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Exploring the proper experimental conditions in 2D thermal cloaking demonstration

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Abstract
Although thermal cloak has been studied extensively, the specific discussions on the proper experimental conditions to successfully observe the thermal cloaking effect are lacking. In this study, we focus on exploring the proper experimental conditions for 2D thermal cloaking demonstration. A mathematical model is established and detailed discussions are presented based on the model. The proper experimental conditions are suggested and verified with finite element simulations.

Keywords: thermal cloaking, experimental condition, heat conduction, heat convection

S Online supplementary data available from stacks.iop.org/JPhysD/49/415302/mmedia

(Some figures may appear in colour only in the online journal)

Introduction

Inspired by the optical invisible cloak, a thermal cloak, which can steer the heat flux around an object without disturbing the outside temperature distribution, and may be used in thermal protection and sensing, has attracted considerable attention recently [1–9]. Similar to thermal cloaking, many new heat-transfer phenomena are observed based on thermal metamaterials, such as thermal harvesting [10], inversing [11], rotating [12], illusions [13], lens [14], diode [15], etc. These new physical phenomena are not only verified in theory, but also observed in experiments in the lab. Almost all the experiments are conducted as follows: keeping the two ends of a plate at constant high and low temperatures to realize heat diffusion from one end to the other spontaneously, and using an infrared camera to observe the 2D steady/transient temperature profiles in the plate. Actually, though heat is expected to diffuse along the plate to observe the 2D temperature profile, heat convection with the ambient air seems unavoidable more or less [16]. After all, the plate is a 3D object in the real world. Heat dissipation via convection decreases the amount of heat via conduction along the plate, which will change the desired temperature profile greatly. Therefore, proper experimental conditions are of great significance to observe the desired thermal cloaking effect in 2D temperature profiles.

When focusing on the conditions of existing thermal cloaking experiments, as listed in table 1, we can find that these conditions are different from one another [17–24]. Different experimental materials, dimensions and temperature conditions can be observed. Deciding whether to consider the heat convection is also a matter of preference. A comprehensive suggestion on the proper experimental conditions will help researchers/engineers to arrange experiments better to successfully observe the desired results.

In this paper, we focused on exploring the proper experimental conditions for 2D thermal cloaking demonstrations. Mathematical modeling of heat conduction along the plate was modeled, and z-plane thickness, boundary conditions, heat convection coefficient and thermal conductivity were discussed based on the model. Numerical simulations were conducted to verify the suggested experimental conditions.

Table 1. Review of experimental conditions.

No.	Authors	Year	Background materials	*z*-plane thickness	Exp. conditions	Considering convection?
1	Narayana and Sato [17]	2012	Agar-water block	50 mm	BC.: 0 °C and 41 °C Ambient temp: -	No
2	Schittny *et al* [18]	2013	Copper plate	2 mm	BC.: 25 °C and 80 °C Ambient temp: 25 °C	With PDMS coating
3	Han *et al* [19]	2013	Sealant	35 mm	BC.: 0 °C and 60 °C Ambient temp: 25 °C	No
4	Ma *et al* [20]	2013	Brass	—	BC.: 25 °C and 85 °C Ambient temp: -	By vacuum chamber
5	Lan *et al* [21]	2015	Stainless steel	—	BC.: 0 °C and 80 °C Ambient temp: -	No
6	Nguyen *et al* [22]	2015	Carbon steel	5 mm	BC.: 0 °C and 60 °C Ambient temp: -	No
7	Han *et al* [23]	2015	Stainless steel	—	BC.: 0 °C and 60 °C Ambient temp: -	With PDMS coating
8	Chen and Lei [24]	2015	Nickel steel	—	BC.: 0 °C and 100 °C Ambient temp: -	With PDMS coating

