Analyses of an air conditioning system with entropy generation minimization and entransy theory*

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In this paper, based on the generalized heat transfer law, an air conditioning system is analyzed with the entropy generation minimization and the entransy theory. Taking the coefficient of performance (denoted as *COP*) and heat flow rate $Q_{\rm out}$ which is released into the room as the optimization objectives, we discuss the applicabilities of the entropy generation minimization and entransy theory to the optimizations. Five numerical cases are presented. Combining the numerical results and theoretical analyses, we can conclude that the optimization applicabilities of the two theories are conditional. If $Q_{\rm out}$ is the optimization objective, larger entransy increase rate always leads to larger $Q_{\rm out}$, while smaller entropy generation rate does not. If we take *COP* as the optimization objective, neither the entropy generation minimization nor the concept of entransy increase is always applicable. Furthermore, we find that the concept of entransy dissipation is not applicable for the discussed cases.

Keywords: entropy generation, entransy increase, entransy dissipation, optimization analyses, finite time thermodynamics, air conditioning system

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1. Introduction

Air conditioning systems are widely used in many buildings. The analyses and optimizations of air conditioning systems have attracted more and more attention because they are very important for energy conservation and the reduction of cost.[1–10] In order to improve the system performance and increase the energy utilization, some optimization theories have been developed, such as the entropy generation minimization[11] and the entransy theory.[8]

The entropy generation minimization has been widely used in the analyses and optimizations of thermal systems.[12–17] In air conditioning systems, this theory has also been applied.[18,19] However, some researchers further found that the entropy generation minimization does not always lead to the optimal performances for different optimization objectives. For example, when the refrigeration capacity is not fixed, Klein and Reindl[20] found that minimizing the entropy generation rate does not always result in the same design as maximizing the system performance, and when larger heat flow into the high temperature heat source is the objective, the entropy generation minimization is not always applicable, either.[8]

The entransy theory was proposed by Guo *et al.*[21] for heat transfer and it has been widely applied to analyzing heat transfer processes.[21–32] This theory has also been extended to the analyses of thermodynamic processes.[33–36] Cheng and Liang[33] defined a new concept of entransy loss rate. For the discussed systems, it was shown that the entransy loss rate maximum results in the output power maximum.

For the heat pump system, Chen *et al.*[18] applied the entropy concept to its optimization. But Klein and Reindl[20] found that the entropy generation rate minimum does not always result in the best system performance. So the discussion of the applicability of the entropy generation minimization to the heat pump systems is still necessary. Recently, Cheng and Liang[8,10,19] used the entransy theory to analyze air conditioning systems. They found that the concept of entransy increase is applicable for the analyses of the heat flow into the high temperature heat source. However, there are not many papers on the analyses of air conditioning systems with the entransy theory. Further investigations are still necessary.

In this paper, based on the generalized heat transfer law, an air conditioning system is analyzed with the entransy theory and the entropy generation minimization. The coefficient of performance (denoted as *COP*) and the heat flow rate $Q_{\rm out}$ which is released into the high temperature heat source are taken as the optimization objectives, and the applicabilities of the entropy generation minimization and the entransy theory to the optimizations are also discussed.

2. Entransy theory and entropy generation minimization

In the analogy between the electrical and heat conductions, Guo *et al.*[21] noted that the thermal system lacks the

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parameter corresponding to the electrical potential energy. With this consideration, they proposed the concept of entransy, which can be expressed as[36,37]

$$G = \frac{1}{2}UT, \tag{1}$$

where U is the internal energy and T is the temperature. It is shown that this concept can describe the potential energy of heat in an object, and reflect the thermal energy of thermomass for the object.[37] In practical heat transfer, it was proved that there always exists entransy dissipation.[20,38] With the concepts of entransy, entransy flow and entransy dissipation, the principle of least action and the entransy balance equation in heat transfer can be obtained.[37] Then, the extremum entransy dissipation principle and the minimum entransy dissipation based thermal resistance principle for heat transfer were developed and applied to the analyses and optimizations of many heat transfer processes.[21–32,36–44]

Furthermore, Cheng and Liang[33] and Cheng *et al.*[34] proposed the concept of work entransy, with which the entransy balance equation for thermodynamic cycles can be set up. Then, the concept of entransy loss was developed.[33] For a thermodynamic system, it was shown that entransy loss is the difference between the entransy flows that get into and out of the system, and the consumed entransy.[33,37] When there is no work done in the thermodynamic system, the thermodynamic system becomes a heat transfer system, and the entransy loss equals the entransy dissipation.[37] Cheng and Liang[33] found that larger entransy loss leads to larger output work when some conditions are satisfied. In some application cases, the concept of entransy loss was found to be effective for the analyses and optimizations of some thermodynamic systems.[33–37,45–48]

