Role of entropy generation minimization in thermal optimization*

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Thermal optimization is very important for improving the performances of thermal systems. In engineering, the entropy generation minimization (EGM) has been widely used to optimize and evaluate the performances of thermal systems. However, the consistency between the EGM and the optimization objective should be specified when the EGM is used. In this paper, we discuss the view angle of irreversibility of entropy generation, and show that entropy generation directly reflects the exergy destruction or the ability loss of doing work. As the design objective in a thermal system is not often consistent with the view angle of irreversibility of entropy generation, the EGM may not lead to the optimal value of the design objective. In heat transfer and heat-work conversion, the inconsistence between the design objectives and the EGM is shown with some examples, and the applicability of the EGM is found to be conditional. The "entropy generation paradox" in heat exchanger analyses is also discussed, and it is shown that there is no direct monotonic relation between the minimum entropy generation rate and the best heat transfer performance of heat exchangers.

Keywords: entropy generation, thermal analysis, heat transfer, heat-work conversion

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1. Introduction

The design of the thermal system is very important for improving the system performance and reducing the cost.[1–3] For instance, the analysis and optimization design of the thermal control system are necessary because they are beneficial to the effective and steady operation of the spacecraft.[4] In the design of thermal power plants, the thermal processes should also be optimized to increase the output power.[5] Hence, this topic receives great attention from researchers.

In thermal optimizations, the concept of entropy generation is very often used because it can measure the irreversibilities of thermal processes. Many researchers have made contributions in this aspect. For instance, Li and Lai[6] optimized the performance of the ground heat exchanger with single U-tube by the entropy generation minimization method. Abbassi[7] applied the concept of entropy generation to the analyses of a uniformly heated microchannel heat sink. Baytaş[8] discussed the entropy generation for the natural convection in an inclined porous cavity. A lot of interesting and important results had been obtained when the concept of entropy generation was used.

On the other hand, it has been shown that the entropy generation minimization (EGM) does not always lead to the best system performance.[9–14] In heat exchanger analyses, the "entropy generation paradox"[9] is a well-known example. It was found that the heat exchanger effectiveness does not always increase with reducing entropy generation rate or entropy generation number. In refrigeration systems, Klein and Reindl[10] found that minimizing the entropy generation rate does not always result in the same design as maximizing the system performance unless the refrigeration capacity is fixed. In the analyses of an air conditioning system for room heating, Cheng and Liang[11] found that the EGM does not always lead to the increase of the heat flow rate into the room.

Therefore, it is worth making more efforts to discuss the role of EGM in thermal optimization. In this paper, the view angle of the irreversibility of entropy generation is analyzed, and the applicability of the EGM to the thermal optimizations is discussed. Some examples on heat transfer and heat-work conversion are also presented.

2. Irreversibility, entropy generation and system performance

2.1. View angle of irreversibility of entropy generation

Irreversibility is an important characteristic of physical process in nature, which results in the symmetry breaking and the unidirectionality of time. Therefore, for any system with fixed boundary conditions, we can find a function that varies monotonically with time when an irreversible process happens. This function is called the Lyapounov function[15] and can be used to measure the irreversibility. In "From Being to Becoming" by Prigogine,[15] it was pointed out that the criterion of the Lyapounov function is that the positive or negative symbol of the derivative of the function with respect to time must be different from that of the function itself. For instance,

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for a closed system with fixed temperature and pressure, the Gibbs free energy satisfies the criterion, so it is the Lyapounov function and the time arrow of the system. For a closed system with fixed temperature and volume, the Helmholtz free energy is the Lyapounov function.

From the above, it can be seen that we could have different Lyapounov functions for the systems with different boundary conditions. Even for the same system, the criterion of the Lyapounov function does not refuse two or more ones, which means that we may have different Lyapounov functions for one specific system as long as the functions satisfy the criterion. These functions may be different projections of the irreversibility from different view angles. Obviously, the view angles of irreversibility for the Gibbs free energy and the Helmholtz free energy are different. Therefore, the discussion on the view angle of the Lyapounov functions is necessary for understanding the characteristics of the functions.

