Dynamic manipulation of conductive, convective, and radiative heat

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Introduction

It is known that heat transfer involves three basic modes including conduction, convection, and radiation, each with distinct mechanisms. Considering their diverse combination, we get various inspiration for on-demand heat management. We introduce extreme convection and intelligence to enhance thermal conductivity and responsiveness than common conduction [1-4]. Through the inclusion of laminar convection [5], we report a liquid-solid hybrid thermal material to achieve an enlarged tunability of heat flux. By means of a reconfigurable array of radiating units [6], we create the thermal image of any object in VR, effectively rendering it *in-situ* with its thermal signature, enhancing the users' immersive experience.

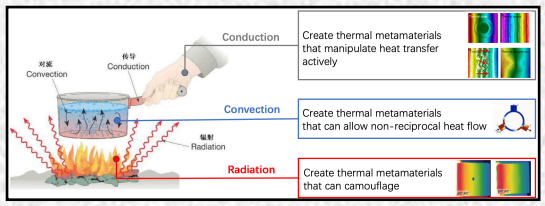


Fig. 1 Three modes of heat transfer

Conduction

Research object: Bilayer structures, spinning solid-like fluid, extreme convection [4]

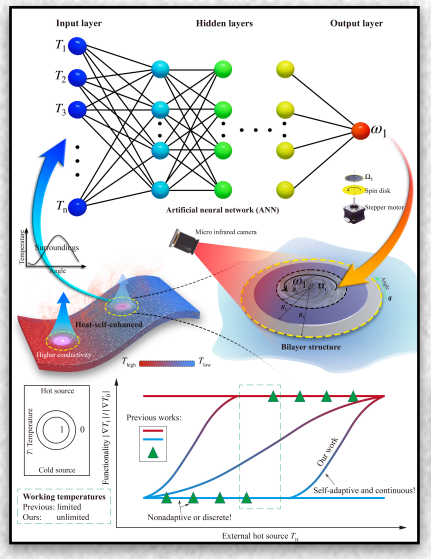


Fig. 2 Schematic diagram

Purpose: When ambient temperature changes, appropriate thermal conductivity κ of the core region are adjusted.

Approach: Deep learning

① Data Preparation (Comsol+Matlab)

② Artificial Neutral network (ANN) training (Python)

③ MSE examination (Mean Square Error)

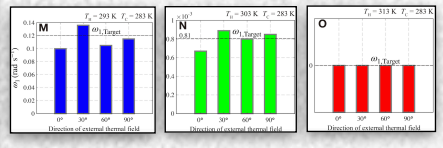


Fig. 3 Performance of the ANN

Results: $T_{\text{round}} \longrightarrow \omega_1 \longrightarrow \kappa$

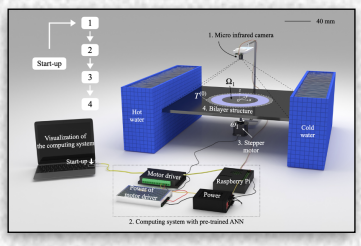


Fig. 4 Experimental device

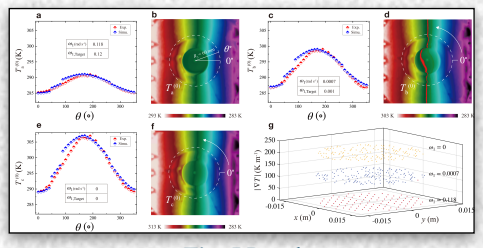


Fig. 5 Results

Convection

Research object: Porous structures, liquid-solid hybrid thermal material [5]

Purpose: Simultaneously and independently manipulate both conductive and convective heat flows.

Designed parameters:
Thermal conductivity κ
Liquid permeability σ

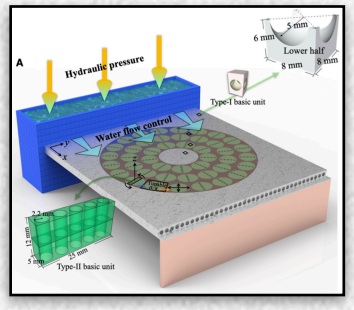


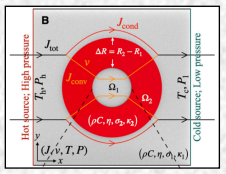
Fig. 6 Schematic diagram

Approach:

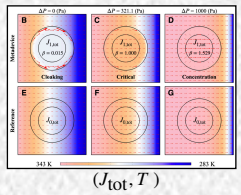
① Basic unit design (independently local control over κ and σ)

② Transformation thermotics (Design the spatial profiles of κ and σ)

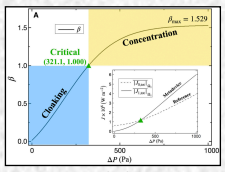
③ Achieve the targeted thermal functions



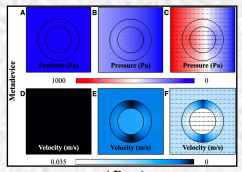
Schematic



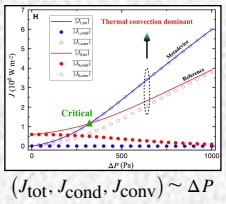
(J_{tot}, T)