However, some researchers[49,50] thought that the entransy theory was a copy of the entropy generation minimization, or gave the same optimization results as those of the entropy generation minimization. In heat transfer and thermodynamic cycles, many comparisons showed that the two theories are different.[22–24,33,34,37] We also did some work on the analyses of an endoreversible Carnot heat engine with the entransy theory and the entropy generation minimization.[51] The results showed that the two theories are not the same, and the major problems in Ref. [51] were pointed out. In the present work, this issue will also be discussed in the analyses of an air conditioning system.

3. The discussed air conditioning system

The discussed air conditioning system is shown in Fig. 1.[8]

In this system, the heat flow rate $Q_{\rm in}$, which is from the environment at temperature T_0, flows into the Carnot heat pump, which works between temperatures T_1 and T_2. During the cycle, the input power is $P_{\rm in}$, and the heat flow rate $Q_{\rm out}$ is released to the room at temperature $T_{\rm H}$. The heat leak rate $Q_{\rm Leak}$ between the environment and the room is considered.

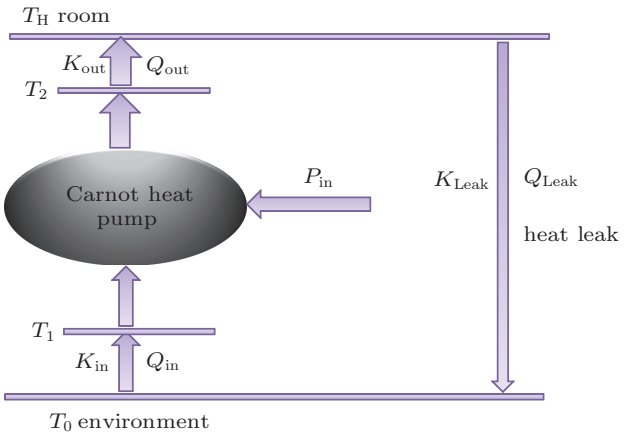


Fig. 1. (color online) An air conditioning system.

We assume that the heat transfer processes satisfy the generalized heat transfer law,[52–55] there are

$$Q_{\rm in} = K_{\rm in}\left(T_0^n - T_1^n\right)^m, \tag{2}$$

$$Q_{\rm out} = K_{\rm out}\left(T_2^n - T_{\rm H}^n\right)^m, \tag{3}$$

$$Q_{\rm Leak} = K_{\rm Leak}\left(T_{\rm H}^n - T_0^n\right)^m, \tag{4}$$

where m and n are constants, $K_{\rm in}$ is the product of the heat transfer area and the corresponding heat transfer coefficient between the environment and the working fluid of the reverse Carnot cycle, $K_{\rm out}$ is the product of the heat transfer area and the corresponding heat transfer coefficient between the working fluid of the reverse Carnot cycle and the room, and $K_{\rm Leak}$ is the product of the heat transfer area and the corresponding heat transfer coefficient between the room and the environment.

Considering the energy conservation, there is

$$Q_{\rm out} = Q_{\rm in} + P_{\rm in}. \tag{5}$$

According to the Carnot theorem, we have

$$\frac{Q_{\rm out}}{Q_{\rm in}} = \frac{T_2}{T_1}. \tag{6}$$

The system *COP* is

$$COP = \frac{Q_{\rm out}}{P_{\rm in}} = 1 + \frac{Q_{\rm in}}{P_{\rm in}}. \tag{7}$$

The entropy generation rate $S_{\rm g}$ of this system is[37]

$$\begin{aligned} S_{\rm g} &= \frac{Q_{\rm out} - Q_{\rm Leak}}{T_{\rm H}} - \frac{Q_{\rm in} - Q_{\rm Leak}}{T_0} \\ &= -\left(\frac{1}{T_0} - \frac{1}{T_{\rm H}}\right)Q_{\rm in} + \frac{1}{T_{\rm H}}P_{\rm in} - \frac{Q_{\rm Leak}}{T_{\rm H}} + \frac{Q_{\rm Leak}}{T_0}. \end{aligned} \tag{8}$$

According to the definition of entransy increase rate $G_{\rm inc}$, we can obtain[8]

$$G_{\rm inc} = \left(Q_{\rm out} - Q_{\rm Leak}\right)T_{\rm H} - \left(Q_{\rm in} - Q_{\rm Leak}\right)T_0$$

$$= (T_{\rm H} - T_0)\, Q_{\rm in} + T_{\rm H} P_{\rm in} + T_0 Q_{\rm Leak} - T_{\rm H} Q_{\rm Leak}. \quad (9)$$

