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Technical Note

From thermomass to entransy

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ABSTRACT

The concepts of entransy and thermomass have been developed for heat transfer analyses and optimizations. Thermomass is the equivalent mass of heat based on the Einstein's mass–energy relation. The concept of entransy reflects the energy of thermomass. The entransy balance equations of heat conduction and heat convection, which are the basis of the heat transfer optimization principles, are derived from the energy equation of thermomass in this paper. The relationship between the entransy and the thermomass is discussed.

1. Introduction

Heat transfer analyses and optimization are important topics because of the worldwide energy demand [1,2]. There are several new theories on heat transfer analyses and optimizations [1–4], such as the entransy theory [1] and the thermomass theory [2–4]. The entransy theory was applied to the optimizations of heat conduction [1,5–7], heat convection [1,8], thermal radiation [9], and heat exchanger designs [10], and the thermomass theory was used to analyze heat transfer from the viewpoint of the Einstein's mass–energy relation [2–4,11].

The concept of entransy was proposed by the analogy between heat conduction and electrical conduction, which corresponds to the electrical potential energy in a capacitor [1]. Guo et al. [1] and Cheng et al. [12] proved that the total entransy always decreases during any practical heat transfer process. Therefore, the loss in entransy due to heat transport, called entransy dissipation, is an irreversibility description of heat transfer [1,12]. With the concept of entransy dissipation, the entransy balance equation of heat transfer was set up and the minimum entransy dissipation principle for prescribed heat flow boundary conditions and the maximum entransy dissipation principle for prescribed temperature boundary conditions were derived [1]. These two principles are referred to as the extremum entransy dissipation principle and are further summarized into the minimum thermal resistance principle by defining the equivalent thermal resistance based on the entransy dissipation. The minimum entransy-dissipation-based thermal resistance principle states that lower thermal resistance leads to better heat transfer. Some heat transfer processes were optimized with these principles [1,5–10].

On the other hand, the thermomass theory [2–4] was proposed based on the Einstein's mass–energy relation. The equivalent mass of phonon gas energy is calculated by the Einstein's mass–energy relation. The momentum conservation equation of the thermomass was established based on the Newtonian mechanics [2,3], which considers the inertial force of thermomass. The inertia of thermomass is only important at very lower temperature and very high heat flux. The momentum conservation equation reduces to the Fourier's law when the inertial force can be ignored. Wang et al. [4] analyzed the heat flow in carbon nanotubes based on the thermomass theory and indicated that heat flow choking may happen in nanotube under very large heat flux.

The entransy and thermomass theories are in the developing period and still need testing with time. There is plenty of room for their growth, for instance, the relationship between the entransy theory and the thermomass theory. The basis for the applicability of the entransy theory to heat transfer analyses and optimizations is the entransy balance equation [1,13]. There is no derivation of the entransy balance equation from the viewpoint of thermomass though Guo et al. [11] showed that the concept of entransy reflects the thermal energy of thermomass of the object. It is worth of making further investigations on this topic.

2. Entransy balance equation and optimization principles for heat transfer

If we do not consider the inner heat source and the viscous dissipation, the energy conservation for heat convection can be expressed as

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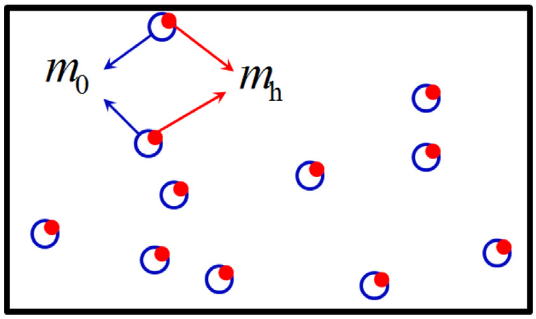

Fig. 1. Relationship between the rest mass and the equivalent mass of heat.

$$\rho_0 c_V \frac{\partial T}{\partial t} + \rho_0 c_V(\mathbf{u}_0 \cdot \nabla T) = -\nabla \cdot \mathbf{q}, \quad (1)$$

where ρ_0 is the density of the fluid, c_V is the specific heat capacity, T is temperature, t is time, $\mathbf{u}_0$ is the fluid velocity, and $\mathbf{q}$ is the heat flux density. When the value of $\mathbf{u}_0$ is zero, Eq. (1) reduces to the energy equation of heat conduction.

The left of Eq. (1) is zero for steady heat transfer. Multiplying Eq. (1) with temperature and applying the Fourier law yield [1,13]

$$\mathbf{u}_0 \cdot \nabla\left(\frac{1}{2}\rho_0 c_V T^2\right) = -\nabla \cdot (T\mathbf{q}) - k(\nabla T)^2, \quad (2)$$

where k is the thermal conductivity. The left-hand side is the entransy increase per unit volume due to convection. On the right-hand side, the first term is the net entransy flux into per unit volume associated with heat flux, while the second term is the entransy dissipation per unit volume. Eq. (2) is the entransy balance equation for heat convection. When $\mathbf{u}_0$ is zero, this equation reduces to the entransy balance equation for heat conduction.

