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A Heat Flux Optimization Method of Illusion Thermal Device for Location Camouflage

Anqi Zou, Qiuwang Wang, Cunlu Zhao*

Key Laboratory of Thermo-Fluid Science and Engineering of MOE, School of Energy and Power Engineering，Xi’an Jiaotong University, Xi’an 710049, China
mclzhao@xjtu.edu.cn

Based on the development of thermal metamaterials, numerous novel heat devices were reported to realize the continuously increasing demands in the field of thermal management. In this paper, we proposed an efficient optimization method for the design of illusion thermal device which can provide an artificial signal of heat source for devices to conceal the real ones. The key for the reported optimization method is a model of heat flux manipulation formulated according to the topology optimization. With the formulated model, we realize the design of illusion thermal devices in a typical condition. Besides, a kind of double-layer device are proposed to realize more flexible location camouflage of heat source. Compared with the traditional methods, the new design method is suited for more flexible shapes and distances of artificial heat sources, and has a better adaptability in the broad field of heat flux manipulation.

1. Introduction

Heat flux is an important concept in traditional heat transfer field (Guo et al., 2019). Recently, the development of transformation thermodynamics has provided novel perspectives and methods for heat flux control. Based on this concept, a series of illusion thermal devices are designed. It is a kind of device which provide artificial signals to conceal the original ones, can protect the devices from being detected and ensure the security of devices in the battle field. For example, Xu et al. (2014) have experimentally realized a thermal cloak which can shield an air bubble in a bulk metal without distortion in the external thermal flux. Han et al. (2014) has made use of a bilayer cloak to disguise the arbitrary thermal scattering signature as multiple expected objects. Chen et al. (2015) fabricated an illusion device making use of lead, steel, aluminum, and copper to disguise a good thermal conductor as a poor one. Yang et al. (2016) has reported a theory about transition-state thermal camouflage which realize a thermal camouflaging device with better performance. More recently, Dede et al. (2018) has introduced topology optimization into the thermal cloak design, which provide a new framework for the realization of transformation thermodynamics. It seems that most of these devices are concentrated on thermal invisible cloak, heat flux reverser and heat flux concentrator which have been widely researched under different conditions.

The illusion thermal devices mentioned above can only hide some signature about material and structure in certain thermal field, and cannot conceal or disguise the real heat source. Even though heat flux concentrators can focus the heat flux into a narrow region or heat flux reversers can reserve the direction of heat flux to some extent, the heat source still has the highest temperature in the whole field and can be detectable. The method of hiding/disguising real heat source is needed for some practical occasion. Specially, to conceal real heat source, Hou et al. (2016) have designed an illusion thermal device with one homogeneous material. They drilled holes with different structure in a steel plane to realize the anisotropic thermal conductivity. And the thermal conductivity at each point was calculated by means of coordinate transformation. Similar method has also been used by Hu et al. (2018) who split the original real heat source into multi-location illusion heat sources. This makes the real source difficult to be detected by infrared cameras because of multiple artificial heat sources around the real one. Yet, the coordinate transformation calculation adopted by these studies for designing illusion thermal devices is mathematically complicated and only applicable to simple geometries. The designed

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thermal conductivities from this approach are normally in a wide and continuous range and varying in different directions, which add difficulties in manufacturing corresponding metamaterials from homogeneous natural materials. As a result, an efficient design method with better manufacturability of metamaterials is needed.

Nowadays, topology optimization is believed to be an advanced non-intuitive design method with a high degree of freedom, which shows a good compatibility with the heat flux manipulation (Guo et al., 2020). Although state-of-the-art investigations use it to design thermal cloak, it also has good potential in heat source camouflage. To pursue a more efficient and manufacturable design method of heat source camouflage, in this paper, a kind of illusion thermal device for heat source camouflage is designed by means of topology optimization method. For the convenience of optimization formulation and good manufacturability, a kind of composite metamaterial with insulating matrix and conductive inclusion is introduced. The anisotropic conductivity of the metamaterial in each unit is determined by the angle of conductive inclusion in the insulating matrix. By optimizing the angle distribution of conductive inclusion, the metamaterial which can rearrange the temperature field and artificially relocate the real heat source can be designed.

