# Thermal metadevices: From single function to multi-function and intelligence

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## Introduction

Theoretical thermotics makes it possible for human to manipulate macroscopic heat flow at will. Recently, thermal metamaterials are used to design thermal metadevices with novel functions. For one type of heat transfer, single functional devices could be well developed, such as cloaking, sensing [1,2], rotating, and concentrating. For multiple types of heat transfer, researchers have fabricated switchable multi-function devices [3]. Also, with the development of smart algorithms like machine learning, intelligent thermal metadevices [4] will arouse more widespread attention in future.

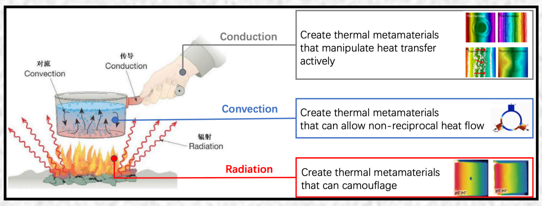



**Fig. 1** Three types of heat transfer

## Single function

**Research object:** Anisotropic monolayer structure

**Purpose:** Making thermal sensors accurate and invisible

**Approach:** Laplace equations

① **General solution:**

$T_1 = A_0 + A\, r \cos\theta$ $\quad m_{1,2} = \pm\sqrt{\frac{\kappa_{\theta\theta}}{\kappa_{rr}}}$

$T_2 = A_0 + B\, r^{m_1} \cos\theta + C\, r^{m_2} \cos\theta$

$T_3 = A_0 + D\, r \cos\theta + E\, r^{-2} \cos\theta$

② **Continuity conditions:**

$$\begin{cases} T_1(R_1) = T_2(R_1) \\ T_2(R_2) = T_3(R_2) \\ \left(-\kappa_1 \frac{\partial T_1}{\partial r}\right)_{R_1} = \left(-\kappa_{rr} \frac{\partial T_2}{\partial r}\right)_{R_1} \\ \left(-\kappa_{rr} \frac{\partial T_2}{\partial r}\right)_{R_2} = \left(-\kappa_3 \frac{\partial T_3}{\partial r}\right)_{R_2} \end{cases}$$

Accurate: A = D
Invisible: E = 0

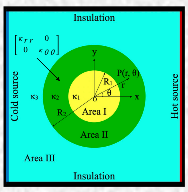



**Fig. 2** Schematic diagram

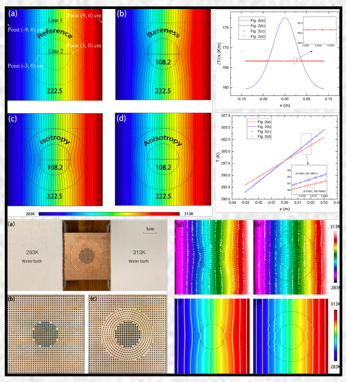



**Fig. 3** Results

**Research object:** Bilayer structure

**Purpose:** Making thermal sensors flexible

**Approach:** Optimization algorithms

Accurate: $\psi_s = \frac{1}{N_s}\sum_{i=1}^{N_s} |T_i - T_i^{ref}|$

Invisible: $\psi_b = \frac{1}{N_b}\sum_{i=1}^{N_b} |T_i - T_i^{ref}|$

$\mathbf{v}_j^{i+1} = w\,\mathbf{v}_j^i + c_1 d_1 \left(\mathbf{P}_j^i - \mathbf{R}_j^i\right) + c_2 d_2 \left(\mathbf{P}_g - \mathbf{R}_j^i\right)$