The optimization principles of heat conduction and heat convection can be derived based on Eq. (2). For steady incompressible heat convection, the entransy dissipation can be expressed as [13,14]

$$\dot{G}_{\mathrm{dis}} = \int_V k(\nabla T)^2 \mathrm{d}V = -\int_A T\mathbf{q} \cdot \mathbf{n}\mathrm{d}A - \int_A \left(\frac{1}{2}\rho_0 c_V T^2\right)\mathbf{u}_0 \cdot \mathbf{n}\mathrm{d}A, \quad (3)$$

where V is the volume, A is its surface, and $\mathbf{n}$ is the normal vector of the surface. The second term on the right-hand side of Eq. (3) is zero for a closed system. In this case, we can define the heat transfer rate of the system as

$$Q_c = -\int_{A_{\mathrm{in}}} \mathbf{q}_{\mathrm{in}} \cdot \mathbf{n}\mathrm{d}A_{\mathrm{in}} = \int_{A_{\mathrm{out}}} \mathbf{q}_{\mathrm{out}} \cdot \mathbf{n}\mathrm{d}A_{\mathrm{out}}, \quad (4)$$

where $\mathbf{q}_{\mathrm{in}}$ is the heat flux into the system through boundary area A_{in}, while $\mathbf{q}_{\mathrm{out}}$ is that out of the system through boundary area A_{out}. With Eq. (4), the equivalent boundary temperature from which the system takes heat can be defined as

$$T_{in} = \left(-\int_{A_{\mathrm{in}}} T\mathbf{q}_{\mathrm{in}} \cdot \mathbf{n}\mathrm{d}A_{\mathrm{in}}\right)/Q_c, \quad (5)$$

while the equivalent boundary temperature that releases heat out of the system is

$$T_{\mathrm{out}} = \int_A T\mathbf{q}_{\mathrm{out}} \cdot \mathbf{n}\mathrm{d}A/Q_c. \quad (6)$$

Therefore, Eq. (3) becomes [13,14]

$$\dot{G}_{\mathrm{dis}} = Q_c(T_{\mathrm{in}} - T_{\mathrm{out}}) = Q_c \Delta T_c, \quad (7)$$

where ΔT_c is the equivalent heat transfer temperature difference for the closed system. The entransy-dissipation-based thermal resistance of the closed system can be defined as [13,14]

$$R_c = \dot{G}_{\mathrm{dis}}/Q_c^2 = \Delta T_c/Q_c. \quad (8)$$

Eqs. (7) and (8) are also tenable for heat conduction.

The heat transfer rate for a steady open system can be defined as

$$Q_{\mathrm{op}} = \int_A \rho_0 c_V T\mathbf{u}_0 \cdot \mathbf{n}\mathrm{d}A = \int_{A_{\mathrm{f\text{-}out}}} \rho_0 c_V T\mathbf{u}_{\mathrm{out}} \cdot \mathbf{n}\mathrm{d}A_{\mathrm{f\text{-}out}} + \int_{A_{\mathrm{f\text{-}in}}} \rho_0 c_V T\mathbf{u}_{\mathrm{in}} \cdot \mathbf{n}\mathrm{d}A_{\mathrm{f\text{-}in}}, \quad (9)$$

where $\mathbf{u}_{\mathrm{in}}$ is the velocity of the inlet fluid and $A_{\mathrm{f\text{-}in}}$ is the corresponding inlet area, while $\mathbf{u}_{\mathrm{out}}$ is the velocity of the outlet fluid and $A_{\mathrm{f\text{-}out}}$ is the corresponding outlet area. The equivalent temperature of the boundaries can be defined as

$$T_b = \left(-\int_A T\mathbf{q} \cdot \mathbf{n}\mathrm{d}A\right)\Big/Q_{\mathrm{op}}, \quad (10)$$

while the equivalent fluid temperature can be defined as

$$T_f = \int_A \left(\frac{1}{2}\rho_0 c_V T^2\right)\mathbf{u}_0 \cdot \mathbf{n}\mathrm{d}A/Q_{\mathrm{op}}. \quad (11)$$

Then, Eq. (3) reduces to

$$\dot{G}_{\mathrm{dis}} = Q_{\mathrm{op}}(T_b - T_f) = Q_{\mathrm{op}}\Delta T_{\mathrm{op}}, \quad (12)$$

where ΔT_{op} is the equivalent heat transfer temperature difference for the open system. Similar to Eq. (8), the thermal resistance of the open system can be defined as

$$R_{\mathrm{op}} = \dot{G}_{\mathrm{dis}}/Q_{\mathrm{op}}^2 = \Delta T_{\mathrm{op}}/Q_{\mathrm{op}}. \quad (13)$$

Eqs. (7) and (12) state that the maximum entransy dissipation rate corresponds to the maximum heat transfer rate for prescribed equivalent heat transfer temperature difference, while the minimum entransy dissipation rate corresponds to the minimum equivalent heat transfer temperature difference for prescribed heat transfer rate [1]. This is the extremum entransy dissipation principle. It can be seen from Eqs. (8) and (13) that the extremum entransy dissipation corresponds to the minimum thermal resistance, which is called the minimum thermal resistance principle [1]. These principles have been used to analyze and optimize heat conduction and heat convection problems [1,5–10].

From the above discussion, it can be found that Eq. (2), the entransy balance equation, is the basis of the optimization principles of heat transfer. Next section will display its derivation from the viewpoint of the thermomass theory.

3. Derivation of entransy balance equation from the viewpoint of thermomass

3.1. Relationship between the concepts of entransy and thermomass

Thermomass, the equivalent mass of heat in an object, which is the relativistic mass, is defined according to the Einstein mass–energy relation [2–4]

$$m_h = E_V/c^2, \quad (14)$$

where E_V is the internal energy, and c is the velocity of light (3×10^8 m/s). The internal energy is the kinetic energy of atoms' random movement. There should be a corresponding relativistic mass that is attached to the rest mass m_0 as shown in Fig. 1. With this definition, heat transfer can be treated as the movement of thermomass, which is described by the motion equation in fluid mechanics [2–4].

When the medium's temperature is much higher than the Debye temperature, its internal energy at constant volume can be expressed as [15]