As is well known, entropy is a Lyapounov function of the isolated system, and is also widely used to measure the irreversibilities of physical processes. This concept was introduced by Clausius when he investigated the Carnot cycle in 1854.[16] The expression of entropy is

$$\mathrm{d}S = (\delta Q/T)_{\mathrm{rev}}, \tag{1}$$

where $\mathrm{d}S$ is the differentiation of entropy, δQ is the heat exchange between the system and the environment, T is the temperature of the heat source that is also the environment temperature for the reversible process, and the subscript, rev, means that the process is an ideal reversible process. Furthermore, Clausius derived the Clausius inequality for entropy that entrusts the second thermodynamic law with mathematical expression and makes it possible to calculate the irreversibility in quantity. The concept of entropy generation is the key parameter for the calculation. For a non-equilibrium system, there is[16]

$$\mathrm{d}s = \delta s_{\mathrm{f}} + \delta s_{\mathrm{g}}, \tag{2}$$

where $\mathrm{d}s$ is the entropy change rate, δs_{f} is the entropy flow rate, and δs_{g} is the entropy generation rate. As is well known, larger entropy generation rate means larger irreversibility. At the same time, we may ask one question here: what is the view angle of irreversibility of entropy generation? This question is not easy to answer because the concept of entropy has already been extended to many academic fields. Therefore, we only discuss it in thermal science below.

In thermal science, entropy was first introduced in analyzing the Carnot cycle, and the main view angle of irreversibility of entropy generation may be related to heat–work conversion although entropy has been applied to many other thermal problems. To simplify the problem, we can analyze a steady system here. With Eq. (2), we can obtain[12,17]

$$e_{\mathrm{net}} = w + T_0 s_{\mathrm{g}}, \tag{3}$$

where e_{net} is the net exergy into the system, w is the output power, and T_0 is the reference temperature. In Eq. (3), $T_0 s_{\mathrm{g}}$ is called the exergy destruction rate, which is indicated by the Gouy–Stodola theorem,

$$e_{\mathrm{des}} = T_0 s_{\mathrm{g}}. \tag{4}$$

Exergy destruction means the ability loss of doing work. As the reference temperature is always fixed, equation (4) shows that entropy generation directly reflects the exergy destruction or the ability loss of doing work. This is the main view angle of entropy generation when it is used to measure the irreversibilities of thermal processes.

2.2. System performance optimization

In thermal engineering, the concept of entropy generation is taken as an important tool to optimize the system performance in many cases. As the decrease of entropy generation means the decrease of irreversibility, it is believed that the entropy generation would decrease with increasing system performance. However, researchers have shown that the concept of entropy generation does not take effect in this way sometimes.[9–14]

In practical applications, the system performance may mean different objectives, such as the maximum heat transfer rate,[18] the maximum heat exchanger effectiveness,[13] the minimum average temperature of the heated domain,[19] the maximum output power,[20] the maximum COP of the heat pump systems,[21] etc. When the system performance maximization is consistent with the EGM, it is very sure that the decrease of entropy generation will lead to the performance improvement. On the other hand, if the performance maximization and the EGM lead to different targets, the EGM may not be applicable for improving the performance. In other words, the best system performance may not need to correspond to the minimum irreversibility measured by entropy generation. Whether a parameter can be used to evaluate the performance of a system depends on its consistency with the design objective of the system. This rule also holds true when the EGM is used to evaluate thermal systems and should be paid enough attention to. In the following, some heat transfer and heat–work conversion problems will be taken for example to explain the point in detail.

3. Examples in heat transfer

In a pure heat transfer process without work interaction, heat is only transferred for heating or cooling objects. There have been many different design objectives in practical applications, such as the system mass minimization,[22] the homogenization of temperature field,[4] the heat transfer

rate maximization,[18] the heat transfer temperature difference minimization,[18] etc. It is very obvious that these objectives are not always consistent with the EGM because they are not related to the exergy destruction or the ability loss of doing work. Therefore, the irreversibility minimization from the viewpoint of entropy generation will not always benefit the design objectives. Some simple examples are presented below.

3.1. A heat transfer process with fixed heat transfer rate

In the system shown in Fig. 1, there are two devices with fixed heat payloads, Q_1 and Q_2, which are released into the environment at temperature T_0. The heat transfer coefficients, k_1 and k_2, to each payload are also fixed. The heat transfer areas of the devices are A_1 and A_2, respectively. The limiting condition of the heat transfer problem is

$$A = A_1 + A_2 = \text{const}, \tag{5}$$

and the design objective is to minimize the average temperature of the devices,

$$T = (T_1 Q_1 + T_2 Q_2)/(Q_1 + Q_2), \tag{6}$$

where T_1 and T_2 are the temperatures of the devices. It can be seen that the average temperature is defined as the equivalent working temperature weighted by heat flow rate of the devices. This problem has been discussed numerically in Ref. [23]. Its theoretical analysis is given below.

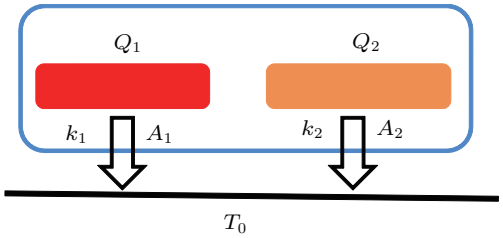


Fig. 1. (color online) Heat transfer process with fixed heat transfer rate.