This paper is organized as follows. Firstly, a metamaterial composed of the conductive inclusion material and the insulating matrix material is introduced. Based on the metamaterial, a topology optimization method is formulated to find the optimal distribution of the angle field of inclusion material. Then, a typical illusion thermal device is designed by this optimization method and the distribution of material is exported in post-process for the convenience of manufacture. In order to achieve a more separated artificial heat sources which are harder to be detected, a double layer method is furtherly proposed. Compared with the traditional methods, the new optimization method is not only suited for more flexible shapes and distances of artificial heat sources, but also increases the efficiency of design process, having a high potential for designing new metamaterials for the heat flux manipulation. The heat flux manipulation not only can apply to location camouflage of heat source, but also has broad applications in the energy saving, e.g., in waste heat recovery field where the heat flux can be focused to the thermoelectric device by metamaterials to generate more electricity.

2. Formulation

2.1 Metamaterial

Metamaterial used in this paper is regularly composed of insulating matrix material and conductive inclusion material. As shown in Figure 1, each unit of matrix material is populated with a conductive rectangular inclusion. And the thermal conductivity of each unit is function of the inclusion angle α. For a 2D problem, the conductivity of metamaterial can be assumed as a symmetric second rank tensor:

$$\begin{bmatrix} K_{11} & K_{12} \\ K_{21} & K_{22} \end{bmatrix} \tag{1}$$

$$K_{ij}=K_{ji},\ \ i,j=1,2 \tag{2}$$

Where K_{11} and K_{22} represent conductivity in the x and y directions individually and they vary between the maximum and minimum conductivity of this metamaterial.

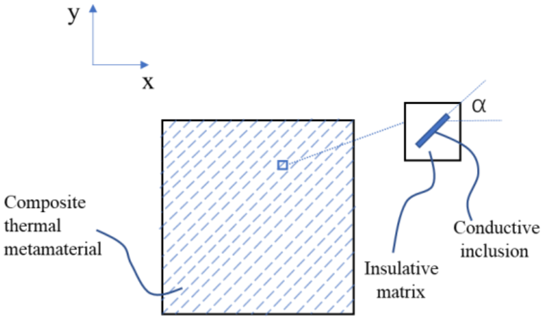

Figure 1: Metamaterial composed of insulating matrix and conductive inclusion

The maximum and minimum conductivity is determined by the conductivities of matrix and inclusion, as reported by Dede (2010). The conductivity parallel or vertical to the inclusion is:

$$k_{11}=v\cdot k_i+(1-v)\cdot k_m \tag{3}$$

$$k_{22}=\left(\frac{v}{k_i}+\frac{(1-v)}{k_m}\right)^{-1} \tag{4}$$

Where, k_i means the inclusion conductivity, k_m means the matrix conductivity and v is the volume fraction of inclusion. As the inclusion with an arbitrary angle α, the conductivity of this unit in different directions can be defined by the following equations:

$$K_{11}=k_{11}\cdot\cos^2(\alpha)+k_{22}\cdot\sin^2(\alpha) \tag{5}$$

$$K_{22}=k_{11}\cdot\sin^2(\alpha)+k_{22}\cdot\cos^2(\alpha) \tag{6}$$

$$K_{12}=(k_{11}-k_{22})\cdot\sin(\alpha)\cdot\cos(\alpha) \tag{7}$$

In Eqs (5) to (7), the variable α is function of γ, defined as $\alpha = \gamma^{\,p}\cdot\pi$, where γ is global variable in topology optimization with a range between 0 and 1. While γ is equal to 0, corresponding inclusion angle α is equal to 0°and while γ with value of 1, corresponding inclusion angle α is equal to 180°. By optimizing γ field, the optimal distribution of angle α can be found to realize the artificial heat source. And p is the penalization parameter which influences the optimized result of γ.