The entransy dissipation rate $G_{\rm dis}$ is[56]

$$G_{\rm dis} = Q_{\rm in}\,(T_0 - T_1) + Q_{\rm out}\,(T_2 - T_{\rm H}) + Q_{\rm Leak}\,(T_{\rm H} - T_0)\,. \quad (10)$$

4. Numerical examples and discussion

Taking COP and $Q_{\rm out}$ as the optimization objectives, we analyze the relationships of COP, $Q_{\rm out}$, $S_{\rm g}$, $G_{\rm inc}$, and $G_{\rm dis}$ below. Five cases will be calculated numerically.

In the first case, we assume that $T_{\rm H} = 300$ K, $T_0 = 275$ K, and $Q_{\rm in} = 200$ W. When $m = n = 1$, the heat transfer law is the Newton heat transfer law. With this law, we assume $K_{\rm Leak} = 0.8$ W/K and $K_{\rm in} + K_{\rm out} = 30$ W/K. As $K_{\rm leak}$, $K_{\rm in}$, and $K_{\rm out}$ are the products of the heat transfer areas and the corresponding heat transfer coefficients, their values depend on the size of the heat pump and the corresponding heat transfer performance. So, the values may be different for different heat pumps. In this paper, the data are set to be close to those in Ref. [8]. With Eqs. (2)–(10), the variations of COP, $Q_{\rm out}$, $S_{\rm g}$, $G_{\rm inc}$, and $G_{\rm dis}$ with $K_{\rm in}$ can be shown in Fig. 2.

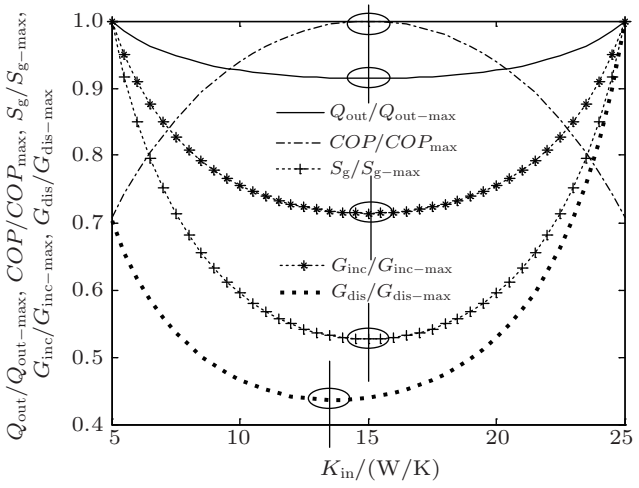


Fig. 2. Variations of COP, $Q_{\rm out}$, $S_{\rm g}$, $G_{\rm inc}$, and $G_{\rm dis}$ with $K_{\rm in}$ when $Q_{\rm in}$ is fixed and $m = n = 1$.

It can be seen that COP reaches its maximum value for $K_{\rm in} = 15.0$ W/K, while $Q_{\rm out}$, $S_{\rm g}$, and $G_{\rm inc}$ reach their minimum values. However, $G_{\rm dis}$ reaches neither its minimum value nor its maximum value at the same point. Furthermore, we can calculate two more heat transfer laws. When we assume that $m = 1.2$, $n = 1.5$, $K_{\rm Leak} = 1 \times 10^{-2}$ W/K$^{1.8}$, and $K_{\rm in} + K_{\rm out} = 2$ W/K$^{1.8}$, the variations of COP, $Q_{\rm out}$, $S_{\rm g}$, $G_{\rm inc}$, and $G_{\rm dis}$ with $K_{\rm in}$ can be shown in Fig. 3. When we assume that $m = 1$, $n = 5$, $K_{\rm Leak} = 0.8 \times 10^{-10}$ W/K^5, and $K_{\rm in} + K_{\rm out} = 3 \times 10^{-9}$ W/K^5, the variations of COP, $Q_{\rm out}$, $S_{\rm g}$, $G_{\rm inc}$, and $G_{\rm dis}$ with $K_{\rm in}$ can be shown in Fig. 4. From Figs. 2–4, we can find that the variation tendencies of COP, $Q_{\rm out}$, $S_{\rm g}$, $G_{\rm inc}$, and $G_{\rm dis}$ in Figs. 3 and 4 are the same as those in Fig. 2.

