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Comparison of entropy generation minimization principle and entransy theory in optimal design of thermal systems

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ABSTRACT

In this study, the relationship among the concepts of entropy generation rate, entransy theory, and generalized thermal resistance to the optimal design of thermal systems is discussed. The equations of entropy and entransy rates are compared and their implications for optimization of conductive heat transfer are analyzed. The theoretical analyses show that based on entropy generation minimization principle by decreasing irreversibility, thermodynamic optimization can be obtained. Significantly, the entransy concept merely describes the heat transfer ability and the minimum and maximum entransy dissipation principle can only lead to thermal optimization. However, due to decreasing thermal resistance both principles are considered as optimization tools for the optimal design of energy and thermal systems. Also, it is shown that the concept of entransy theory is more suitable than the concept of entropy generation for optimizing the performance of heat transfer processes.

Keywords: Entropy Generation; Entransy Theory; Thermal Resistance; Optimization.

1. Introduction

Nowadays, the architecture of engineering systems is moving towards structures that facilitate better performance of the system--i.e., they facilitate reaching the system's objectives. Optimization principles such as minimizing the time of movement, minimizing the flow resistance, minimizing the entropy generation rate, and minimizing the costs have been presented in the development trend of engineering science and have been utilized by numerous scholars as acceptable principles in different fields [1–6]. Several analyses for optimizing thermodynamic cycles have been developed in the last decade with the entropy generation minimization and the entransy theory. Comparison between their results show that the applicability of entropy generation minimization and entransy theory to the optimizations of thermodynamic cycles is conditional, depending on the optimization objectives [7–9]. Bejan [10], the first proposer of the constructal theory, reviewed all the recent studies on this theory and introduced the constructal principle alongside the first and second laws of thermodynamics as the promoter of thermodynamics towards the science of systems' structures. By reviewing many studies on optimization in different

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fields, he indicated that all the optimized structures of the systems have followed principles which at times seem to be contradictory. Some of these optimization principles include entropy generation minimization in engineering systems, maximizing entropy in geophysics, minimizing flow resistance in heat and mass flows of energy systems, and maximizing heat flow resistance in insulators. These are used depending on the type and purpose of the system. Bejan has explained and interpreted all the above-mentioned contradictory statements in the light of constructal theory. He also considered the tendency of systems to optimize performance based on structural change as a physical principle and regarded the system's capability of change as essential for constructal theory. Furthermore, in another study, Bejan [11] investigated the fundamentals of the methods of thermodynamic optimization. He indicated that allocation and geometrical structure of systems are caused by a series of thermodynamic optimization processes under the constraints of the whole system. It is shown that this principle generates structures not only in engineering but also in physical and biological sciences. Reis [12], while reviewing and examining some of the broad applications of constructal theory in different sciences, investigated the relation between constructal law and the thermodynamic optimization method of entropy generation minimization. Further, it is shown that constructal theory, from the conceptual perspective, is the basis of structures of flow systems with internal flow such as mass flow, heat flux, electric current, and goods transfer. Cheng and Liang [13] compared the applicability between concepts of entropy generation in terms of thermal conductance and generalized thermal resistance to analyze heat exchangers. They showed that for the discussed three-stream heat exchangers, the concept of generalized thermal resistance is more appropriate than the concept of entropy generation in terms of thermal conductance for describing the performance of the discussed heat exchangers. Furthermore, in another study, they [14] reviewed and discussed the development of the concept of entransy and its applications to the analyses and optimizations of heat transfer and heat-work conversion processes. One of the most important features of this work is that the concept of entransy loss is applicable for heat-work conversion analyses and optimizations. Chen et al. [15] used the minimum entropy generation and entransy dissipation extremum principles to optimize the convective heat-transfer process. Their results showed that the entransy dissipation extremum principle is more suitable than the minimum entropy generation principle for optimization of the convective heat-transfer processes not involving heat-work conversion. Cheng et al. [16] indicated that the applicability of the concepts of minimum entropy generation principle end entransy theory to analyses of heat pump systems is conditional, depending on the design objectives. They showed that all seven evaluation parameters (entropy generation rate, entropy generation number, revised entropy generation number, exergy efficiency, entransy increase rate, entransy increase coefficient, and entransy efficiency) always decrease with increase in COP except for the entransy increase rate, which increases only when the design objective is larger heat flow rate into the high temperature heat sources. In this paper, the balance equations of entropy and entransy for conductive heat transfer are derived and their implications based on thermal resistance minimization principle for optimization of this type of heat transfer are analyzed.

