Tunable hybrid thermal metamaterials with a topology transition

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Abstract

Thermal metamaterials provide rich control of heat transport which is becoming the foundations of cutting-edge applications ranging from chip cooling to thermal camouflage and heat harvesting. However, due to the fundamental laws of physics, the manipulation of heat is much constrained in conventional thermal metamaterials where effective heat conduction with Onsager reciprocity dominates. Here, through the inclusion of thermal convection and breaking the Onsager reciprocity, we unveil a regime in thermal metamaterials and transformation thermotics that goes beyond effective heat conduction. By designing a solid-liquid hybrid thermal metamaterial, we demonstrate for the first time a continuous switch from thermal cloaking to thermal concentration in one device with external tuning. Underlying such a switch is a topology transition in the virtual space of the thermotic transformation which is achieved by tuning the liquid flow via external control. These discoveries illustrate the extraordinary heat transport in complex multi-component thermal metamaterials and pave the way toward a unprecedented regime of heat manipulation.

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Developing rapidly in the past decade, thermal metamaterials [1, 2] and transformation thermotics [3–5] have greatly enriched heat manipulation which are valuable for applications ranging from thermal cloaking and camouflage [6–8], heat management in chips [9–14], to daily-life energy saving [15–17]. However, by far the development in this discipline is mainly focused on conductive thermal metamaterials [18–24] where thermal transport is dominated by diffusive or effective heat conduction which is restricted by Onsager’s reciprocity. The manipulation of heat in such thermal metamaterials are constrained in many aspects. Furthermore, the functions of conventional thermal metamaterials cannot be modified when the temperature settings are given [18, 20], lacking the on-demand control that are desired in many situations.

Thermal convection [25–30] is another major thermal transport mechanism that has distinct nature. For a long time, thermal convection has been ignored in the study of thermal metamaterials and transformation thermotics. Only very recently, the theory of transformation thermotics has been extended to include thermal convection by developing an entirely different framework [31, 32]. With such theoretical advancement, a new realm is open and the development of novel thermal metamaterials with thermal convection is highly desirable. However, fusing thermal convection in liquids and thermal conduction in solids together to form hybrid thermal metamaterials is very challenging since these distinct thermal transport channels must balance and cooperate with each other to form stable heat and liquid flows that fulfill the underlying thermotic transformation. Technically, thermal convection and thermal conduction must be manipulated in the same location simultaneously. The design of such hybrid thermal metamaterials is thus more complicated than the conventional all-solid thermal metamaterials. To date, experimental progresses in this direction are still anticipated, although the integration of thermal convection has been exploited to achieve effective thermal conductivity (with synthetic Onsager reciprocity) in unprecedented parameter regimes [28–30]. Thermal metamaterials in a broad sense with simultaneous manipulation of conductive and convective heat flows beyond Onsager reciprocity is still missing.

Here, we solve this challenge by integrating thermal convection and thermal conductivity into one metamaterial-based device (a “metadevice”) using fine-designed porous structures. Our design provides a prototype on how to control the conductive and convective properties of thermal transport independently in a single unit volume and thus opens a pathway towards a horizon for novel heat manipulation and applications, e.g., the continuous tunability and the attainability of a broad range of thermal transport properties. Besides, with the inclusion of thermal convection, the Onsager reciprocity breaks down and directional heat control becomes possible. Here, us-
FIG. 1. Solid-liquid hybrid thermal metamaterial. (A) Illustration of the metadevice based on the solid-liquid hybrid thermal metamaterial. (B) Schematic depiction of the metadevice from top-view. The convective heat flux is designed to realize thermal concentration, while the conductive heat flux is designed to realize thermal cloaking. (C) The switch between thermal cloaking and thermal concentration corresponds to a topological switch in virtual space. (D) The heat flux amplification factor $\beta$ can be tuned continuously by the external hydraulic pressure. Meanwhile, the function of the metadevice is switched.