Considering the heat transfer law, we have

$$\begin{aligned} T &= \frac{\left(\dfrac{Q_1}{k_1 A_1} + T_0\right) Q_1 + \left(\dfrac{Q_2}{k_2 A_2} + T_0\right) Q_2}{Q_1 + Q_2} \\ &= \frac{1}{Q_1 + Q_2}\left(\frac{Q_1^2}{k_1 A_1} + \frac{Q_2^2}{k_2 A_2}\right) + T_0. \end{aligned} \tag{7}$$

To find the minimum value of Eq. (7) under the limitation condition of Eq. (5), a function can be set up,

$$F = \left(\frac{Q_1^2}{k_1 A_1} + \frac{Q_2^2}{k_2 A_2}\right) \Big/ (Q_1 + Q_2) + T_0 + \lambda\,(A_1 + A_2 - A), \tag{8}$$

where λ is the Lagrange multiplier. The variations that lead to the minimum value of Eq. (7) should satisfy

$$\frac{\partial F}{\partial A_1} = \frac{\partial F}{\partial A_2} = \frac{\partial F}{\partial \lambda} = 0. \tag{9}$$

Solving Eq. (9) gives

$$A_1 = A \Big/ \left(1 + Q_2 \sqrt{k_1/k_2}/Q_1\right), \tag{10}$$

$$A_2 = A \Big/ \left(1 + Q_1 \sqrt{k_2/k_1}/Q_2\right). \tag{11}$$

When the heat transfer area is distributed according to Eqs. (10) and (11), the average temperature reaches its minimum value.

If we use the concept of entropy generation to analyze the process, we have

$$\begin{aligned} s_{\mathrm{g}} &= \frac{Q_1 + Q_2}{T_0} - \left(\frac{Q_1}{T_1} + \frac{Q_2}{T_2}\right) \\ &= \frac{Q_1 + Q_2}{T_0} - \left(\frac{Q_1}{\dfrac{Q_1}{k_1 A_1} + T_0} + \frac{Q_2}{\dfrac{Q_2}{k_2 A_2} + T_0}\right). \end{aligned} \tag{12}$$

To minimize Eq. (12), a function can also be set up,

$$\begin{aligned} H &= \frac{Q_1 + Q_2}{T_0} - \left(\frac{Q_1}{\dfrac{Q_1}{k_1 A_1} + T_0} + \frac{Q_2}{\dfrac{Q_2}{k_2 A_2} + T_0}\right) \\ &\quad + \beta\,(A_1 + A_2 - A), \end{aligned} \tag{13}$$

where β is the Lagrange multiplier. The variations that minimize Eq. (13) should satisfy

$$\frac{\partial H}{\partial A_1} = \frac{\partial H}{\partial A_2} = \frac{\partial H}{\partial \beta} = 0. \tag{14}$$

Solving Eq. (14) gives

$$A_1 = \left[A - \frac{Q_2}{T_0}\left(\frac{1}{\sqrt{k_1 k_2}} - \frac{1}{k_2}\right)\right] \Big/ \left(1 + \frac{Q_2}{Q_1}\sqrt{\frac{k_1}{k_2}}\right), \tag{15}$$

$$A_2 = \left[A - \frac{Q_1}{T_0}\left(\frac{1}{\sqrt{k_1 k_2}} - \frac{1}{k_1}\right)\right] \Big/ \left(1 + \frac{Q_1}{Q_2}\sqrt{\frac{k_2}{k_1}}\right). \tag{16}$$

When the heat transfer area is distributed according to Eqs. (15) and (16), the entropy generation rate reaches its minimum value.

Comparing the distribution results shown in Eqs. (10), (11), (15), and (16), we can find that the design objective and the EGM are consistent only when $k_1 = k_2$. If $k_1 \neq k_2$, the EGM will not lead to the lowest average temperature of the devices. As there is no work interaction in the system, equation (3) can be changed into

$$e_{\mathrm{net}} = e_{\mathrm{in}} - e_{\mathrm{out}} = T_0 s_{\mathrm{g}}, \tag{17}$$

where e_{in} is the exergy flow rate into the system, and e_{out} is that out of the system and it is zero because the heat flow rates from the devices are both released to the environment. Therefore, entropy generation expresses the exergy flow into the system. However, what is of interest to us in this problem is the average temperature of the devices, which is different from what the EGM brings to us.

3.2. One-dimensional heat transfer processes

As shown in Fig. 2, there are four infinite heat sources, a, b, c, and d, whose temperatures are T_a, T_b, T_c, and T_d, respectively. There are two heat transfer processes. The heat transfer rate between the heat sources a and b is Q_1, while that between the heat sources c and d is Q_2. Assume that $T_a > T_c$. What we focus on here are the heat transfer rate, the heat transfer temperature difference and the thermal resistance, which is very common in heat transfer analyses. With this consideration, the heat transfer performances of the two heat transfer processes can be compared.