Nomenclature

c	Specific heat capacity (J kg^{-1} k^{-1})
E	Entransy (J k)
e	Entransy per unit mass (J k kg^{-1})
$\dot{E}_{\varphi}$	Entransy dissipation rate (W k)
h	Enthalpy (J kg^{-1})
I	Electrical current (A)
K	Thermal conductivity (W m^{-1} k^{-1})
M	Mass (Kg)
Q	Thermal energy (J)
$\dot{Q}$	Heat flow rate (W)
q	Heat flux (Wm^{-2})
$\dot{q}$	Heat generation rate (W m^{-3})
R_e	Electrical resistance (Ω)
R_h	Thermal resistance (Kw^{-1})
s	Entropy per unit mass (J kg^{-1} k^{-1})
$\dot{S}_{gen}$	Entropy generation rate (W k^{-1})
T	Temperature (K)
t	Time (s)
V	Electrical potential difference (V)

Greek symbols

ρ Density (Kg m^{-3})

2. Entropy generation and internal flow resistance

The rate of entropy generation is a measure of how internal flows deviate from their ideal limit (flow without resistances or without irreversibility). Therefore, according to the principle of entropy generation minimization, the internal flows of a system occur with minimum flow resistance (optimal performance). In the present study, the relationship between rate of entropy generation and flow resistance is examined. Eq. (1) is used to define the internal flow resistance of a system where flow I occurs under potential V.

$$R = \frac{V}{I} \quad (1)$$

Here, I (flow rate) and V (flow potential) are proposed generally, and, based on the type of flow, the flow rate can be fluid flow rate, electric current, or heat flow rate. Hence, the flow potential will be pressure difference, electric potential difference, or temperature difference respectively. For the sake of simplicity in writing, in comparing these flows with electrical current, the entropy generation rate based on thermodynamic temperature of system (T) can be illustrated as follows:

$$\dot{S}_{gen} = \frac{V.I}{T} \quad (2)$$

By combining Eqs. of (1) and (2), flow resistance based on entropy generation rate can be written as:

$$R = \frac{T \cdot \dot{S}_{gen}}{I^2} \quad (3)$$

According to Eq. (3), it can be observed that minimizing the flow resistance for a system with constant flow (I) corresponds to the principle of entropy generation minimization. In fact, for minimizing irreversibility (thermodynamic optimization), the designer or analyst of energy systems must obtain the entropy generation rate function ($\dot{S}_{gen}$) as a function of dimensional and physical parameters of the system by focusing on principles of heat transfer, thermodynamics, and fluids sciences; then, by changing one or some physical or geometrical variables, the analyst or designer should try to minimize the entropy generation rate under the constraints of the system so that the optimal structure of the system is achieved. This is used as a means of achieving purposes and concepts of constructal theory; in other words, based on constructal theory, the optimal structure of flows can be determined through principles such as entropy generation minimization.

3. Applicability of entropy generation and entransy theory in heat transfer optimization

3.1. Entransy dissipation, entropy generation, and irreversibility of heat transfer

From the thermodynamic point of view, heat transfer is an irreversible process. For the first time, Bejan proposed the principle of entropy generation minimization as the purpose of optimization of heat transfer processes in the engineering field and obtained equations for heat exchangers and thermal equipment optimization. With the passage of time and on account of the numerous investigations conducted in the field of optimization of heat transfer processes, especially heat exchangers, contradictions were observed in application of entropy generation in thermal engineering. Some scholars revealed that the principle of entropy generation minimization is not always true in all cases, especially in heat exchangers: i.e., a system's performance can increase, decreases, or remain constant by minimizing entropy generation [17]. To resolve this contradiction, Guo introduced two new physical concepts—entransy and entransy dissipation—for describing the irreversibility of heat transfer processes. Entransy is proposed as a new physical quantity which describes the heat transfer ability. This quantity is defined based on the analogy between electrical conduction and heat conduction and has been set as the foundation of optimization of heat transfer processes. The differential form of entransy of a body at equilibrium state is defined as [18]:

$$dE = (McT)dT \quad (4)$$

where M is the mass, c is the specific heat capacity, and T is the thermodynamic temperature of the body.