Using the designed solid-liquid hybrid thermal metamaterials, we demonstrate experimentally the continuous switch between thermal cloaking and thermal concentration in one metadevice, which reveals the significant tunability of the hybrid thermal metamaterial. These discoveries indicate that the interplay and synergy between thermal conduction and thermal convection open a realm with unprecedented heat manipulation.
Designing hybrid thermal metamaterial. To create the hybrid thermal metamaterial, we use porous materials to allow thermal convection and thermal conduction to share the same space (Fig. 1A). The whole design involves two levels. At the first level, through the design of the basic unit, we create a porous material to achieve independent control over the thermal conduction and thermal convection properties locally. At the second level, we use the generalized theory of transformation thermotics to design the spatial profiles of the thermal conduction and thermal convection properties to achieve the targeted functions of the thermal metadevice.

When considering steady-state thermal transport in the hybrid metamaterial, the total heat flux ($J_{\text{tot}}$) is governed by the conservation equation,

$$\nabla \cdot J_{\text{tot}} = \nabla \cdot (J_{\text{cond}} + J_{\text{conv}}) = 0.$$  \hspace{1cm} (1)

The total heat flux consists of the conductive heat flux described by Fourier’s law $J_{\text{cond}} = -\kappa \cdot \nabla T$ ($\kappa$ is the thermal conductivity tensor and $T$ is the temperature) and the convective heat flux described by Darcy’s law $J_{\text{conv}} = \rho C \nu T$ (velocity of the laminar fluid is $\nu = -\sigma \cdot \nabla P$ where $\rho$, $C$, $\sigma$, $\eta$, and $P$ are separately the mass density, the heat capacity, the permeability, the dynamic viscosity, and the hydraulic pressure of the liquid in the hybrid system). The material parameters are considered here as position-dependent. Eq. (1) is then expressed as

$$\nabla \cdot \left(-\kappa \cdot \nabla T + \rho C \left(-\frac{\sigma}{\eta} \cdot \nabla P\right) T\right) = 0.$$  \hspace{1cm} (2)

The above equation holds when the liquid and heat flows are stable as well as local thermal equilibrium is reached everywhere. The inclusion of thermal convection expands the physical fields to a much larger set ($J_{\text{tot}}$, $\nu$, $T$, $P$). The material parameter space is also extended to ($\kappa$, $\rho$, $C$, $\sigma$, $\eta$). The enriched physical fields and enlarged parameter space give rise to rich thermal transport and manipulation. Here, we focus on the laminar thermal convection regime with low fluid velocity to avoid possible turbulence and nonlinear effects. Thanks to the excellent control of the hydraulic pressure and the fluid velocity, thermal transport in our solid-liquid hybrid thermal metamaterial can be tuned continuously.

The local control over the conductive and convective thermal properties is realized by the basic units design. We have two types of units. The type-I unit is a cuboid with a hemispherical region filled with water (see upper-right inset of Fig. 1A). Type-II unit is a cuboid with cylindrical five air holes. The effective thermal conductivity of each unit is given by $\kappa = (1 - \phi_l - \phi_a) \kappa_s + \phi_l \kappa_l + \phi_a \kappa_a$ where $\kappa_s$, $\kappa_l$, and $\kappa_a$ are separately the thermal conductivity of the solid, liquid, and air. $\phi_l$ and $\phi_a$ are
the filling fraction of the liquid and air region, respectively. In each unit, the thermal conductivity can be tuned by the choice of the solid material and the filling fractions $\phi_l$ and $\phi_a$. Meanwhile, the permeability $\sigma$ can be tuned via the geometry of the liquid or air region. For instance, in the type-II units air holes are used to deflect the liquid flow. The orientation of such units can be used to tune the permeability $\sigma$ (materials and methods S1).

**Cotransformation of thermal conduction and convection.** The starting point of the generalized transformation thermotics theory is to note that the Eq. (2) is invariant under the coordinate transformation that satisfies the following relations (materials and methods S2),

$$
\nabla \cdot (\kappa \cdot \nabla T) = 0, \quad \nabla \cdot (\rho C_v T) = 0.
$$

(3)

In the terminology of transformation thermotics, under a transformation from real space to virtual space, the thermal conductivity transforms as follows, $\kappa' = \Xi \kappa \Xi^T / \det \Xi$, where $\Xi$ is the Jacobian matrix of the transformation for thermal conduction. Meanwhile, the permeability transforms according to the following relation, $\sigma' = \Lambda \sigma \Lambda^T / \det \Lambda$ where $\Lambda$ is the Jacobian matrix of the transformation for thermal convection. These two transformations are independent, since they are acting on different degrees of freedom.

