

Edited by Tao Deng

Bioinspired Engineering of Thermal Materials



A comprehensive overview and summary of recent achievements and the latest trends in bioinspired thermal materials.

Following an introduction to thermal properties of materials and the engineering history of thermal materials, the text discusses thermal materials for enhanced boiling and evaporation that are inspired by biological systems. Bioinspired engineering of photothermal materials and microfluidic cooling systems are also discussed in the text, which are followed by the descriptions of the basics, measurement, and biological examples of thermal emissivity. A discussion of thermal detection materials -that are inspired by biological systems, such as skin and proteins, and thermal insulation materials that are inspired by biological systems, such as birds and mammals, is rounded off by the discussion of bioinspired icephobic materials.

Straightforward and well structured, this is an essential reference for newcomers as well as experienced researchers in this exciting field.



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Deng (Ed.)

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Introduction to Thermal Properties of Materials

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This introductory chapter encompasses the basic principles and calculation methods for the heat transfer process and the advanced thermal properties. Various thermal applications of bioinspired functional materials will also be briefly discussed. To elucidate the basic principles of thermal theory, several analytical examples involving heat source and boundary conditions, uniform and nonuniform mesh structures, multiphase transfer, phase change, and convection in fluidic cases are also described. Noticing that micro/nanoscale materials exhibit unique thermal properties in modern materials scientific research, in this chapter the new developments in micro/nanoscale heat transfer theory are also discussed and some of the theoretic solutions drawn in calculating the thermal conductivity of micro/nanomaterials are shown. Biological systems set numerous examples in teaching humans how to collect, convert, and harness thermal energy from nature. In the last section of this chapter, practical approaches are discussed in an overview of bioinspired thermal materials. Typical thermal applications of functional materials (e.g., thermal nanofluids such as nanosuspension of colloidal particles in solution, the rapid charging of thermal energy storage, the phase change energy conversion by photothermal membrane, and the sensing of infrared radiation by bioinspired materials) are presented to show how the modern conventional and micro/nano heat transfer theory is related to advanced thermal functions of bioinspired materials.

1.1 Conventional Macroscale Heat Transfer

Heat transfer forms a vital kinetic force in the maintenance of the basic energy operation of the whole natural system for the activities of all the creatures on earth. As an engineering discipline, the inherent laws of heat transfer do not merely explain the way of energy transportation but also deal with the thermodynamics of both objects and the equilibrium principle under specified conditions. Fundamental learning of the equilibrium principle is provided by the first and second laws of thermodynamics, and follows the classic mechanics of

conduction, convection, and radiation. In the following sections, the conduction, convection, and radiation of macroscale heat transfer problems will be shown and the working principles formulated by energy equations. In thermal physics and engineering problems, we use critical quantitative criteria to characterize the thermal properties of material. These thermal properties are modified as representations of thermal energy transportation and energy conservation models, and can be used to analytically or numerically solve problems in thermal engineering and nature. Therefore, in the following sections, the basic principles of thermal transfer will be introduced first through a discussion of the thermal energy transportation and energy conservation models.

1.1.1 Normalization

To describe the process of heat transfer based on quantitative criteria, the primary quantities involved in a thermal process are listed in Table 1.1 and the quantitative criteria of thermal process are derived by these basic units. For analyzing much more complicated situations, the units of some derived quantities in Table 1.2 are defined as scientific descriptions of thermal properties of materials. Especially in numerical calculations and study of material heat transfer models, these derived units such as specific heat capacity C_p , thermal conductivity κ , heat flux q and thermal diffusivity α in thermodynamics cases will facilitate the systematic learning and understanding of the details of heat transfer.

In developing and judging thermal properties of new materials, normalizing the units of critical parameters may help us to better learn and understand different thermal properties.

1.1.2 Thermal Equilibrium and Nonequilibrium

Thermal equilibrium and nonequilibrium are the descriptions of the energy state of a thermal system. In an isolated steady thermal system, the state of thermal equilibrium will become stable without any external energy input. Once higher/lower temperature occurs at a specific point of the system, local thermal nonequilibrium exists. Meanwhile, the temperature difference will force the thermal energy to be transported from a region with higher temperature to a region with lower temperature. The system will eventually be in an equilibrium state after a spontaneous transformation process. The process of turning

Table 1.1 Basic parameter units.

Primary quantity	Parameter
Length	L (m)
Time	t (s)
Mass	m (kg)
Temperature	T ($^{\circ}\text{C}$ or K)
Current	J_e (A)

Table 1.2 Parameter units driven by the primary quantities in Table 1.1.