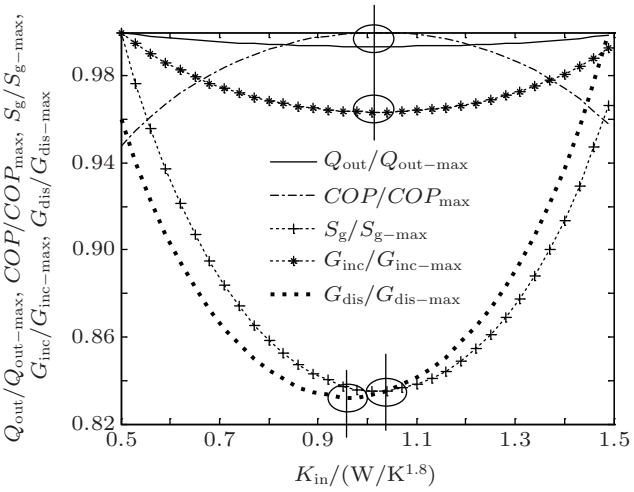


Fig. 3. Variations of COP, $Q_{\rm out}$, $S_{\rm g}$, $G_{\rm inc}$, and $G_{\rm dis}$ with $K_{\rm in}$ when $Q_{\rm in}$ is fixed, $m = 1.2$ and $n = 1.5$.

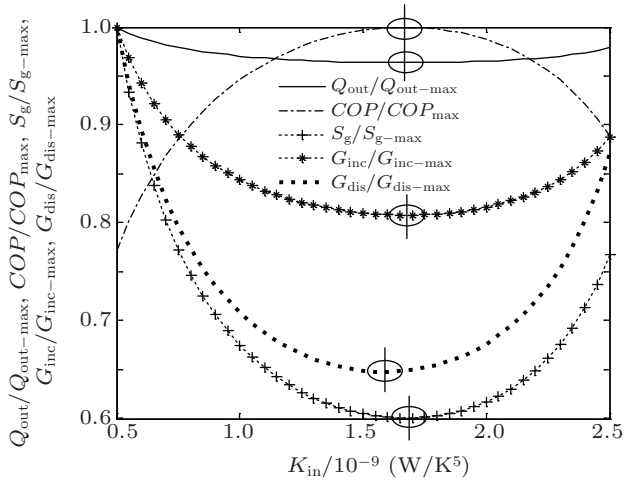


Fig. 4. Variations of COP, $Q_{\rm out}$, $S_{\rm g}$, $G_{\rm inc}$, and $G_{\rm dis}$ with $K_{\rm in}$ when $Q_{\rm in}$ is fixed, $m = 1$ and $n = 5$.

In this case, $Q_{\rm in}$, $T_{\rm H}$, T_0, and $Q_{\rm Leak}$ are all given. We can find that the variation tendencies of $Q_{\rm out}$, $S_{\rm g}$, and $G_{\rm inc}$ are the same as that of $P_{\rm in}$ in Eqs. (5), (8), and (9). Furthermore, equation (7) shows that COP and $P_{\rm in}$ have opposite variation tendencies, with $Q_{\rm in}$ fixed. These are the reasons why the curves behave in the way shown in Figs. 2–4 when $Q_{\rm in}$, $T_{\rm H}$, T_0, and $Q_{\rm Leak}$ are prescribed.

As above, we show that both the entropy generation minimization and the entransy increase minimization lead to the maximum COP in this case. On the other hand, if larger $Q_{\rm out}$ is our objective, larger entransy increase rate leads to larger $Q_{\rm out}$, while smaller entropy generation rate does not. This conclusion is consistent with that obtained by Cheng and Liang[8] when they analyzed a heat pump system with the concepts of entropy generation and entransy increase. Furthermore, our results show that the concept of entransy dissipation is not applicable for the optimizations, and this conclusion is consistent with that obtained by Cheng *et al.*[37,55] when they reviewed the entransy theory.

In the second case, we assume that $T_H = 300$ K, $T_0 = 275$ K, and $P_{in} = 300$ W. With Eq. (6), we can find that COP is proportional to Q_{out}, with P_{in} fixed, which means that the variation tendencies of COP and Q_{out} are the same. So, we will not calculate Q_{out} below. Considering that the heat transfer laws may be different, the three heat transfer laws discussed in the first case are also analyzed here. When $m = n = 1$, we assume that $K_{Leak} = 1$ W/K and $K_{in} + K_{out} = 25$ W/K. With Eqs. (2)–(10), the variations of COP, S_g, G_{inc}, and G_{dis} with K_{in} can be shown in Fig. 5, which shows that COP and G_{inc} both reach their maximum values for $K_{in} = 12.6$ W/K, while S_g arrives at its minimum value. At the same point, G_{dis} reaches neither its minimum value nor its maximum value.