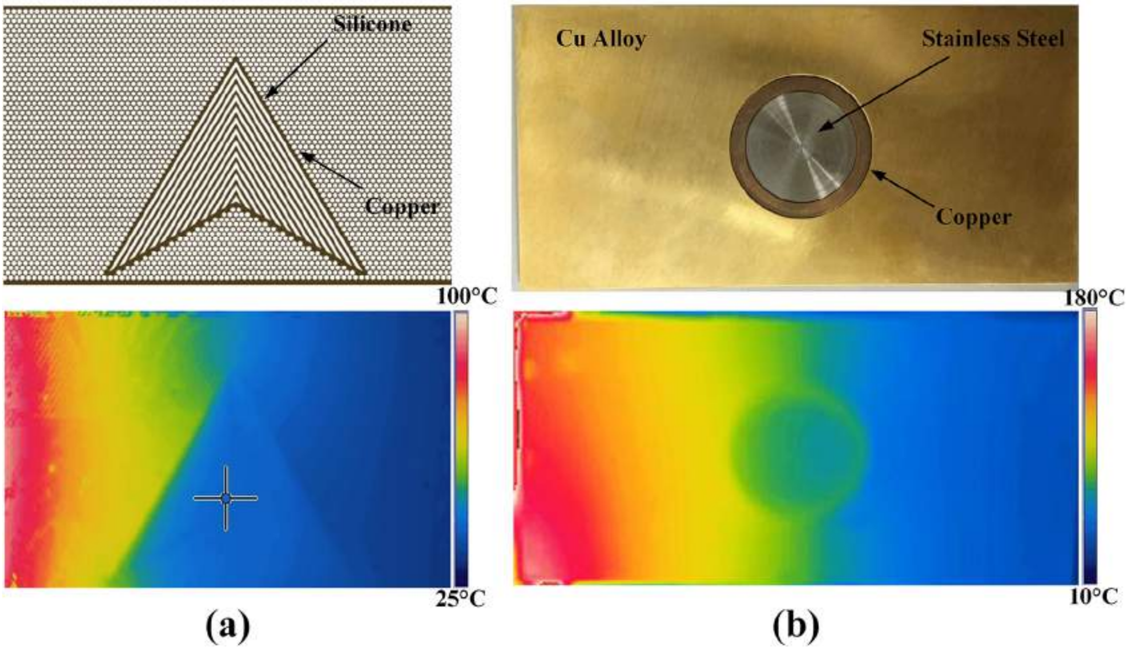

Figure 1. Two failure experiments for 2D thermal cloaking demonstration: (a) carpet thermal cloak and (b) isotropic thermal cloak.

Consequence of improper conditions

In our previous study [25], we designed a layered structure in the copper plate to experimentally observe the carpet thermal cloaking effect, as shown in figure 1(a). The composite copper plate was 250 mm long, 100 mm wide and 2 mm thick. The copper plate was drilled with holes whose diameter was 1.5 mm. All the holes were filled with silicone (Dow Corning OE6550). The carpet cloak was made by alternative layers of copper and silicone. The thickness of the alternative layers is 1 mm. The thermal conductivities of copper and silicone are 398 and 0.5 W m^{-1} K^{-1}, respectively. The composite copper plate was coated with a thin layer of silicone to decrease the convection. In the experiment, two feet were added at the left and right boundaries to insert in the hot water and cold water respectively. The left one was

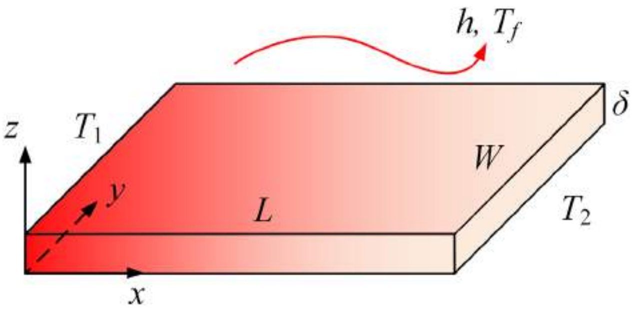

Figure 2. Schematic of the heat conduction along a plate.