2.2 Topology optimization

As the illusion thermal device relates to steady state physical model, the governing equation for optimization is typical Fourier equation:

$$-\nabla\, k\nabla\, T=Q \tag{8}$$

where k is the conductivity tensor of material which is shown as Eq (1) and Q is the heat source. The topology optimization can be described as:

$$\begin{aligned} &\text{Maximize.} && f(\gamma)\\ &\text{Subject to.} && \text{Eqs(1)-(8)}\\ &&& \alpha=\gamma^{\,p}\cdot\pi\\ &&& 0<\gamma<1 \end{aligned} \tag{9}$$

$f(\gamma)$ is the objective of optimization. In this paper, $f(\gamma)$ can be written as the difference between temperature integrated in region of illusion heat source and real heat source:

$$f(\gamma)=A_1\int_{S_1} T\,dS - A_2\int_{S_2} T\,dS \tag{10}$$

where, S_1 is the area of artificial heat source and S_2 is the area of real heat source, A_1 and A_2 represent the weight of integral temperature in different heat source regions, which are used to control the results of optimization. While the temperature in a region is higher than the temperature of original heat source, this region will become a visual heat source instead.

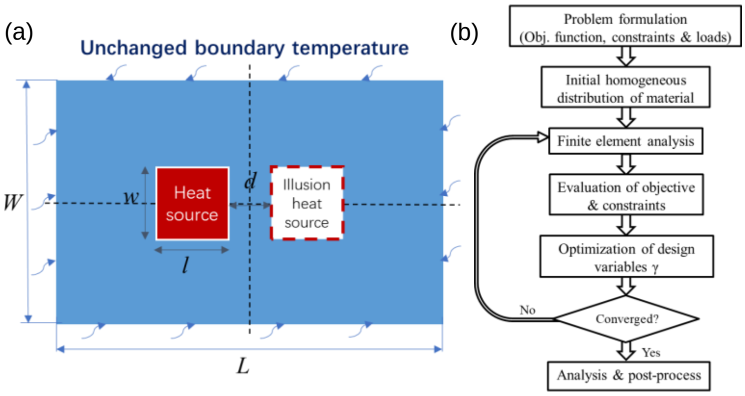

Figure 2: (a) 2D topology optimization domain with fixed boundary temperature; (b) Topology optimization process

In this work, geometry parameters shown in Figure 2(a) are defined as: L=W=0.2 m, l=w=0.04 m and d=0 m. When it comes to material properties, set the inclusion conductivity k_i as 300 $\mathrm{W/(m \cdot K)}$, the matrix conductivity k_m as 0.1 $\mathrm{W/(m \cdot K)}$ and the volume fraction v as 0.16. Optimization procedure is implemented in a commercial software COMSOL Multiphysics based on finite element analysis. The whole process of topology optimization is shown in Figure 2(b). Heat transfer model in this work is a steady-state heat conduction model calculated by Heat Transfer in Solids Module with constant temperature boundary conditions as 293 K and heat source of $10^6\ \mathrm{W/m^3}$. Topology optimization is carried out in Optimization Module with an initial homogeneous γ value of 0.5 and a gradient-based MMA optimizer is chosen for its efficiency and stability. Penalization parameter p is set as 1, and the weights of objective are set as A_1=1, A_2=3. The parameters used are shown as Table 1.

Table 1: Optimization parameters

Parameter	Unit	Value	Parameter	Unit	Value
L	[m]	0.2	k_i	$[\mathrm{W/(m \cdot K)}]$	300
W	[m]	0.2	k_m	$[\mathrm{W/(m \cdot K)}]$	0.1
l	[m]	0.04	v	[-]	0.16
w	[m]	0.04	Q	$[\mathrm{W/m^3}]$	10^6
d	[m]	0	A_1	[-]	1
p	[-]	1	A_2	[-]	3

3. Results and discussion

As shown in Figure 3(a), there is an isotropic plane with heat source originally located at left of the line where x=0.1 m. Thermal gradient of the original heat source is relatively low in different directions. In order to conceal the left heat source, a planar illusion thermal device is designed by topology optimization method mentioned above. As a result, a typical field of optimization variable γ is demonstrated in Figure 3(d) which reflects the rotation angle α of inclusion material. How to transfer the γ field into α field will be discussed later. After being covered by the illusion thermal devices, Figure 3(c) shows an artificial heat source at right of the line where x=0.1 m. As the non-homogeneous distribution of metamaterial, thermal gradient of this artificial source turn to be larger horizontally and be lower vertically. Furtherly, the temperature profile along the horizontal central line of both (a) and (c) are demonstrated in Figure 3(b). It shows that with the illusion device, the maximum temperature of the artificial heat source is around 60 K higher than that of the real heat source. Unlike the original source with smooth profile like a mountain peak, the artificial one faces sharp increase and decrease at its edge, and keep a constantly highest temperature at around 450 K between x = 0.1 m and x = 0.5 m.