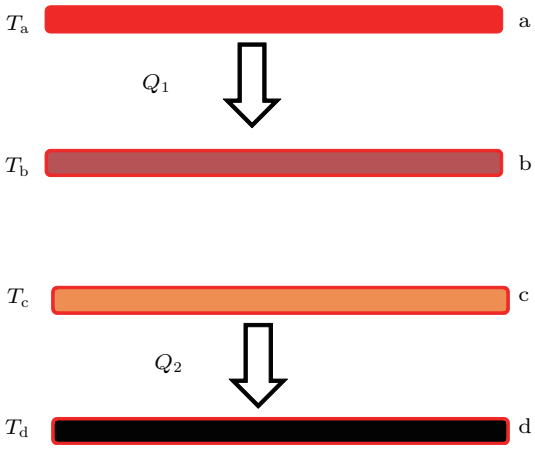


Fig. 2. (color online) One-dimensional heat transfer process.

First, we consider a case in which the heat transfer temperature differences are $T_a - T_b = T_c - T_d$ and the heat flow rates are identical, i.e., $Q_1 = Q_2$. It can be seen that the thermal resistances are also the same. Therefore, from the viewpoint of heat transfer, the performances of the two processes are the same. However, if we calculate the entropy generation rates of the processes on the assumption that $T_a > T_c$, we have

$$\begin{aligned} s_{g-1} &= Q_1\left(\frac{1}{T_b}-\frac{1}{T_a}\right) = \frac{Q_1(T_a-T_b)}{T_aT_b} < \frac{Q_2(T_c-T_d)}{T_cT_d} \\ &= Q_2\left(\frac{1}{T_d}-\frac{1}{T_c}\right) = s_{g-2}, \end{aligned} \tag{18}$$

where s_{g-1} and s_{g-2} are the entropy generation rates. It can be seen that the heat transfer performances are different from the viewpoint of entropy generation. Equation (3) indicates that smaller irreversibility from the viewpoint of entropy generation means smaller exergy destruction rate, which is not the objective that we are concerned with here.

The difference between our objective and the EGM can also be found in the case in which $s_{g-1} = s_{g-2}$ and $Q_1 = Q_2$. From the viewpoint of entropy generation, the irreversibilities and the exergy destruction rates of the two processes are the same. However, if we calculate the heat transfer temperature differences, we can find that

$$T_a - T_b > T_c - T_d. \tag{19}$$

It is shown that the heat transfer between the heat sources a and b needs a larger temperature difference when the same heat transfer rate is obtained. It means that the thermal resistance between the heat sources a and b is larger, so the heat transfer performance between the heat sources a and b is lower than that between the heat sources c and d. As the view angles are not consistent with each other, different conclusions can be obtained with different concepts.

3.3. Two-stream heat exchanger

As shown in Fig. 3, the inlet and outlet temperatures of the hot and cold streams are T_{in-h}, T_{in-c}, T_{out-h}, T_{out-c}, and the heat capacity flow rates are C_h and C_c, respectively. In many practical cases, the applications of two-stream heat exchangers are irrelevant to doing work, and they are only used to heat or cool streams, so we mainly focus on the heat transfer performances of heat exchangers here. The objective can be the heat transfer rate or the heat exchanger effectiveness, ε.

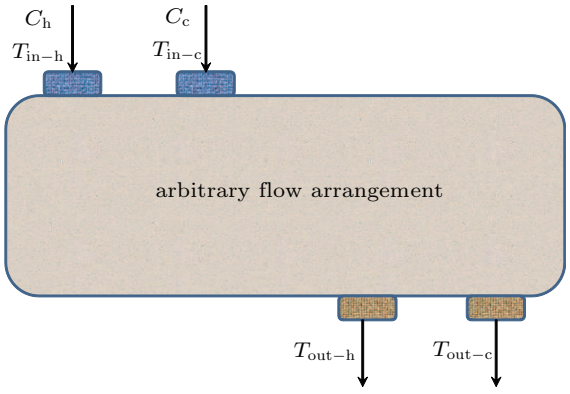


Fig. 3. (color online) A two-stream heat exchanger.[24]

The heat transfer rate and the effectiveness are

$$Q = C_h(T_{in-h} - T_{out-h}) = C_c(T_{out-c} - T_{in-c}), \tag{20}$$

$$\varepsilon = \frac{Q}{Q_{max}} = \frac{C_h(T_{in-h}-T_{out-h})}{C_{min}(T_{in-h}-T_{in-c})} = \frac{C_c(T_{out-c}-T_{in-c})}{C_{min}(T_{in-h}-T_{in-c})}, \tag{21}$$

where Q_{max} is the maximum possible heat transfer rate, and

$$C_{min} = \min(C_h, C_c). \tag{22}$$

From Eqs. (20) and (21), we cannot find any direct relationship between ε (or Q) and the exergy destruction, so it will not be strange if inconsistence occurs between the EGM and the heat transfer performances of the heat exchangers.