We design a metashell structure where the thermal conductivity $\kappa'$ distribution is targeted for thermal cloaking as dictated by our choice of the transformation $\Xi$ (Fig. 1A). This transformation maps to a virtual space with a hole at the center. The hole in the virtual space is exactly the origin of the thermal cloaking effect: The heat flows cannot touch any object in the hole in the virtual space, while in real space, an object in the core region is not affected by the heat flows. On the other hand, the liquid permeability distribution $\sigma'$ is generated by the transformation of the thermal convection $\Lambda$, which is designed for thermal concentration. This transformation maps to a virtual space with no hole. From the geometric point of view, the virtual space with a hole is topologically distinct from the virtual spaces with no hole. Therefore, with increasing hydraulic pressure difference $\Delta P = P_h - P_l$ ($P_h$ and $P_l$ are the hydraulic pressure at the hot and cold sides of the metadevice, respectively), thermal convection becomes dominant and the device function switches from thermal cloaking to thermal concentration (see Fig. 1B). Meanwhile, the virtual space undergoes topology switch (see Fig. 1C). Specifically, the nontrivial topology in the virtual space for thermal cloaking implies that there are some properties robust to external conditions. These properties are the heat current in the core region. In the thermal cloaking regime, such a heat current is irrelevant with external temperature distributions. In contrast, for thermal concentration,
the heat current in the core region is highly sensitive to external temperature regions. The switch between these two functions reflect the topology change in the virtual space.

To ensure the above features, a core region ($\Omega_1$) with isotropic thermal conductivity ($\kappa_1$) and permeability ($\sigma_1$) is placed at the center of the device (Fig. 1B). Meanwhile, outside the metadevice is the background ($\Omega_3$) with the same physical parameters as the core $\Omega_1$. In the metamaterial region ($\Omega_2$) both the thermal conductivity $\kappa'$ and the liquid permeability $\sigma'$ are engineered according to the transformations $\Xi$ and $\Lambda$. Here, we focus on the two-dimensional transformation described in the cylindrical coordinate ($r \cos \theta, r \sin \theta$). In the device region, the both the thermal conductivity $\kappa'$ and the liquid permeability $\sigma'$ are anisotropic. They are expressed as the diagonal tensors, $\kappa_2 = \text{diag}(\kappa_{rr}, \kappa_{\theta \theta})$ with $\kappa_{rr} \kappa_{\theta \theta} = \kappa_1^2$ and $\sigma_2 = \text{diag}(\sigma_{rr}, \sigma_{\theta \theta})$ with $\sigma_{rr} \sigma_{\theta \theta} = \sigma_1^2$. Here, we choose transformations with weak position dependence in the region ($\Omega_2$) and realize them with approximately $r$-independent structures. The specific forms of these quantities are given in materials and methods S2.

To characterize quantitatively the function of the designed metadevice, we introduce the heat flux amplification factor $\beta$ which is given by the averaged amplitude of the total heat flux in the core region ($\Omega_1$) over the same quantity when the system is as uniform as the background (henceforth denoted as “the reference”). The $\beta$ factor characterizes the function of the metadevice,

$$\beta(\Delta P) = \frac{\left. J_{1,\text{tot}}(\Delta P) \right|_{\Omega_1}}{\left. J_{0,\text{tot}}(\Delta P) \right|_{\Omega_1}}$$

where $J_{1,\text{tot}}$ and $J_{0,\text{tot}}$ are, respectively, the total heat flux in the core region for the metadevice and the reference. Remarkably, the different functions listed above can be achieved in the designed metadevice by tuning the external hydraulic pressure $\Delta P$ (Fig. 1D).