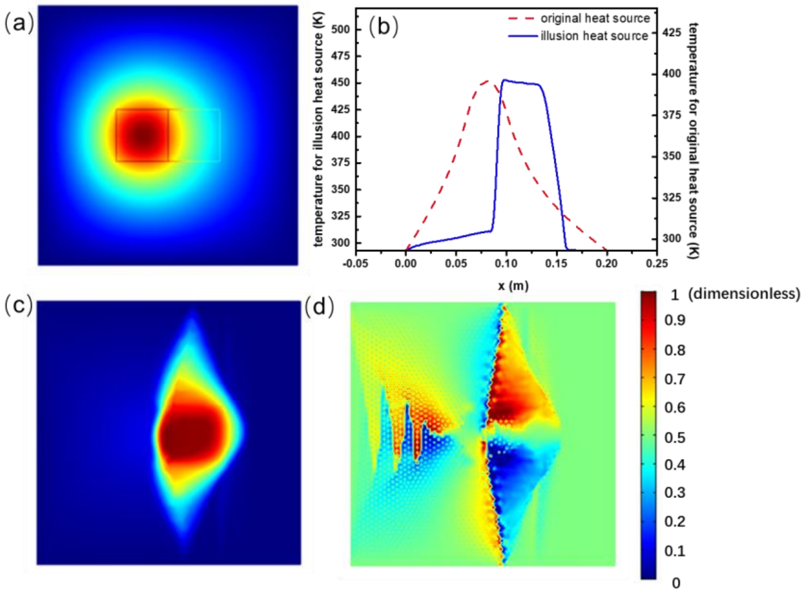

Figure 3: Optimized temperature profiles (a) without and (c) with thermal illusion devices; (b) Temperatures at the central line parallel to x axis; (d) Distribution of design variable γ, which suggests the rotation angle α of inclusion material

Although Figure 3(d), shows the optimized γ field of the illusion thermal device, it is hard to gain the distribution of metamaterials directly. Figure 4 (a) furtherly describes how to transfer γ field into corresponding metamaterial distribution. In the post-process, create an arrow-surface with x component of $\cos(\alpha)$ and y component of $\sin(\alpha)$, then the rotation of inclusion in each unit can be directly shown referring to its value of γ. It is clear that, angle α will change from 0 ° to 180 ° with corresponding γ from 0 to 1. As the inclusion material always owns symmetry structure like rectangle, the angle range of 0 °-180 ° can describe all the possibility of the composite material. The real distribution of material is shown as Figure4(b) from which we can extract some typical arrangements which contribute to control heat flux. In Figure 4(c), top arrangement alternates inclusion material with opposite angle. This arrangement corresponds γ field alternates red and blue color. Locating at left of the original heat source, it is responsible for impeding heat flux and keeping higher temperature at right. In the bottom arrangement, inclusion materials arrange like a series of curves located upon or under the artificial heat source. This type can focus heat flux on the central region. These two types of arrangement not only contribute to this illusion thermal device, but also can be used in other heat flux control field. Once the field of α is exported, it is easy to manufacture this kind of illusion device by 3D printing method.

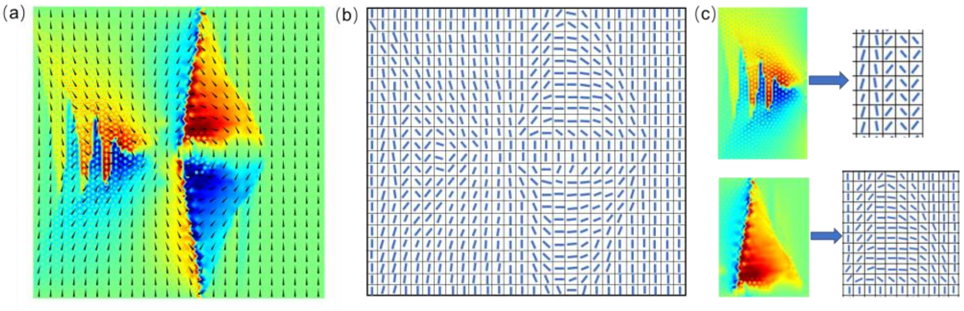

Figure 4: (a) Diagram of α field compared with corresponding γ field; (b) Distribution of metamaterial; (c)Typical metamaterial distribution