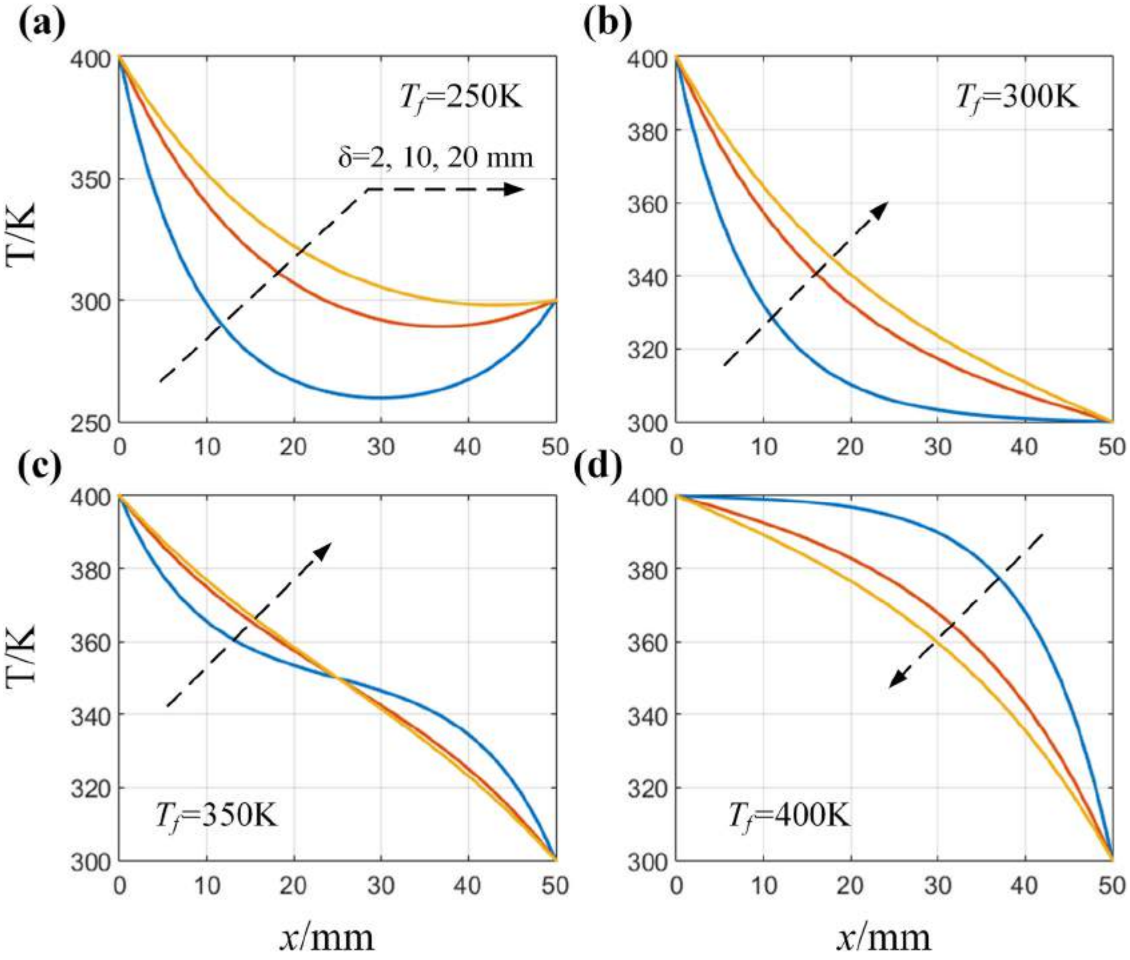

Figure 3. Variation of temperature profiles along the plate with different plate thicknesses and ambient temperatures.

put into a tank of boiled water (100 °C) and the right one was put into a tank of water at room temperature (25 °C). In our other unpublished work, as shown in the supplementary material (stacks.iop.org/JPhysD/49/415302/mmedia)[1], we designed a bi-layer structure with homogeneous materials to verify the cloaking effect of isotropic thermal cloaks. As shown in figure 1(b), the background material was copper alloy, the cloaking region is made of copper, and the center region consisted of stainless steel. The experimental sample was wrapped with transparent adhesive tape to make the emissivity consistent, and to decrease the thermal convection effect. The left boundary was kept at 180 °C with an electric heater, while the right boundary was kept at 10 °C with a thermoelectric cooler. Both of these experiments were conducted at room temperature.