When analyzing the balanced counterflow heat exchanger with zero pressure-drop irreversibility, Bejan[9] first noted that the entropy generation rate or entropy generation number does not decrease with increasing ε when $\varepsilon \in [0, 0.5]$. Instead, the entropy generation rate or entropy generation number increases and reaches its maximum value at $\varepsilon = 0.5$. This behavior of entropy generation was called "entropy generation paradox". Bejan[9,25] explained that the origin of this paradox was

clear and that the "entropy generation maximum" (at $\varepsilon = 0.5$) associated with it is of little practical consequence[9] and the "paradox" disappears if one considers the effect of heat exchanger size not on the heat exchanger alone, but on the whole energy system in which the heat exchanger is an organ.

However, as a performance evaluation parameter, the consistency between the parameter and the optimization objective is necessary. The variation tendency between EGM and the effectiveness does not follow this rule when $\varepsilon \in [0, 0.5]$. For a heat exchanger with arbitrary flow arrangement shown in Fig. 3, the entropy generation rate or entropy generation number still increases with increasing ε in the range of the effectiveness, which is given as[26]

$$\varepsilon \in [0,\ 1/(1+C^*)]\,, \tag{23}$$

where C^* is the ratio of $C_{\min}$ to the bigger one between $C_{\rm h}$ and $C_{\rm c}$. The value of ε cannot be close to zero but some other values in the range of Eq. (23). In particular, in parallel flow heat exchanger, ε always increases with increasing entropy generation rate or entropy generation number because the maximum value of ε in parallel flow heat exchanger is $1/(1+C^*)$. It can be seen that the concept of entropy generation is unsuitable for evaluating the heat transfer performance here. For the energy system in which the heat exchanger is an organ, it may not be a pure heat transfer system, but a system with heat-work interaction in which the purpose of heat transfer is to do work. In this case, the entropy generation paradox is not settled down and there remains further discussion on this issue.[13,24,26–31]

It is shown in Eq. (4) that the objective of the EGM is to minimize the ability loss of doing work, while the usual objective for heat exchangers is to maximize Q or ε. The view angle of irreversibility of entropy generation is different from that of the design objective of heat exchanger. Bejan[25] had to admit that the effectiveness (ε) is not a relevant measure of the thermodynamic performance of a heat exchanger. The entropy generation paradox just shows the difference. In other words, entropy generation is not a proper parameter to evaluate the heat transfer performance itself of heat exchangers.

As below, a numerical example with zero pressure-drop irreversibility is presented. Assume that $C_{\rm h} = C_{\rm c} = 1$ W/K, $T_{\rm in-h} = 500$ K, $T_{\rm in-c} = T_0 = 300$ K. The inlet exergy flow rate into the system is fixed because the inlet parameters of the streams are fixed. From Eq. (17), it can be seen that smaller entropy generation refers to larger exergy flow out of the system, which means that the EGM leads to the maximization of the ability to do work for the streams out of the heat exchanger. The exergy flow rate out of the heat exchanger can be calculated from

$$\begin{aligned} e_{\rm out} \ =\ & C_{\rm h}\left[T_0 \ln\left(T_0/T_{\rm out-h}\right) + \left(T_{\rm out-h} - T_0\right)\right] \\ & + C_{\rm c}\left[T_0 \ln\left(T_0/T_{\rm out-c}\right) + \left(T_{\rm out-c} - T_0\right)\right], \end{aligned} \tag{24}$$

and the entropy generation rate can be calculated from[24]

$$s_{\rm g} = C_{\rm h} \ln\left(T_{\rm out-h}/T_{\rm in-h}\right) + C_{\rm c} \ln\left(T_{\rm out-c}/T_{\rm in-c}\right). \tag{25}$$

With Eqs. (20)–(25), the variations of the entropy generation rate and the exergy flow rate out of the heat exchanger with the effectiveness are shown in Fig. 4. The results show that the curve of exergy flow rate out of the heat exchanger versus effectiveness has a minimum value, and which corresponds to the maximum entropy generation rate. The variation tendency of the exergy flow rate is opposite to that of the entropy generation rate. If the outlet maximum exergy flow rate is the design objective for the heat exchanger, the EGM is applicable, while it is not applicable if the effectiveness is the objective. The numerical results verify the theoretical analyses above.