Every heat transfer process is accompanied by entransy transfer; due to irreversibility and loss of the heat transfer ability, entransy is destroyed. Considering the boundary conditions, when the entransy dissipation is minimized or maximized, heat transfer process is optimized. This is called the principle of minimum and maximum entransy dissipation in optimization of heat transfer processes [19]. To illustrate this issue and compare entransy and entropy, the conductive heat transfer process has been examined in this paper.

Differential equation of heat conduction in solid or liquid bodies is written as illustrated in Eq. (5):

$$\rho c \frac{\partial T}{\partial t} = -\nabla \cdot q + \dot{q} \tag{5}$$

where q is heat flux vector going through the body, $\dot{q}$ is heat generation rate per unit volume, and ρ and c are density and specific heat capacity of the body respectively.

The entropy balance equation for this kind of heat transfer and the relation between enthalpy (h) and entropy (s) for an incompressible body can be written as displayed in Eqs. (6) and (7) [20, 21]:

$$\rho \frac{\partial s}{\partial t} = -\nabla \cdot \left(\frac{q}{T}\right) + K \frac{(\nabla T)^2}{T^2} + \frac{\dot{q}}{T} \tag{6}$$

$$T \frac{\partial s}{\partial t} = \frac{\partial h}{\partial t} = c \frac{\partial T}{\partial t} \tag{7}$$

where K is thermal conductivity of the body. The left term in Eq. (6) indicates the time variation of the entropy stored per unit volume. The first term on the right hand side of Eq. (6) represents the rate of entropy transfer from one part of the body to another part; the second term indicates the entropy generation rate induced by the heat transfer irreversibility; and the third term is an internal heat source in the form of entropy expression. The first and second terms on the right hand side of Eq. (6) can be rewritten as shown in Eq. (8).

$$-\nabla \cdot \left(\frac{q}{T}\right) = -\frac{1}{T} \nabla \cdot q + \frac{q}{T} \cdot \left(\frac{\nabla T}{T}\right) \tag{8-a}$$

$$K \frac{(\nabla T)^2}{T^2} = \frac{q}{T} \cdot \left(\frac{-\nabla T}{T}\right) \tag{8-b}$$

Multiplying the sides of the entropy balance equation by T^2 and combining it with Eqs. (7) and (8) lead to:

$$\rho c T \frac{\partial T}{\partial t} = -\nabla \cdot (qT) - K(\nabla T)^2 + \dot{q}T \tag{9}$$

According to Eq.(4), the differential relation of entransy rate per unit mass is obtained as:

$$\frac{\partial e}{\partial t} = cT \frac{\partial T}{\partial t} \tag{10}$$

By placement in Eq.(9), the entransy balance equation is written as:

$$\rho \frac{\partial e}{\partial t} = -\nabla \cdot (qT) - K(\nabla T)^2 + \dot{q}T \tag{11}$$

where $\rho \frac{\partial e}{\partial t}$ is the time variation of the entransy stored per unit volume, $-\nabla \cdot (qT)$ is the rate of entransy transfer associated with the heat transfer, $K(\nabla T)^2$ is the entransy dissipation rate induced by the heat transfer irreversibility, and $\dot{q}T$ is internal heat source in form of entransy expression.

Essentially, the entransy balance equation and the concept of entransy dissipation are derived from the energy conservation equation, which can be seen across literature [14, 18, 22, 23]. Here, the entransy rate equation for conductive heat transfer was derived from the second law of thermodynamics. In fact, the entropy balance equation was also derived from the energy conservation equation. Comparison between the relations of entropy and entransy balances (relations (6) and (11)) shows that in entropy rate equation the expression of entropy generation resulted by heat transfer ($K\frac{(\nabla T)^2}{T^2}$) is consistently positive and has a direct relationship with the square of the temperature gradient and a reverse relationship with square of absolute temperature. On the other hand, in entransy rate equation the expression of entransy dissipation resulted by heat transfer ($K(\nabla T)^2$) is only dependent to the square of the temperature gradient. It is indicated that entropy in a heat transfer process tends to increase while entransy changes in the opposite direction. In other words, the entransy decrease principle is equivalent to the second law of thermodynamics in heat transfer and both the expression of entransy dissipation and entropy generation can be used as the irreversibility measurements for heat transfer processes. Furthermore, for the problem of heat transfer optimization, the temperature gradient and consequently the thermal resistance of the body will not necessarily decrease by minimizing the entropy generation rate, but the minimum thermal gradient can be obtained by minimizing the entransy dissipation rate.