Unfortunately, though some methods have been adopted to decrease the heat convection, like coating with silicone or wrapping with transparent adhesive tape, poor thermal cloaking effect was observed in both experiments. When heat reached the centerline, no obvious temperature gradient could be observed due to the insufficient insulation against heat convection with the ambient air. From these two failure experiments, we are aware that the proper experimental conditions should be well analyzed and the feasible conditions should be suggested. Thus we try to find the answers to this question in the following sections.

Mathematical modeling

Regardless of whether the experimental purpose is to observe thermal cloaking, concentrating or rotating, it is a heat conduction problem in essence. To simplify the analyses, we just consider the heat conduction along a homogeneous plate, as shown in figure 2. Since heat mainly diffuses along the x-axis in the plate, and the temperature along the z-axis can be assumed as uniform, the present problem can be simplified as a 1D heat conduction problem. The governing equation can be expressed as

$$\frac{\mathrm{d}^2T}{\mathrm{d}x^2} - \frac{hP}{\kappa A_\mathrm{c}}(T - T_\mathrm{f}) = 0 \tag{1}$$

with boundary conditions as

$$\begin{cases} x = 0,\ T = T_1 \\ x = L,\ T = T_2 \end{cases} \tag{2}$$

where h is the convection coefficient, P the perimeter, A_c the uniform cross-sectional area, k is the thermal conductivity of the plate, T_f the ambient temperature, L the length of the plate along the x-axis, as shown in figure 2. T_1 and T_2 are the temperatures of the two ends of the plate. The solution to equation (1) can be obtained as

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[1] See supplementary material for details of the isotropic thermal cloak.