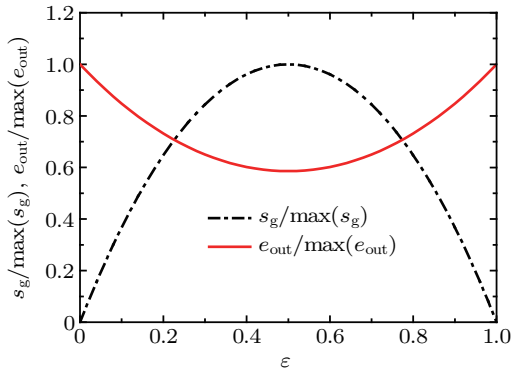


Fig. 4. (color online) Variations of the entropy generation rate and the exergy flow rate out of the heat exchanger with heat exchanger effectiveness.

4. Examples in heat–work conversion

In heat–work conversion, we also may have many different design objectives, such as the output power,[20] the thermal efficiency,[32] the thermoeconomic performance,[33] the COP of heat pump systems,[21] the heat flow rate into the high temperature heat source in heat pump systems,[21] etc. Some of them may be consistent with the design direction of the EGM, while some may be not. So, the applicability of the EGM also needs further investigating.

4.1. Output power analyses

Equation (3) is the relationship between the entropy generation rate and the output power. The entropy generation does not describe the output power directly, but reflects the output power indirectly by measuring the exergy destruction. Therefore, the applicability of the EGM to optimizing output power is conditional, and the precondition under which the minimum entropy generation rate corresponds to the maximum output power is that the net exergy flow rate into the system is fixed.[17] The EGM may not lead to the maximum output power if the precondition is not satisfied. Different groups have addressed this issue,[12,17,34] and even the effects from

different heat transfer laws were investigated.[34] Many examples showed the inconsistence between the EGM and the output power maximization.[5,17,20,32,34,35] In the present work, it is not necessary to add another new example to confirm the obtained conclusions about the applicability of the EGM to the optimization of output power.

Here, we come to discuss another precondition. Researchers showed that the entropy generation rate associated with dumping the used streams into the environment must be taken into account in the analyses of the power plant besides the entropy generation rate in the heat exchangers.[9] Other research[20,32,36] also showed that the entropy generation associated with dumping the used streams into the environment should be considered, otherwise the EGM will not lead to the maximum output power. However, this precondition may be fictitious because the used streams may not be dumped into the environment in practical applications. The thermal energy in the used streams can be used in many ways. It even can be stored in some phase change materials. So, the question is why the fictitious precondition should be satisfied? Considering Eqs. (3) and (17), we have

$$e_{\rm in} = (w + e_{\rm out}) + T_0 s_{\rm g}. \tag{26}$$

From the viewpoint of $e_{\rm in}$, some of it turns to be output power, some is destroyed because of irreversibility, and the rest is stored in the used streams out of the system. The sum of the output power and the rest exergy flow rate in the used streams can be defined as the remaining exergy flow rate,

$$e_{\rm R} = w + e_{\rm out}. \tag{27}$$

When we assume that the used streams are dumped into the environment and consider its virtual entropy generation rate, we can find from Eq. (26) that $e_{\rm out}$ is zero. Then, the EGM leads to the maximum output power as long as the inlet parameters are fixed. If the fictitious precondition is not considered, equations (26) and (27) indicate that the practical smaller entropy generation rate may not lead to larger output power, but leads to larger $e_{\rm R}$ for fixed $e_{\rm in}$. A simple example is presented to show this point numerically below.

As shown in Fig. 5, the heat flow rate $Q_{\rm H}$ in the hot stream is transferred into a Carnot engine through a heat exchanger. In the Carnot engine, the output power is w and the heat flow rate released to the environment is $Q_{\rm L}$. The outlet temperature of the used stream is $T_{\rm out}$. For the hot stream, assume that the heat capacity flow rate $C = 1$ W/K, and the inlet temperature $T_{\rm in} = 600$ K. Assume the environment temperature $T_0 = 300$ K, and the thermal conductance of the heat exchanger $U = 2$ W/K. Then, $Q_{\rm H}$ can be calculated from

$$Q_{\rm H} = C\,(T_{\rm in} - T_{\rm W})\,[1 - \exp\,(-U/C)]\,, \tag{28}$$

where $T_{\rm W}$ is the wall temperature of the heat exchanger, and w can be calculated from

$$w = Q_{\rm H}\,(1 - T_0/T_{\rm W})\,. \tag{29}$$

So, it is a constant surface temperature boundary condition for the heat transfer process between the hot stream and the heat exchanger.

