valid and we also must ensure $B_1^2 = 0$. Thus the required relationship of conductivities and shape parameters is finally derived to be

$$\frac{\kappa_1}{\kappa_2} = \frac{R_2^2 + R_1^2}{R_2^2 - R_1^2}. \tag{4}$$

For further discussion, the material of extension background (areas outside the red dashed lines) is also chosen to be Material II of κ_2 for simplicity.

3. Simulation and experiment

In this study, the Material I in the areas of two quarter rings is chosen to be Copper with thermal conductivity of 400 W·(m·K)$^{-1}$. The inner and outer radiuses are set to be R_1 = 2 cm and R_2 = 4 cm, respectively. Then the thermal conductivity κ_2 of Material II in the connection and extension areas is calculated from Eq. (4) to be 240 W·(m·K)$^{-1}$.

Fig. 1b performs the simulated (*Comsol*) expanding effect of the thermal expander on a heat flow of line-shape front. The front of heat flow keeps line-shape in the connection area and also on the end-position of thermal expander, which verifies that the Eq. (4) is valid.

Interestingly, the simulation shown in Fig. 1c infers that the thermal expander could also efficiently rectify a crooked heat flow to be a line-shape one. As the crooked heat flow is from a point heat source, Fig. 1c also indicates that the thermal expander could act as a point-to-line heat source convertor.

For experimental demonstration of the thermal expander, the samples are fabricated on a homogeneous copper plate with thickness 0.1 mm. To obtain the thermal conductivity κ_2 of Material II, the effective medium approach [30] is adopted. As shown in Fig. 2, holes filled with Polydimethylsiloxane (PDMS) are hexagonally placed in the area of Material II with a lattice constant 4 mm. The corresponding thermal conductivity of PDMS is 0.15 W (m K)$^{-1}$. The holes are achieved through wet-etching method [31]. The volume fraction f of hole is calculated from the Bruggeman formula [32].

$$(1-f)\frac{\kappa_{Cu} - \kappa_2}{\kappa_{Cu} + 2\kappa_2} + f\frac{\kappa_{PDMS} - \kappa_2}{\kappa_{PDMS} - 2\kappa_2} = 0. \tag{5}$$

Then the diameter of each hole is realized to be 2.2 mm.

A thin film (about 0.1 mm thick) PDMS is also deposited on the surface of each sample ro reduce the heat conduction and convection by air [16]. This PDMS film could also minimize the influence of high reflection by copper surface on the experimental observation [16]. The thermal distribution of each sample is then observed through a *FlirE*60 infrared camera. For comparison, a referenced samples is also fabricated by replacing the thermal expander with a copper plate, while the extension background is kept the same. Illustrations for the referenced sample could be found in Fig. 3b.

The expanding effects of these designed samples are first verified by simulation. Results are shown in Figs. 3a and 3b. For experiments, the

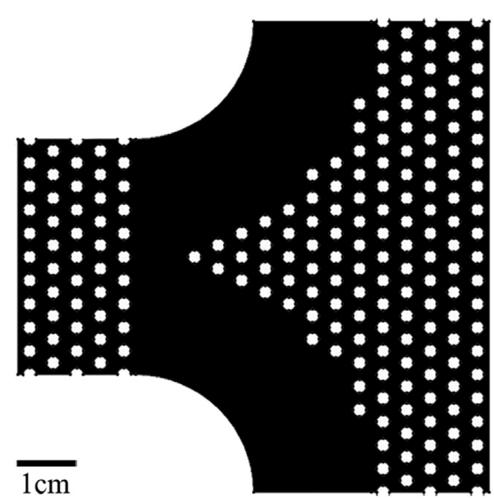

Fig. 2. Blueprint of the designed thermal expander for experiment. The black regions are copper and the white regions are PDMS with thermal conductivities of 400 and 0.15 W·(m·K)$^{-1}$, respectively. The white holes are of diameter 2.2 mm and hexagonally placed with a lattice constant 4 mm.