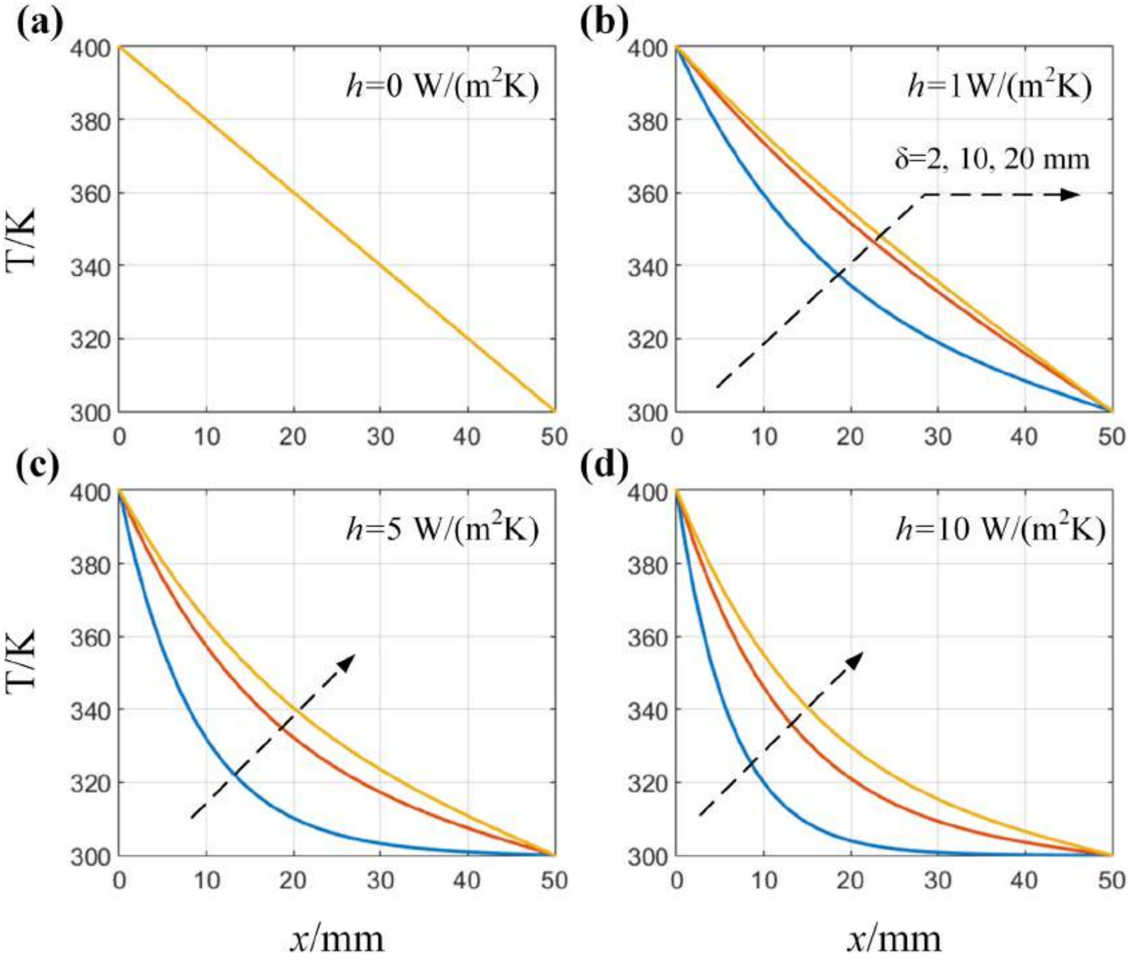

Figure 4. Variation of temperature profiles along the plate with different plate thicknesses and a convection coefficient at 300 K.

$$T = \frac{(T_2 - T_f)e^{mL}}{e^{2mL} - 1}e^{mx} + \frac{(T_1 - T_f)e^{2mL} - (T_2 - T_f)e^{mL}}{e^{2mL} - 1}e^{-mx} + T_f \tag{3}$$

where $m = \sqrt{hP/(\kappa A_c)}$. From the notions in figure 2, we can easily obtain that $P = 2(W + \delta)$ and $A_c = W\delta$. Now we can plot the temperature profile by varying the conditions to find out which is the best.

Results and discussions

In order to find out the proper experimental conditions for 2D thermal cloaking observation, we analyzed the effects of ambient temperatures, plate thickness, convection coefficient and background materials based on the above model and then verified with finite-element simulations. In our model, the rectangular plate was made of copper with a dimension of 50 mm in both length and width. The two boundary temperatures were kept as constant at 400 and 300 K, respectively. Other initial conditions included: plate thickness of 2 mm, convection coefficient of 5 W m^{-2} K^{-1}, ambient temperature of 300 K.

The temperature profiles along the *x*-axis with different plate thicknesses and ambient temperatures were shown in figure 3. It is seen that aside from the ambient temperature variations, the thinner plate has faster response in temperature and an unstable gradient, while the thicker plate has a more stable temperature gradient. To overcome the unobvious temperature gradient along the heat conduction, a thicker plate seems preferable. On the other hand, the ambient temperature also makes a difference. To make the temperature gradient as uniform as possible, the ambient temperature should fall in the scope of two boundary temperatures, as shown in figure 3(c). When the ambient temperature is close to the low boundary temperature, the gradient becomes indistinct in the downstream close to the low-temperature boundary, as shown in figure 3(b). This is just the case in figure 1. When the ambient temperature is close to the high boundary temperature, the gradient becomes indistinct in the upstream, as shown in figure 3(d). The worst case is when the ambient temperature is less than the low boundary temperature, as shown in figure 3(a). Somewhere along the plate will even have lower temperature than the low boundary temperature due to the existence of convection.