$\mathbf{R}_j^{i+1} = \mathbf{R}_j^i + \mathbf{v}_j^{i+1}$

$w = w_s - (w_s - w_e)\frac{i}{i_{max}}$

**Result:**

$\psi = \psi_s + \psi_b$

$\mathbf{R} = (R_1, R_2, R_3)$

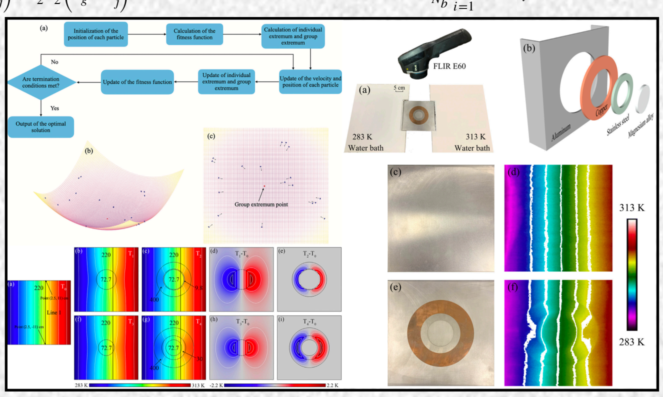



**Fig. 4** Results

## Multi-function

**Research object:** Anisotropic monolayer structure

**Purpose:** Fluid is used to adjust the total heat flow in working zone of Darcy's heat convection model.

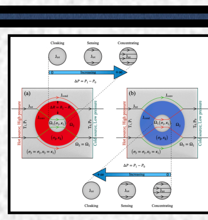


**Fig. 5** Schematic diagram

**Theoretical analysis:**

$\nabla \cdot J_{tot} = \nabla \cdot (J_{cond} + J_{conv}) = 0$

$J_{cond} = -\kappa \nabla T \quad J_{conv} = \rho C_p v T \quad v = -\frac{\sigma}{\eta}\nabla P$

**Dimensionless:** $\gamma = \frac{L \rho C_p v_x}{\kappa}$

**Heat flow amplification factor:**

$$\beta(\Delta P) = \frac{|J(\Delta P)|_{\Omega_c}}{|J_0(\Delta P)|_{\Omega_c}} \begin{cases} \beta > 1, \text{ concentrating} \\ \beta = 1, \text{ sensing} \\ 0 < \beta < 1, \text{ cloaking} \\ \beta = 0, \text{ perfect cloaking} \end{cases}$$

$$\beta_{max} = \frac{1}{\left(\frac{R_2}{R_1}\right)^{\frac{\sigma_1}{\sigma_{rr}}} - 1}$$