Sometimes, just one artificial heat sources may still be easy to detected. Multi-target artificial heat source is reported in Figure 5(b) where two artificial heat sources are located on the different side of the original one. And the temperature profiles along the horizontal central line of both original source and artificial heat source are demonstrated in Figure 5(c). It shows a similar larger thermal gradient in the illusion heat source profile. The changes of temperature gradient make the unclear edge between illusion and original heat source and the artificial heat sources are close to the real one, which make the real one easy to be detected. It may stem from that the objective of topology optimization cannot satisfy the need of artificial heat source perfectly like human design.

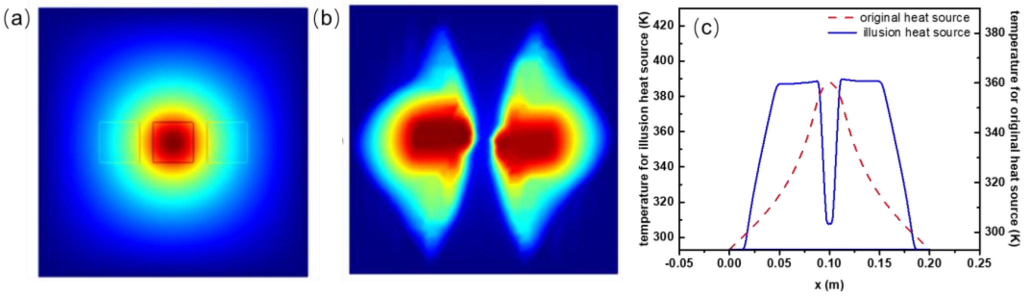

Figure 5: (a) Temperature profile of original heat source in a homogeneous plane; (b) Temperature profiles with multi-artificial heat source; (c) Temperatures at the central line parallel to x axis

In order to realize a more flexible artificial heat source which is far from the original heat source, double heat flux control layers can be used. That is, the plane with heat source like Figure 5(a) is firstly covered an illusion thermal device which decrease the thermal gradient in the whole plane. Then, a second illusion thermal device is used to cover on them to create the artificial heat source. Figure 6(a) shows the temperature profile on the second illusion thermal device with clearly separated two artificial heat sources.

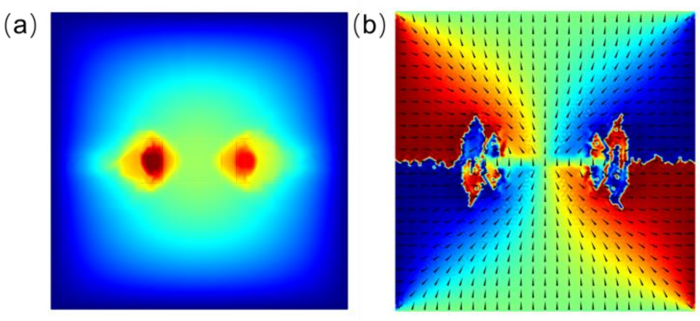

Figure 6: (a) Temperature profile of separated two artificial heat sources; (b) Diagram of α field compared with corresponding γ field

4. Conclusion

In this paper, a topology optimization method for thermal illusion device design is introduced. This method manipulates the heat flux on a plane by optimizing the distribution of composite metamaterial. Some artificial heat sources are manipulated to conceal the real one from being detected. Different from the original heat source, artificial heat source shows large thermal gradient. Its thermal profile changes and maximum temperature suffers an acceptable increase. The typical thermal illusion device suffers unclear edge to the real heat source, which reduces the usefulness of this method. A double-layer thermal illusion device is provided to eliminate such drawback. The final distribution of metamaterial can be easily exported for reconstruction and fabrication by 3D printing method. In summary, this work makes use of topology optimization to design illusion thermal device for location camouflage suitable for more flexible shapes and distances of artificial heat sources, can be a useful reference in the broad field of heat flux manipulation.

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