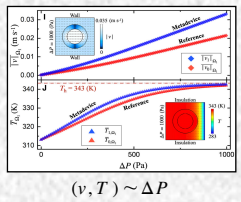
Evolution



(P, v)



$(J_{\text{tot}}, J_{\text{cond}}, J_{\text{conv}}) \sim \Delta P$



$(v, T) \sim \Delta P$

Fig. 7 Simulation results

Theoretical analysis:

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

$$\nabla \cdot \left(-\kappa \cdot \nabla T + \rho C \left(-\frac{\sigma}{\eta} \cdot \nabla P\right) T\right) = 0$$

Enlarged parameter space: $(\kappa, \rho C, \sigma, \eta)$

↓

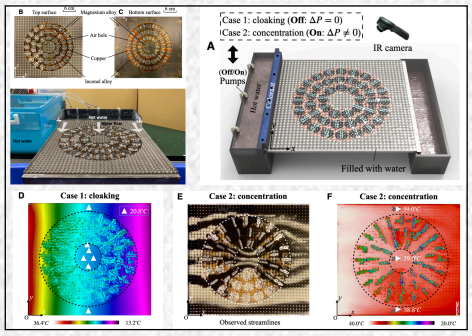
Enriched physical fields: $(J_{\text{tot}}, v, T, P)$

Cloaking:

$$\kappa' = \begin{pmatrix} M & 0 \\ 0 & 1/M \end{pmatrix} \kappa,\ M < 1$$

Concentration:

$$\sigma' = \begin{pmatrix} N & 0 \\ 0 & 1/N \end{pmatrix} \sigma,\ N > 1$$



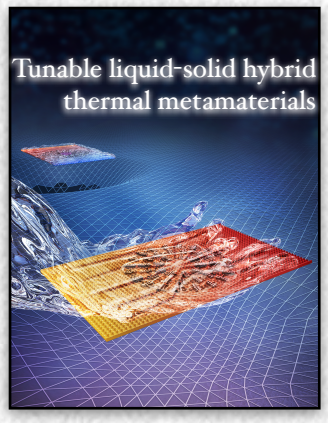


Fig. 8 Experimental setup and results

Results: Continuous transition from thermal cloaking to thermal concentration

Radiation

Research object: Cylindrical cavities, made of the same material [6]

Purpose: *In-situ* simulation of thermal reality, see conceptual diagram in Fig. 9.

Approach: Calculation of the cavity effective emissivity ϵ_e,

$$\epsilon_e = [1 + \frac{S_2}{S_1 + S_2}(\frac{1}{\epsilon} - 1)]^{-1}$$

where S_1 and S_2 are the areas of the lateral and bottom surfaces, and ϵ is the material emissivity.

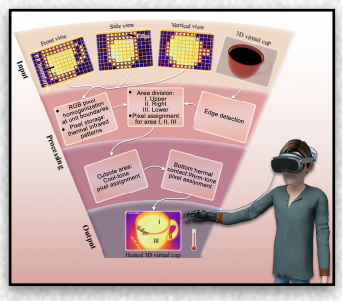


Fig. 10 Results

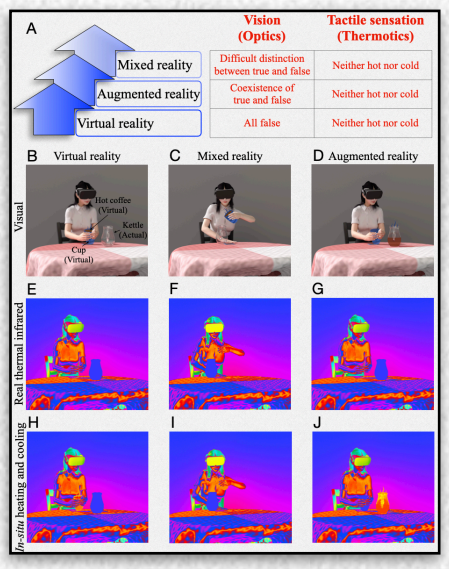


Fig. 9 Concept

Results: Making users have immersive experience with *in-situ* thermal tactile sensation

Conclusion

- A deep learning-assisted intelligent system is introduced into conventional material design, resulting in a self-adaptive thermal metamaterial. (Conduction)
- We develop a liquid-solid hybrid thermal metamaterial that supports both thermal convection and thermal conduction in the same material with a tunable fashion. (Convection)
- We develop an advanced technological platform that allows *in-situ* thermal rendering of virtual objects within simulated reality environments. (Radiation)

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). **26** cited [IF: 5.431]

[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). [IF: 5.431]

[3] F. Yang, **P. Jin** et al., Space-time thermal binary coding by spatiotemporally modulated metashell, ***Phys. Rev. Appl.*** in press (2023).

[4] **P. Jin** et al., Machine-learning-assisted environment-adaptive thermal metamaterials, **Preprint** at https://arxiv.org/abs/2301.04523 submitted, (2023).

[5] **P. Jin** et al., Tunable liquid-solid hybrid thermal metamaterials with a topology transition, ***Proc. Natl. Acad. Sci. U.S.A.*** 120, e2217068120 (2023). **5** times cited

[6] **P. Jin** et al., *In-situ* simulation of thermal reality, submitted, (2023).