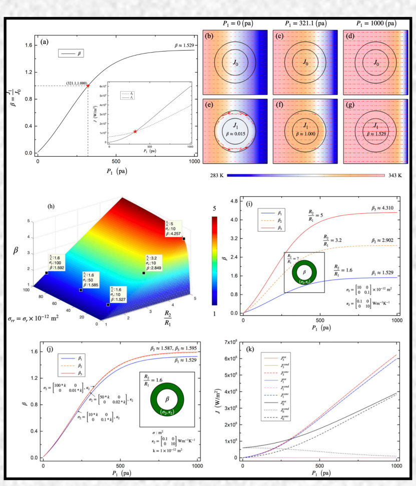


**Fig. 6** Results

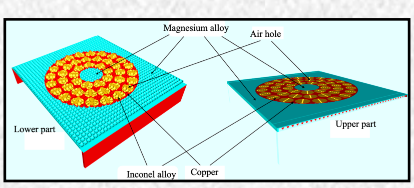



**Fig. 7** Experimental device

**Result:** Switchable three-function thermal metadevice

## Intelligence

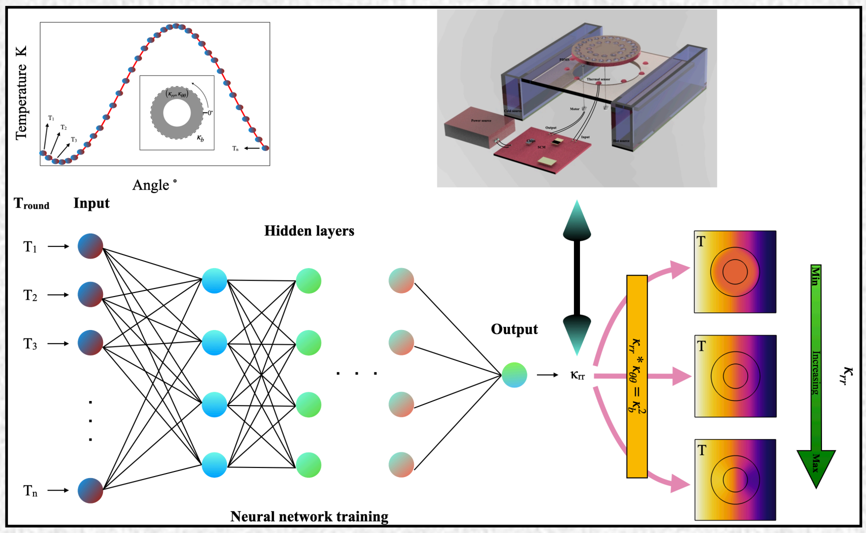



**Fig. 8** Schematic diagram

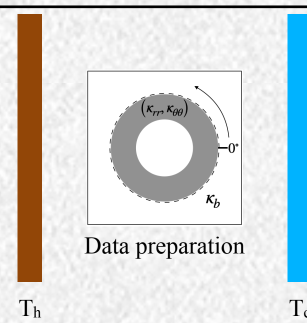
**Research object:** Anisotropic monolayer structure

**Purpose:** When ambient temperature changes, the appropriate thermal conductivity of metashell is given (thermal strategy).

**Approach:** Machine learning

① Data Preparation (Comsol+Matlab)
② Neutral network training (Python)
③ MSE examination (Mean Square Error)

**Result:** $T_{round} \longrightarrow \kappa_{rr}$



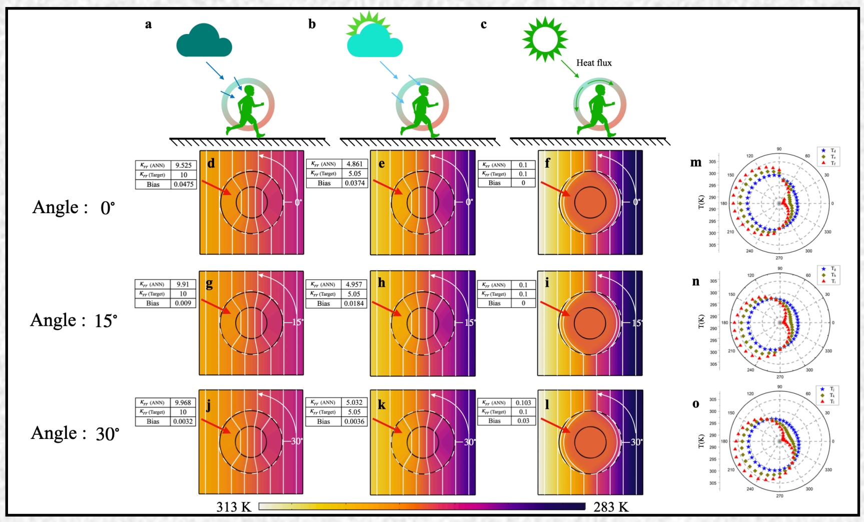




**Fig. 9** Results

## Conclusion

- An anisotropic monolayer scheme are proposed to make thermal sensors accurate and thermally invisible. (Single function)
- An optimization model with particle swarm algorithms are designed to realize bilayer thermal sensors with bulk isotropic materials. (Single function)
- We propose a hydrodynamic-assisted switchable three-function thermal metadevice in convection-diffusion systems. (Multi-function)
- Using machine-learning algorithm, thermal metadevice dynamically regulates heat flow in working zone based on information of ambient temperature. (Intelligence)

## References

[1] **P. Jin** et al., Making thermal sensors accurate and invisible with an anisotropic monolayer scheme, *Int. J. Heat Mass Transf.* 163, 120437 (2020). [IF: 4.947]

[2] **P. Jin** et al., Particle swarm optimization for realizing bilayer thermal sensors with bulk isotropic materials, *Int. J. Heat Mass Transf.* 172, 121177 (2021).

[3] **P. Jin** et al., Hydrodynamic-assisted switchable three-function thermal metadevice in convection-diffusion systems, to be submitted.

[4] **P. Jin** et al., Machine-learning intelligent thermal strategy with feeling, to be submitted.