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Macroscopic networks of thermal conduction: Failure tolerance and switching processes

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ABSTRACT

The world is so wonderful and colorful thanks to the analytic discontinuities and singularities of phase transitions. Here we propose a class of macroscopic networks of thermal conduction that combine regular networks with macroscopic thermally conductive systems. We find that their phase transition phenomena (variation tendency) cannot be explained simultaneously by existing theories of networks, percolation or effective media. We report the *bond-free property* of these networks and the associated three switching processes caused by the geometric property of bonds, and we reveal the effect of single-point connection. Also, we propose some potential applications including thermal diodes. Our results are confirmed by finite-element method simulation and experiment. This work offers different insights into the theories of networks, percolation and effective media. It also provides a different method to design thermal metamaterials and manipulate thermal conductivities.

1. Introduction

Since the models of small-world networks and scale-free networks [1,2] were proposed at the end of the last century, much breakthrough has been made in the field of network science. As a young discipline, its research contents can be combined with physics, computer science, biology and sociology. However, heat conduction is a traditional field, which can be described by Fourier's law in macroscopic situations. It is interesting to ask what people may get if these two fields are combined. In fact, one can use the method of heat conduction to develop the network theory, as what recommendation model does [3,4], or can directly study the characteristics of heat conduction in regular or complex networks [5–15]. Based on the latter idea, a lot of effort have been paid to explain the abnormal phenomenon in microscopic heat transport, such as thermal rectification, flux localization and interfacial resistance [5–11]. However, studies concerning macroscopic thermal networks [12–15] are not as many as the microscopic ones, and most of them are focused on particulate and related multiphase systems [13–15].

Here we come up with a different network model obeying Fourier's law $\boldsymbol{J} = -\kappa\nabla T$ (where $\boldsymbol{J}$ is heat flux density, κ is thermal conductivity, and ∇T is temperature gradient) and study its percolation (variation tendency), known as an important phenomenon in testing the structural robustness of networks [16–20]. Different from the conventional method which only concerns valid/invalid information of the nodes and/or bonds, we conduct our research via finite-element method (FEM) simulation, which calculates 2-dimentional temperature distribution for each node/bond and contains much more detailed information. Due to the information advantage of FEM, it provides more research results that cannot be obtained from the conventional method. We focus on the connectedness and node influence of the whole network under different conditions of bonds, and point out the role of single-point connections in regular thermally conductive networks. As expected, we find that with different connectivities, our thermally conductive networks show different tolerance to node failures. Furthermore, variation tendencies against node failures under different bond conditions [see Figs. 2(a), 3(a) and 4(a)] can be explained by the theory of network (the network will be more stable with larger connection degrees), percolation [it's consistent with the critical points referred in Fig. 3(c)] and effective medium (continuous change), respectively. The simulation results in Figs. 2–4 help to reveal three switching processes due to the lengths and widths of the bonds. These switching processes are reasonable reasons for tiny changes of the geometry properties of the bonds can cause huge distinctions shown in Figs. 2–4. In other words, the switching processes serve as connections between these three theories.

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As it is crucial to develop efficient methods to manipulate heat flux freely at the background of energy crisis, it seems promising to design thermal metamaterials [21] and manipulate thermal conductivities on the basis of the thermally conductive network. We also propose two potential applications at the end of the manuscript as prototypes to achieve these aims.

2. Simulations and results

2.1. The definition of effective thermal conductivity (κ_{eff}) of thermally conductive networks

In order to study the properties of thermally conductive networks, we need firstly to define their effective thermal conductivity κ_{eff} properly. Taking 4-degree connected network as an example, we illustrate two methods to define the κ_{eff} of such networks. The first method is a series connection method. As illustrated in Fig. 1(a), κ_{eff} of the network can be calculated as

$$\kappa_{eff} = \kappa_{ref}\frac{T_{hot} - T_{mid}}{T_{mid} - T_{cold}}. \quad (1)$$

The second method is a heat flux method. As illustrated in Fig. 1 (b), the effective thermal conductivity of the network can be obtained by solving the Fourier's law

$$\kappa_{eff} = J\frac{\Delta x}{T_{hot} - T_{cold}}. \quad (2)$$

Theoretically, we will get exactly the same κ_{eff} by these two methods. However, there exists slight difference. For the heat flux method, there might be certain deviation when COMSOL is estimating the heat flux J around tiny spaces. So, the first method is more accurate and reliable. We get all the relevant results using this method.