3-2- Extremum entransy dissipation and entropy generation minimization principles

Here, the optimization of heat transfer processes based on entransy theory is proposed in terms of minimum or maximum entransy dissipation rate similar to the principle of entropy generation minimization in the second law of thermodynamics. The integrals of local entransy dissipation and local entropy generation are conducive for extremum entransy dissipation and minimum entropy generation principles respectively. However, application of these principles to optimize a heat transfer process can lead to quite different results. By considering the equation entransy dissipation rate, it can be observed that the entransy dissipation rate is merely dependent on heat flux passing through boundaries and temperature boundary conditions of the system.

$$\dot{E}_{\varphi} = K(\nabla T)^2 = -q.\nabla T \tag{12}$$

For a steady state heat conduction process at a given heat transfer rate ($\dot{Q}$) without internal heat sources, the minimum entransy dissipation was obtained as [14, 22, 23]:

$$\delta(\dot{E}_{\varphi}) = \dot{Q}\delta(\overline{\Delta T}) = \delta \iiint_V K|\nabla T|^2 dV = 0 \tag{13}$$

where $\dot{E}_{\varphi}$ is the entransy dissipation rate and $\overline{\Delta T}$ is the average temperature over the entire domain. Eq. (13) indicates that entransy dissipation minimization for the prescribed heat flux conditions leads to minimum temperature difference: i.e., optimized heat transfer. In the same way, for a steady state heat conduction process at a given temperature difference without internal heat sources, maximum entransy dissipation can be written as:

$$\delta(\dot{E}_{\varphi}) = \overline{\Delta T}\delta(\dot{Q}) = \delta \iiint_V \frac{1}{K}|\mathrm{q}|^2 dV = 0 \tag{14}$$

It shows that the entransy dissipation maximization for the prescribed temperature boundary conditions leads to the maximum heat flow rate. Also, for a steady state heat removal process with a prescribed internal heat source ($\dot{q}$), the optimization equation can be presented as [22, 23]:

$$\delta(\dot{E}_{\varphi}) = \dot{q}\delta(\overline{\Delta T}) = \delta \iiint_V -\dot{q}.\nabla T dV = 0 \tag{15}$$

which shows that in a heat removal process, minimizing the entransy dissipation leads to minimum average temperature over the entire domain.

In addition, according to the principle of minimum entropy generation, the integral of local entropy generation for the optimization of a steady-state heat dissipating process can be written as [23]:

$$\dot{Q}\delta\left(\Delta(\frac{1}{T})\right) = \delta \iiint_V \frac{K|\nabla T|^2}{T^2} dV = 0 \tag{16}$$

where $\Delta(\frac{1}{T})$ is the equivalent thermodynamics potential difference. Therefore, the entropy generation minimization principle is equal to minimum exergy dissipation during a heat transfer process.

In summary, the extremum principle or minimum and maximum entransy dissipation suggests that in designing thermal systems (only for heating or cooling processes) with maximum entransy dissipation in specified temperature boundary conditions, maximum heat flux can be obtained; and with minimum entransy dissipation in conditions where there is specified heat flux on system's boundaries, minimum thermal gradient can be obtained. Thus, for heat-work conversion in thermodynamic cycles, the entropy generation minimization principle is suitable to optimize the heat transfer process. In next section, it is indicated that the extremum principle of entransy dissipation corresponds to the principle of minimum thermal resistance in designing heat transfer facilities.

3.3. Minimum thermal resistance principle based on entransy theory

Thermal resistance is defined as the ratio of the temperature difference to the heat flux. This thermal resistance definition, as well as the electrical resistance definition, is only valid for one-dimensional problems. The thermal resistance for multi-dimensional heat transfer problems is difficult (compared to one-dimensional issues) to define, especially with non-isothermal boundary conditions. However, an equivalent thermal resistance can be defined for multi-dimensional problems with complex boundary conditions based on the concept of entransy dissipation. Moreover, by maximizing or minimizing entransy dissipation, thermal systems can be designed with minimum thermal resistance in engineering architecture. To illustrate the relationship between entransy dissipation and thermal resistance, the analogy between heat conduction and electric conduction is used [18, 24]. For the sake of simplicity, one-dimensional electric conduction is taken into consideration. Electrical energy loss per time unit which corresponds to entransy dissipation in heat conduction can be written as:

$$\dot{E}_{\varphi} = R_e I^2 = \frac{V^2}{R_e} \quad (17)$$

where V is potential difference, I is current, and R_e is electrical resistance. Thus, relations of (18) can be written for electrical resistance.