The temperature profiles along the *x*-axis with different plate thicknesses and convection coefficients were shown in figure 4. Similarly, to realize a uniform temperature gradient, thicker plates are preferable. As for the convection coefficient, a larger convection coefficient is unfavorable which leads to temperature gradient variation. A zero convection coefficient, corresponding to totally insulated, has a completely uniform gradient, which is the ideal case for such 2D thermal cloaking demonstration. That is why we should decrease the convection as much as possible to present better observations. The

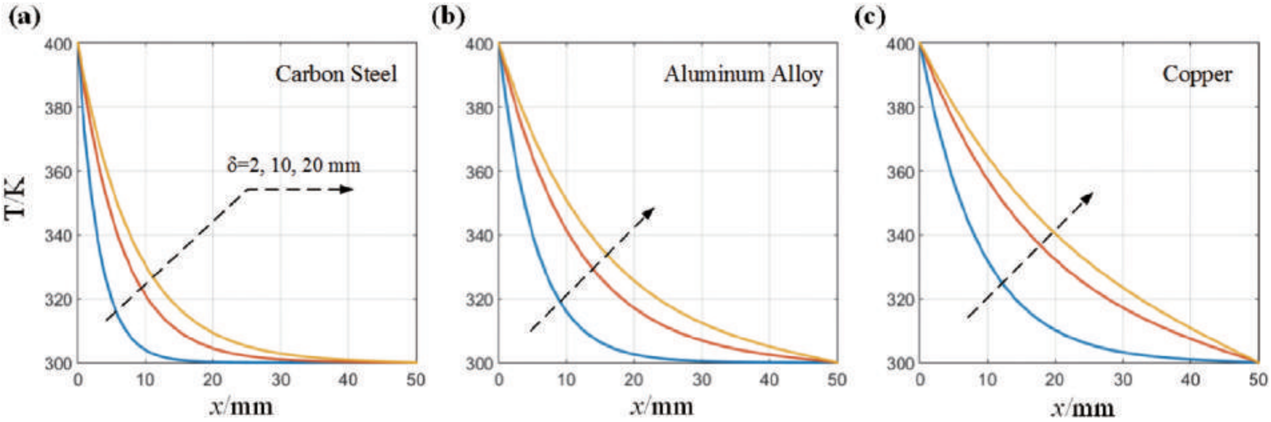

Figure 5. Variation of temperature profiles along the plate with different plate thicknesses and background materials.

related methods include coating a layer of low-κ materials (like silicone, polydimethylsiloxane (PDMS), etc), wrapping with plastic tape, putting in a vacuum chamber, etc. Even when the convection coefficient is not zero, a thicker plate seems to possess a better temperature gradient.

The temperature profiles along the x-axis with different plate thicknesses and background materials were shown in figure 5. Three background materials were considered, i.e. carbon steel (49.8 W m^{-1} K^{-1}), aluminum alloy (160 W m^{-1} K^{-1}) and copper (398 W m^{-1} K^{-1}). It is seen from figure 5 that when compared with carbon steel and aluminum alloy, the copper plate has more a uniform temperature gradient. Thus, background materials with higher thermal conductivity are suggested to be adopted in such experiments. Of course, the main experimental purpose is to observe the thermal cloaking effect, therefore the background materials should also consider the materials of the thermal cloak. On the premise of maintaining the thermal cloaking effect, the background materials should possess higher thermal conductivity.

Although the mathematical model is simplified as 1D based on some assumptions, it is still useful in exploring the proper conditions. From figures 3–5, we can see that regardless of whether the plate thickness is increased, the convection coefficient is decreased, or the thermal conductivity of the plate is enhanced, the essence is to enhance the heat convey ability of conduction against convection. Certainly, the zero convection coefficient is ideal for such experiments, but it is hard to realize. Alternatives are to enhance the conduction ability by increasing the plate thickness or thermal conductivity, or to decrease the convection ability by coating with a thin layer of low thermal conductivity materials or putting in a vacuum chamber. This is the basic rule that directs the design of such experiments.