The practical entropy generation rate is

$$s_{\rm g-p} = Q_{\rm L}/T_0 + C \ln\,(T_{\rm out}/T_{\rm in})\,, \tag{30}$$

the total entropy generation rate with the consideration of the virtual part associated with dumping the used streams into the environment is

$$s_{\rm g-v} = [Q_{\rm L} + C\,(T_{\rm out} - T_0)]/T_0 + C \ln\,(T_0/T_{\rm in})\,, \tag{31}$$

and the exergy flow rate in the used stream is

$$e_{\rm out} = C\,[T_0 \ln\,(T_0/T_{\rm out}) + (T_{\rm out} - T_0)]\,. \tag{32}$$

With Eqs. (26)–(32), the variations of $s_{\rm g-p}$, $s_{\rm g-v}$, w, and $e_{\rm R}$ are shown in Fig. 6. The results show that the minimum $s_{\rm g-v}$ corresponds to the maximum w, while $e_{\rm R}$ increases with $s_{\rm g-p}$ decreasing. Smaller $s_{\rm g-p}$ does not always lead to larger w. The numerical results can verify the theoretical analyses above.

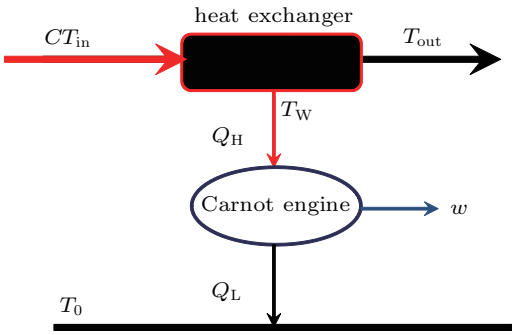


Fig. 5. (color online) Simple heat–work conversion system.

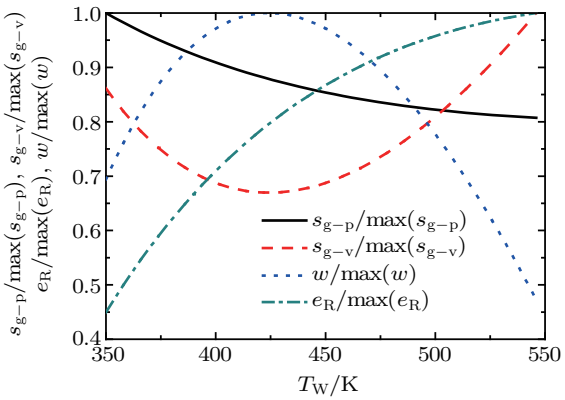


Fig. 6. (color online) Variations of the entropy generation rates, the output power and the remaining exergy flow rate with wall temperature of the heat exchanger.

In addition, if the inlet parameters are not fixed, which means that the exergy flow into the system is not given, we have already proved that the EGM does not lead to the maximum output power even if the virtual entropy generation rate associated with dumping the used streams into the environment is considered.[32] In such a case, the EGM does not correspond to the maximum output power either, which can also

be understood mathematically with Eq. (25). When e_{in} increases, the terms on the right-hand side of the equation may all increase. Then, the output power may not decrease with increasing entropy generation, but increase. Here, it can be seen that the applicability of the EGM to the analyses of heat-work conversion systems is still conditional for the whole energy system in which the heat exchanger is an organ.[25]

4.2. Analyses of other objectives

For other design objectives, the inconsistence between the entropy generation and the objectives has also been noted.

When the thermal efficiency was taken as the design objective, the work of Wang *et al.*[37] showed that the EGM does not always lead to the largest thermal efficiency in the endoreversible Carnot cycle. The same conclusions were also obtained when we analyzed the one-stream heat exchanger networks[32] and the combined endoreversible Carnot heat engines.[33] When the thermoeconomic performance was taken as the design objective, it was also proved that the EGM may not be applicable.[33]

For heat pump systems, the COP and the heat flow rate into the high temperature heat source can be our objectives. For the two objectives, research showed that the applicability of the EGM is also conditional.[21,38] The effects from different heat transfer laws were analyzed,[38] and the conclusions still hold.

From the discussion above, it can be seen that the design objectives of heat–work conversion systems may not always be consistent with the irreversibility measured by entropy generation. Reducing the irreversibility from the viewpoint of entropy generation may reduce the exergy destruction or improve a certain important performance of the system. However, we may not focus on the exergy destruction or the certain performance in many practical applications. We should pay enough attention to this point to avoid abusing the EGM.

5. Conclusions

In this paper, the role of the EGM in thermal optimization is discussed. As is well known, entropy generation can be used to measure the irreversibility of the thermal process. The view angle of irreversibility of entropy generation is analyzed. It is shown that entropy generation directly reflects the exergy destruction or the loss of ability to do work. In the system performance analyses, the EGM may not lead to the optimal value of the design objective because the objective may not always be consistent with the view angle of irreversibility of entropy generation.