2.2. Results of three thermally conductive networks

First, we consider networks with 3,4,5,6-degree connectivity shown in Fig. 2(a), in which the triangles, squares, pentagons and hexagons stand for thermally conductive nodes while the rectangles connecting neighboring nodes stand for thermally conductive bonds. All the bonds are set as 0.2 cm in length and 0.05 cm in width, and the edge lengths of regular polygon nodes in 3,4,6-degree connected networks are set as 0.2 cm. However, regular pentagon cannot tile a plane according to the tessellation theory. So, in order to consist with Fig. 3(a), for the 5-degree connected network, edge lengths of the nodes are set as 0.2, 0.2, 0.2, 0.2 and 0.1464 cm in order to tile the plane. We use the commercial software COMSOL (https://www.comsol.com/) livelink for MATLAB (https://www.mathworks.com/) to simulate the thermally conductive properties of these structures. The thermal conductivity (denoted as κ) of each node is set as 0.026 W/(m·K) (which is the κ of air and can be regarded as failure nodes) or 400 W/(m·K) (which is the κ of red copper and can be regarded as normal nodes). Meanwhile, the thermal conductivities of bonds are all set as 4000 W/(m·K) (which is approximately the κ of graphene and is large enough comparing to that of the nodes). Total size of the 3,4,6-degree connected networks is 50×50 crystal cells, and the size of the 5-degree connected network is 20×20 crystal cells (each crystal cell contains 8 nodes and 20 bonds, and 20×20 crystal cells contains more than 10,000 geometries. Concerning there will be a lot of repeated calculation, it's already a pretty large computing burden). We have verified by simulation that the absolute size of the network-structured domain does not affect the effective thermal conductivity of the entire structure. All the boundaries are set as thermal insulation except for the interfaces and hot/cold sources.

For each simulation, we stochastically choose certain percentage of nodes as failure nodes [0.026 W/(m·K)] and others normal

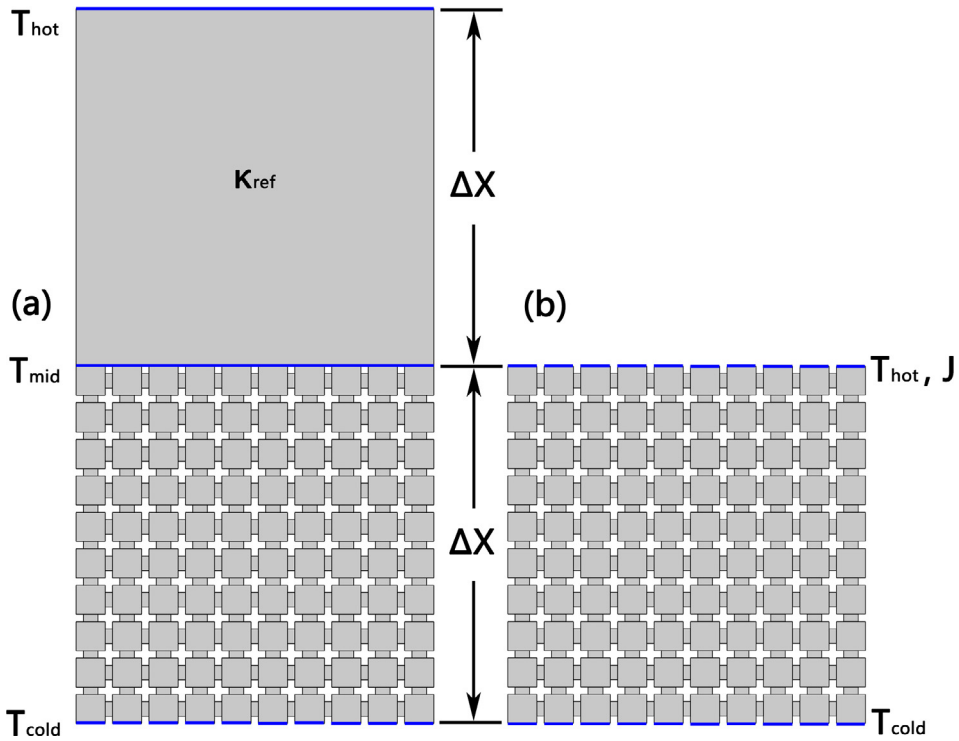

Fig. 1. Two methods to define the effective thermal conductivity. (a) Series connection method. The network is connected with a referential material with the same size and a known thermal conductivity κ_{ref}. The upper boundary of the referential material is set as hot source. The lower boundaries of the network are set as cold sources. The average temperature on the middle line T_{mid} can be obtained by the FEM simulation. (b) Heat flux method. Upper and lower boundaries of the network are set as hot and cold sources. Heat flux on the upper boundary can be obtained by the FEM simulation.