To validate our designs, we employed the COMSOL Multiphysics software to simulate the heat diffusion process in a 100 mm × 50 mm rectangular plane with the isotropic thermal cloak in figure 1(b). The left and right boundaries were kept at constant temperatures (180 °C and 10 °C), which were the same as those in the experiments. Other boundaries were insulated. The inner radius (R_1) of the annular thermal cloak was 10 mm and the outer radius was 12.75 mm. In figure 6(a), the plate thickness was 1 mm, which was the same as that in the experiment. From figure 6(a), we can see that it was difficult to continue conducting heat when heat reached the centerline, which was very similar to the experimental result in figure 1(b). Without changing any of the other boundary conditions, we changed the plate thickness from 1 to 10 mm in figure 6(b); the temperature gradient became much more obvious after the centerline. Since temperature changes along the length of the composite plate, we are unable to evaluate the amount of heat convection or radiation by applying Newton's law or Stefan–Boltzmann's law directly. One feasible solution is to calculate the heat convection or thermal radiation via integrating the convection or radiation all over the plate surfaces. By evaluation, we found that at such experimental temperatures, radiation is much less than convection. The comparison verified that investigation of the proper conditions could benefit from our above analyses and allow better experimental demonstration.

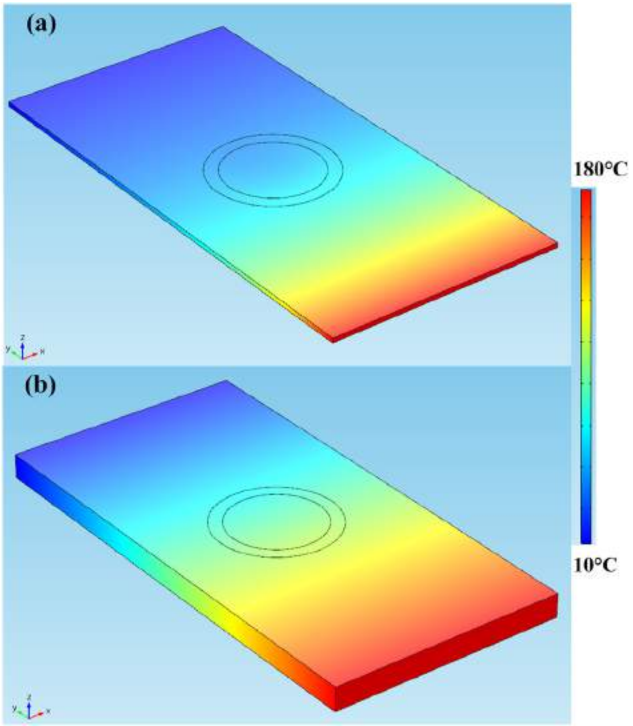

Figure 6. Comparison of temperature profiles with different thicknesses of (a) 1 mm and (b) 10 mm.

Conclusions

In this study, we focused on exploring the proper experimental conditions for 2D thermal cloaking demonstration. From reviewing the literature, we found that improper experimental conditions may lead to the failure of experimental observation of the thermal cloaking effect. A simple mathematical model was established and based on the model, the experimental conditions were specifically discussed. Some methods to enhance the experimental success were proposed, including increasing the plate thickness and thermal conductivity, or decreasing the convection coefficient. With finite element simulations, we verified the above analyses. Investigation of proper experimental conditions for the 2D thermal cloaking effect is verified to benefit from the present analyses.

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References

[1] Guenneau S, Amra C and Veynante D 2012 Transformation thermodynamics: cloaking and concentrating heat flux *Opt. Express* **20** 8207

[2] Hu R, Hu J Y, Wu R K, Xie B, Yu X J and Luo X B 2016 Examination of the thermal cloaking effectiveness with layered engineering materials *Chin. Phys. Lett.* **33** 044401

[3] Hu R, Xie B, Hu J Y, Chen Q and Luo X B 2015 Carpet thermal cloak realization based on the refraction law of heat flux *Europhys. Lett.* **111** 54003

[4] Fan C Z, Gao Y and Huang J P 2008 Shaped graded materials with an apparent negative thermal conductivity *Appl. Phys. Lett.* **92** 251907