**Simulation and characterization.** Before going into the experiments, we first perform simulations based on the designed distributions of the effective parameters (materials and methods S3). The simulation box is $0.1 \times 0.1$ mm$^2$ with $R_1 = 0.02$ mm and $R_2 = 0.032$ mm. We choose the following parameters: The homogeneous background and the core region have the same parameters: the isotropic thermal conductivity $\kappa_1 = 1$ W m$^{-1}$ K$^{-1}$ and the isotropic liquid permeability $\sigma_1 = 10^{-12}$ m$^2$. In the metamaterial region ($\Omega_2$), $\kappa_2 = \text{diag}(0.1, 10)$ W m$^{-1}$ K$^{-1}$ and $\sigma_2 = \text{diag}(10, 0.1) \times 10^{-12}$ m$^2$. The left (right) terminal of the system is connected with a hot (cold) source of temperature $T_h = 343$ K ($T_c = 283$ K). The averaged amplitude of the total heat flux ($J_{\text{tot}}$) in the core
region \((\Omega_1)\) is calculated from finite-element simulations when the external hydraulic pressure \(\Delta P\) is increased from 0 to 1000 Pa with an interval of 10 Pa. As shown in Fig. 2A, the heat flux amplification factor \(\beta\) indeed increases with the hydraulic pressure difference \(\Delta P\).

Figures 2B-D show from finite-element simulations how the functions of the metadevice can be tuned by the external hydraulic pressure. In these figures, the distributions of the temperature (represented by the color profiles) and the total heat flux (depicted by the red arrows) are presented. For \(\Delta P = 0\), the \(\beta\) factor is minimal \(\beta = 0.015\), indicating that the core region \(\Omega_1\) is cloaked from the heat flows. Indeed, the heat flux is deflected by the metamaterial region, as shown in Fig. 2B. For \(\Delta P = 321.1\) Pa (Fig. 2C), \(\beta = 1\) and the heat flux in the core region is the same as the heat flux in the background, indicating the critical situation. For a larger \(\Delta P = 1000\) Pa (Fig. 2D), the \(\beta\) factor is more significant than one, leading to heat flux focused on the core region, i.e., thermal concentration. The above tuning of thermal transport is achieved without disturbing the temperature field in the background, demonstrating an unprecedented regime in heat manipulation.

For comparison, we give the distributions of the heat flux and temperature in Figs. 2E-G for the reference system under the same external hydraulic pressure and temperature setup. In the background region \((\Omega_3)\), our device has nearly the same heat flux and temperature distributions as those in the reference system. In contrast, the heat flux and temperature profiles are substantially manipulated in the metamaterial region \(\Omega_2\) and in the core region \(\Omega_1\). These results demonstrate the continuous tunability and the power of the hybrid thermal metamaterial in the manipulation of heat.

When \(\Delta P\) is large, thermal convection is dominant (see Fig. 2H) which leads to significant thermal concentration effect. In this regime, the isotherm line is pushed close to the cold terminal, and the temperature of the core region approaches \(T_h\). In this limit, \(\beta\) reaches its maximum value

\[
\beta_{\text{max}} = \left(\frac{R_2}{R_1}\right)^{1 - \frac{\sigma_1}{\sigma_r}}
\]

which depends on the geometric and material parameters of the metadevice (supplementary text S1). As shown in Fig. 2A, the \(\beta\) factor can be tuned continuously via the external hydraulic pressure from 0 to a maximum value of \(\beta_{\text{max}} = 1.529\), which agrees with Eq. (5). The dependences of the maximum heat amplification factor \(\beta_{\text{max}}\) on both the geometric and material parameters of the hybrid metamaterial are discussed in more details in supplementary text S1.

Figures 2I-J present the averaged liquid velocity and temperature in the core region as functions of the external hydraulic pressure, respectively. We note that the hybrid metamaterial significantly
modifies the averaged fluid velocity, demonstrating manipulation of liquid flows in parallel with heat manipulation. The averaged temperature in the core region is also considerably changed. The maximum temperature difference between the averaged temperatures of the metadevice and the reference can reach 3°C. With increasing hydraulic pressure difference \( \Delta P \), the averaged temperature of the core region approaches \( T_h = 343 \) K, which is consistent with Figs. 2D and G. In particular, the insets in Figs. 2I and J show the liquid velocity and temperature profiles when \( \Delta P = 1000 \) Pa, demonstrating a concrete thermal concentration effect.