Driven quantity	Parameter
Specific heat capacity	C_p (J/kg K)
Energy	E (J or N m)
Force	F (N m/s ²)
Electric charge	C (coulomb or A s)
Thermal conductivity	k (W/m k)
Pressure	p (Pa or N/m ²)
Heat flux	q (W/m ²)
Heat efficiency	Q (W or J/s)
Velocity	V (m/s)
Viscosity	μ (Pa s)
Density	$A \rho$ (kg/m ³)
Potential	Φ (V or W/A or J/C)

nonequilibrium into equilibrium is dominated by temperature difference. The gradient of temperature difference triggers heat diffusion, which can be ascribed to thermal conduction, thermal convection, and thermal radiation. However, temperature difference in a system does not always dominate thermal energy transportation. Thermal energy transportation can also occur in some cases of nonequilibrium heat transfer including phase change and chemical exothermic reaction or chemical endothermic reaction. The kinetic driving forces in these cases are latent heat and chemical energy. Therefore, the thermal nonequilibrium of a system should be described as the nonequilibrium of energy states to some extent rather than the internal temperature differences.

1.1.3 Integral Structural Heat Transfer

Heat transfer in different media that is induced by thermal nonequilibrium may have different characteristics. The numerical analysis of heat transfer in the integral structure with control surface A and control volume V as boundary is defined as

$$q_{\text{heat}} = q_k + q_u + q_r$$

$$Q = \int_A (q_{\text{heat}} \cdot s_n) dA = \int_A [(q_k + q_u + q_r) \cdot s_n] dA \quad (1.1)$$

With this definition, a schematic of the outward, normal unit vector pointing out a control volume V and control surface A is shown in Figure 1.1a. The dot s_n represents location of the per unit energy state (surface normal vector) on a differential surface area. By integrating the entire surface A , when q is parallel to the surface, the dot product of q and s_n will become zero, which means no heat flows across the control surface. And if q is perpendicular to normal surface s_n ,

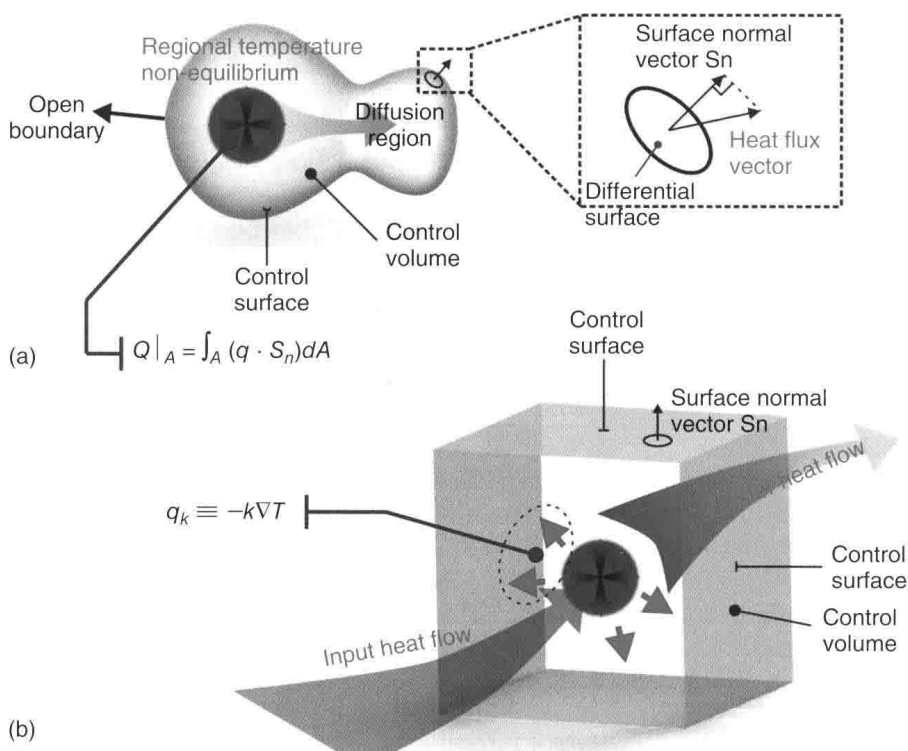


Figure 1.1 Schematic graphs of heat conductance and transfer. (Adapted from Kaviany 2011 [1].)

the dot product will be maximum.

$$Q = \int_A (q \cdot s_n) dA = \begin{cases} > 0 \\ < 0 \\ 0 \end{cases} \quad (1.2)$$

In Eq. (1.2), when the integration of the dot product is a positive quantity, heat flux flows out of the control surface; when it is negative, heat flux flows into the control surface. When a unit control volume owns a higher/lower energy state than its surrounding medium, the region with higher temperature will transport the thermal energy to a region with lower temperature. The total energy in control volume Q represents the sum of the energy integration of the surface area.

The heat flow through the control surface and volume is shown in Figure 1.1b [1], where a rectangular matter in Cartesian coordinate system receives inward energy from an external medium. The heat energy flow into this rectangular matter implies an increase in total energy. The transport of the heat shows the directional quantity, which can be expressed as a product of thermal conductivity and temperature divergence.

1.1.4 Control Volume and Interface

The boundaries of thermal system in the aforementioned model of a control volume and interface heat conductance will be studied and defined as