$$R_e = \frac{\dot{E}_{\varphi}}{I^2} \quad (18\text{-a})$$

$$R_\mathrm{e} = \frac{V^2}{\dot{E}_{\varphi}} \quad (18\text{-b})$$

In multi-dimensional issues for calculating equivalent resistance, the average potential difference and overall flow can be used. Therefore, in heat conduction where heat difference corresponds to electrical potential difference, thermal flow to electrical current, and thermal resistance to electrical resistance, relations (19) can be written for thermal resistance as:

$$R_h = \frac{\dot{E}_{\varphi}}{\dot{Q}^2} \quad (19\text{-a})$$

$$R_\mathrm{h} = \frac{\Delta T^2}{\dot{E}_{\varphi}} \quad (19\text{-b})$$

where $\dot{E}_{\varphi}$ is entransy dissipation and $\dot{Q}$ is the heat flow rate at the system's boundaries, and where average heat difference or the total rate of heat conduction at the boundaries can be used for issues of multi-dimensional heat conduction for defining thermal resistance.

According to the relations between thermal resistance and entransy dissipation, the physics of the principle of minimum and maximum entransy in optimization of heat transfer processes can be understood. Equation (19-a) indicates, by minimizing entransy dissipation for an issue with fixed heat flux at system's boundaries, that thermal resistance can be minimized; and according to Equation (19-b), by maximizing entransy dissipation with fixed boundary thermal conditions, the thermal resistance can be minimized again. In other words, by the principle of minimum and maximum entransy dissipation in thermal systems with constraints such as stability of the volume or the conductive material of the system, the thermal resistance of the system can be minimized in a way that—based on the specified thermal boundary conditions—heat transfer rate is maximized. Besides, in specified heat flux conditions, the internal thermal gradient of the system is minimized and the thermal performance of the system is optimized. Entransy dissipation based on thermal resistance has been used to optimize heat transfer units, including heat exchangers and heat exchanger networks, for energy saving of thermal facilities [17, 25–28].

As it was observed, entransy theory is a new statement of the second law of thermodynamics in thermal systems and the rate of entransy dissipation expresses the degree of irreversibility of the heat transfer process. In addition, the extremum entransy dissipation principle or the thermal resistance minimization principle based on entransy dissipation can be used as the tool of optimization in the design of thermal systems.

4. Conclusion

The optimal design of energy and thermal systems can be determined based on some thermodynamic concepts such as the principle of entropy generation minimization or the principle of entransy dissipation extremum. By examining the relations between entropy and entransy in heat transfer processes, the following concepts can be deduced:

- In irreversible processes such as heat transfer, entropy changes resulting from irreversibility is positive and entransy differences are negative. This issue is the foundation of entropy generation and entransy dissipation in heat transfer processes.
- The entransy dissipation rate, like entropy generation rate, changes in proportion to the irreversibility rate of the system. Hence, entransy as a variable of a system's status in a new expression of the second law of thermodynamics can be used to introduce the irreversibility of the system in the heat transfer process.
- In the heat transfer processes, the entropy generation rate has direct relationship with the square of the temperature gradient and has reverse relationship with square of absolute temperature, while the entransy dissipation function is only correlated with the square of the temperature gradient. Hence, particularly in heat transfer processes and the method of minimizing the entransy dissipation function can be more effective in decreasing the temperature gradient in

comparison with the method of entropy generation minimization.

Generally, both concepts of entropy and entransy are used in thermal systems. The concept of entropy generation or exergy loss describes the loss of ability for performing work and heat processes; based on the entropy generation minimization principle by decreasing irreversibility, thermodynamic optimization can be obtained. Entransy, as a concept, merely describes the heat transfer ability and the minimum and maximum entransy dissipation principle can lead to thermal optimization. However, due to decrease in the thermal resistance both principles are considered as tools for optimal design of energy and thermal systems.

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