For the completeness of the investigations, we also design and study another solid-liquid hybrid thermal metamaterial where convective thermal transport leads to thermal cloaking and conductive thermal transport leads to thermal concentration in the supplementary text S2. We find that with the increase of the external hydraulic pressure, thermal transport switches from conduction dominant to convection dominant. Meanwhile, the function of the thermal metamaterial switches from thermal concentration to thermal cloaking, leading to a topological switch in the virtual space from trivial to topological.

**Experimental realization and measurements.** The metadevice with the solid-liquid hybrid thermal metamaterial is shown in Fig. 3A. In the background region \( \Omega_3 \) and the core region \( \Omega_1 \), the metadevice is based on type-I units made of magnesium alloy. In the shell-like metamaterial region \( \Omega_2 \), both type-I and type-II units are used. Note that in the shining elliptic regions, inconel alloys are used in place of the copper to tune the thermal conductivity, particularly by adjusting the ellipses’ major and minor axes. The type-II units are in the middle of the elliptic regions that can tune the permeability \( \sigma \).

The solid-liquid hybrid metamaterial is mostly made of the type-I unit through which water can flow. The water is connected to a hot tank and a cold tank on the two sides, which serve as heat baths. We exploit three water pumps to tune the hydraulic pressures. As shown on the left side of Fig. 3A, there are two types of boundary conditions adopted in our experiments. Boundary condition I keeps no water pump on, hence \( \Delta P = 0 \). Boundary condition II keeps three water pumps on, each with a flow of 200 mL min\(^{-1}\). These water pumps drive water flow filling up the hot tank and going from the hot source to the cold drain through the metadevice, which provides steady and controllable hydraulic pressure. With such designs, the water-filled background material has effective thermal conductivity with \( \kappa_1 = 27.2 \) W m\(^{-1}\) K\(^{-1}\) and liquid permeability with \( \sigma_1 = 2.68 \times 10^{-9} \) m\(^2\). The fabricated hybrid metamaterial realizes the effective thermal conductivity \( \kappa_2 = \text{diag}(16.6, 38.8) \) W m\(^{-1}\) K\(^{-1}\) and liquid permeability \( \sigma_2 = \text{diag}(2.26, 1.02) \times 10^{-9} \) m\(^2\) in the
region $\Omega_2$. See materials and methods S4 for the sample’s size and effective physical characteristics.

We now demonstrate the switch between thermal cloaking and thermal concentration via controlled hydrodynamics. Under boundary condition I, $\Delta P = 0$, we measure the temperature profile in the metadevice. As shown in Fig. 3D, the temperature distribution recorded by the infrared camera offers a perfect pattern of thermal cloaking that is consistent with the simulation results in Fig. 2B. In particular, the core region has a pretty uniform temperature distribution around 20.8°C which indicates no conductive heat flow in the core region. Moreover, the temperature profile in the background region is nearly undisturbed.

Boundary condition II is used for the implementation of the thermal concentration. We ensure that thermal convection is dominant in such cases (materials and methods S4). Guided by the finite-element simulation results in the insets of Figs. 2I and J, we experimentally demonstrate the performance of thermal concentration from the perspective of fluid flow and temperature profile. To visualize the fluid flow, six holes (black dots marked in Fig. 3A) are punched under the container of a colorant (consisting alkanes and toner). When the system reaches a nonequilibrium steady-state, the colorant is dripped on the left boundary of the metadevice almost simultaneously and equidistantly through the six holes. Fig. 3E displays the six streamlines. The four streamlines in the middle are concentrated into the core region, and all the streamlines outside the region $\Omega_2$ are only slightly distorted. These results indicate that the core region has a larger flow with the same cross-sectional area (or, say, larger fluid velocity) than the background region. Note that in the $\Omega_2$ region, the colorant distributions in the upper and lower parts are different. The underlying reason is that the distribution of type-II basic units is asymmetric, and the six holes are asymmetric with respect to the upper and lower parts as well. Nevertheless, the concentration of the fluid flow is clearly visible in Fig. 3E. We then measure the temperature profile in the metadevice under the same condition. The measured temperature profile (see Fig. 3F) exhibits several features consistent with the simulation results in Fig. 2D. First, the overall temperature of the metadevice is higher than in the cloaking case. Moreover, the temperature gradient is pushed to the right side of the metadevice. There are visible correlations between the temperature profile and liquid flow profile, indicating that the thermal transport is now dominated by the convective heat flow carried by the water. The convective heat flow in the core region is larger than that in the background region because of $v_{\Omega_1} > v_{\Omega_2}$ with $T_{\Omega_1} \approx T_{\Omega_2}$ (see the white triangles in Fig. 3F). The above results are consistent with the simulated results in the insets of Figs. 2I and J (see materials and methods.
S5 for more simulation results). Therefore, the metadevice is tuned into thermal concentration by increasing the external hydraulic pressure.