In the heat transfer process in which heat is transferred only for heating or cooling objects, the inconsistence between the design objectives and the entropy generation rate is presented with some examples. In particular, the "entropy generation paradox" in heat exchanger analyses is discussed. We show that the concept of entropy generation is not a suitable parameter to evaluate the heat transfer performances of heat exchangers.

In the heat–work conversion system, the inconsistence between the design objectives and the EGM is also shown and discussed. As entropy generation may not directly describe the design objectives, but describes the exergy destruction, the applicability of the EGM is conditional.

In the thermal system, the decrease of irreversibility from the viewpoint of entropy generation may reduce the exergy destruction or improve a certain performance of the system that may not be the focus in many practical applications. This point should be considered to avoid abusing the EGM.

References

[1] Bergles A E 1981 *Application of heat transfer augmentation* (Washington DC: Hemisphere)
[2] Chen L G 2012 *Chin. Sci. Bull.* **57** 4404
[3] Wei S H, Chen L G and Sun F R 2011 *Int. J. Therm. Sci.* **50** 1285
[4] Cheng X T, Xu X H and Liang X G 2009 *Sci. China Ser. E: Tech. Sci.* **52** 2937
[5] Sun C, Cheng X T and Liang X G 2014 *Chin. Phys. B* **23** 050513
[6] Li M and Lai A C K 2013 *Energy Convers. Maneg.* **65** 133
[7] Abbassi H 2007 *Energy* **32** 1932
[8] Baytaş A C 2000 *Int. J. Heat Mass Transfer* **43** 2089
[9] Bejan A 1997 *Advanced engineering thermodynamics* (NewYork: John Wiley & Sons)
[10] Klein S A and Reindl D T 1998 *J. Energy Res.* **120** 172
[11] Cheng X T and Liang X G 2013 *Energy Buildings* **67** 387
[12] Salamon P, Hoffmann K H, Schubert S, Berry R S and Andresen B 2001 *J. Non-Equilib. Thermodyn.* **26** 73
[13] Shah R K and Skiepko T 2004 *J. Heat Transfer* **126** 994
[14] Chen Q, Zhu H Y, Pan N and Guo Z Y 2011 *P. Roy. Soc. A-Math. Phys.* **467** 1012
[15] Prigogine I 2007 *From being to becoming* (Beijing: Peking University Press) (in Chinese)
[16] Zhao K H and Luo W Y 2002 *Thermotics* (Beijing: Higher Education Press) (in Chinese)
[17] Cheng X T and Liang X G 2013 *Energy Convers. Manag.* **73** 121
[18] Cheng X T, Zhang Q Z, Xu X H and Liang X G 2013 *Chin. Phys. B* **22** 020503
[19] Guo Z Y, Zhu H Y and Liang X G 2007 *Int. J. Heat Mass Transfer* **50** 2545
[20] Cheng X T and Liang X G 2012 *Energy* **44** 964
[21] Cheng X T and Liang X G 2013 *Chin. Sci. Bull.* **58** 4696
[22] Xu Y C and Chen Q 2012 *Int. J. Heat Mass Transfer* **55** 5148
[23] Cheng X T and Liang X G 2013 *Int. J. Heat Mass Transfer* **64** 903
[24] Cheng X T and Liang X G 2012 *Energy* **46** 386
[25] Bejan A 2016 *Renew. Sustain. Energy Rev.* **53** 1636
[26] Cheng X T and Liang X G 2012 *Energy Convers. Manag.* **58** 163
[27] Guo Z Y, Liu X B, Tao W Q and Shah R K 2010 *Int. J. Heat Mass Transfer* **53** 2877
[28] Hesselgreaves J E 2000 *Int. J. Heat Mass Transfer* **43** 4189
[29] Xu Z M, Yang S R and Chen Z Q 1996 *J. Thermal Sci.* **5** 257
[30] Sahiti N, Krasniqi F, Fejzullahu X, Bunjaku J and Muriqi A 2008 *Appl. Thermal Eng.* **28** 2337
[31] Ogiso K 2003 *ASME J. Heat Transfer* **125** 530
[32] Cheng X T and Liang X G 2012 *Energy* **47** 421
[33] Cheng X T and Liang X G 2015 *Chin. Phys. B* **24** 060510
[34] Wu Y Q 2015 *Chin. Phys. B* **24** 070506
[35] Cheng X T and Liang X G 2013 *Chin. Phys. B* **22** 010508
[36] Chen Q, Wu J, Wang M R, Pan N and Guo Z Y 2010 *Chin. Sci. Bull.* **56** 449
[37] Wang W H, Cheng X T and Liang X G 2013 *Chin. Phys. B* **22** 110506
[38] Wu Y Q, Cai L and Wu H J 2016 *Chin. Phys. B* **25** 060506