[5] Xu H Y, Shi X H, Gao F, Sun H D and Zhang B L 2014 Ultrathin three-dimensional thermal cloak *Phys. Rev. Lett.* **112** 054301

[6] Yuan X B, Lin G C and Wang Y S 2016 Influence of nonlinear coordinate transformation on thermal cloaking performance of multilayered cylindrical thermal cloak *AIP Adv.* **6** 045013

[7] Han T C and Qiu C W 2016 Transformation Laplacian metamaterials: recent advances in manipulating thermal and dc fields *J. Opt.* **18** 044003

[8] Zhang Y M, Xu H Y and Zhang B L 2015 Design, implementation, and extension of thermal invisibility cloaks *AIP Adv.* **5** 053402

[9] Chen T Y, Weng C N and Tsai Y L 2015 Materials with constant anisotropic conductivity as a thermal cloak or concentrator *J. Appl. Phys.* **117** 054904

[10] Hu R, Wei X L, Hu J Y and Luo X B 2014 Local heating realization by reverse thermal cloak *Sci. Rep.* **4** 3600

[11] Keidar M, Shashurin M, Delaire S, Fang X and Beilis I I 2015 Inverse heat flux in double layer thermal metamaterial *J. Phys. D: Appl. Phys.* **48** 485104

[12] Guenneau S and Amra C 2013 Anisotropic conductivity rotates heat fluxes in transient regimes *Opt. Express* **21** 6578–83

[13] He X and Wu L Z 2014 Illusion thermodynamics: a camouflage technique changing an object into another one with arbitrary cross section *Appl. Phys. Lett.* **105** 221904

[14] Liu Y C, Sun F and He S L 2016 Novel thermal lens for remote heating/cooling designed with transformation optics *Opt. Express* **24** 5683–92

[15] Li Y, Shen X Y, Wu Z H, Huang J Y, Chen Y X, Ni Y S and Huang J P 2015 Temperature-dependent transformation thermotics: from switchable thermal cloaks to macroscopic thermal diodes *Phys. Rev. Lett.* **115** 195503

[16] Dede E M, Nomura T, Schmalenberg P and Lee J S 2013 Heat flux cloaking, focusing, and reversal in ultra-thin composites considering conduction-convection effects *Appl. Phys. Lett.* **103** 063501

[17] Narayana S and Sato Y 2012 Heat flux manipulation with engineered thermal materials *Phys. Rev. Lett.* **108** 214303

[18] Schittny R, Kadic M, Guenneau S and Wegener M 2013 Experiments on transformation thermodynamics: molding the flow of heat *Phys. Rev. Lett.* **110** 195901

[19] Han T, Bai X, Thong J T L, Li B and Qiu C W 2014 Experimental demonstration of a bilayer thermal cloak *Phys. Rev. Lett.* **112** 054302

[20] Ma Y G, Lan L, Jiang W, Sun F and He S L 2013 A transient thermal cloak experimentally realized through a rescaled diffusion equation with anisotropic thermal conductivity *NPG Asia Mater.* **5** e73

[21] Lan C W, Li B and Zhou J 2015 Simultaneously concentrated electric and thermal fields using fan-shaped structure *Opt. Express* **23** 24475–83

[22] Nguyen D M, Xu H Y, Zhang Y M and Zhang B L 2015 Active thermal cloak *Appl. Phys. Lett.* **107** 121901

[23] Han C, Bai X, Liu D, Gao D L, Li B W, Thong J T L and Qiu C W 2015 Manipulating steady heat conduction by sensu-shaped thermal metamaterials *Sci. Rep.* **5** 10242

[24] Chen F and Lei D Y 2015 Experimental realization of extreme heat flux concentration with easy-to-make thermal metamaterials *Sci. Rep.* **5** 11552

[25] Hu R, Xie B, Chen Q, Cheng J J and Luo X B 2016 Carpet thermal cloak realization with layered thermal metamterials: theory and experiment *Proc. 2016 IEEE Intersociety Thermal Conf.* pp 1122–5