**Conclusion and discussions.** We propose an approach to realize continuously tunable solid-liquid hybrid thermal metamaterial based on cotransformation of thermal conduction and thermal convection. With such an approach, we realize in experiments a metadevice based on a solid-liquid hybrid thermal metamaterial, which can achieve a continuous switch between thermal cloaking and thermal concentration via controlled hydrodynamics. Such a switch corresponds to a topology transition in the virtual space. A salient feature of our solid-liquid hybrid thermal metadevice is that the heat flow in the central region of the device can be continuously tuned from near zero to a tremendous value. Such significant tuning is achieved without disturbing the temperature field in the background, demonstrating extraordinary heat manipulation that cannot be achieved in conventional thermal metamaterials. Solid-liquid hybrid thermal metamaterials can be valuable in various applications such as cooling and heat management in electronic devices, sustainable infrastructures and intelligent heat control in smart materials and machines.

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**SUPPLEMENTARY MATERIALS**

Materials and Methods
Supplementary Text

Figs. S1 to S8

Reference (33)
FIG. 2. **Characterizing thermal manipulation in the metadevice via finite-element simulations.** (A) Evolution of the heat flux amplification factor $\beta$ with the external hydraulic pressure difference $\Delta P$. The inset shows the dependence of the averaged amplitude of the total heat flux ($J_{\text{tot}}$) in the core region on the pressure difference $\Delta P$. The solid and dashed lines represent the heat fluxes for the metadevice (subscript 1) and the reference (subscript 0), respectively. (B to D) Temperature (color) and heat flux (vectors) profiles in the metadevice with $\Delta P = 0, 321.1, 1000$ Pa, respectively. (E to G) Temperature (color) and heat flux (vectors) profiles in the reference with $\Delta P = 0, 321.1, 1000$ Pa, respectively. (H) The averaged amplitude of the convective ($J_{\text{conv}}$), conductive ($J_{\text{cond}}$), and total ($J_{\text{tot}}$) heat fluxes in the core region as functions of the hydraulic pressure difference $\Delta P$. (I and J) Averaged fluid velocity and temperature in the core region as functions of $\Delta P$ of the metadevice and the reference, respectively. The insets show (I) the fluid velocity (color and vectors), (J) temperature (color), and heat flux (vectors) profiles in the metadevice with $\Delta P = 1000$ Pa, respectively.
FIG. 3. **Experimental setup and measurements.** (A) Schematic of the experimental setup with different boundary conditions: pumps off, \( \Delta P = 0 \); pumps on, \( \Delta P \neq 0 \). (B and C) Photos of the top and the bottom of the sample. Scale bar is 6 cm. (D) Measured temperature profile of the thermal metadevice at \( \Delta P = 0 \). White triangles denote the positions with the temperature of 20.8 °C. (E) Observed streamlines of the thermal metadevice at \( \Delta P \neq 0 \). (F) Measured temperature profile of the thermal metadevice at \( \Delta P \neq 0 \). Horizontal white triangles denote the positions with the temperature (from up to down) of 39.0 °C, 39.0 °C, and 38.8 °C, respectively.
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