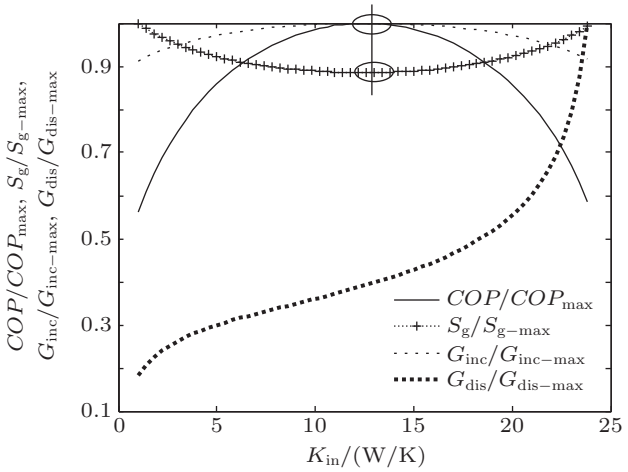


Fig. 5. Variations of COP, S_g, G_{inc}, and G_{dis} with K_{in} when P_{in} is fixed and $m = n = 1$.

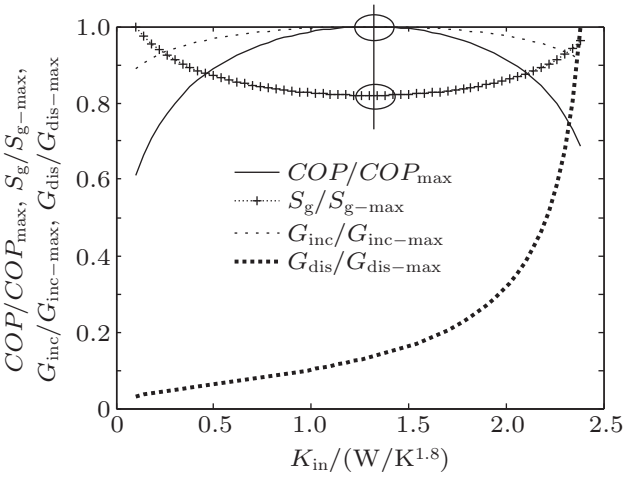


Fig. 6. Variations of COP, S_g, G_{inc}, and G_{dis} with K_{in} when P_{in} is fixed, $m = 1.2$ and $n = 1.5$.

When $m = 1.2$ and $n = 1.5$, we assume that $K_{Leak} = 1 \times 10^{-2}$ W/K$^{1.8}$ and $K_{in} + K_{out} = 2.5$ W/K$^{1.8}$. When $m = 1$ and $n = 5$, we assume that $K_{Leak} = 1 \times 10^{-10}$ W/K^5 and $K_{in} + K_{out} = 2.5 \times 10^{-9}$ W/K^5. For these two heat transfer laws, the variations of COP, S_g, G_{inc}, and G_{dis} with K_{in} are shown in Figs. 6 and 7, respectively. The variation tendencies of COP, Q_{out}, S_g, G_{inc}, and G_{dis} in Figs. 6 and 7 are the same as those in Fig. 5. For different heat transfer laws, our results show that both the entropy generation minimization and the entransy increase maximization lead to the maximum values of Q_{out} and COP. In this case, the concept of entransy dissipation is not applicable.

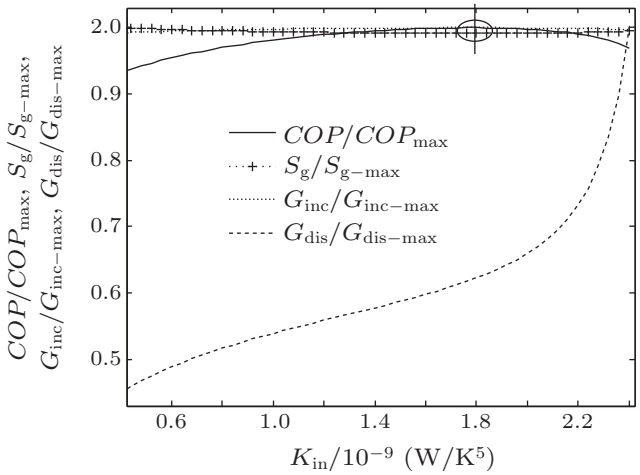


Fig. 7. Variations of COP, S_g, G_{inc}, and G_{dis} with K_{in} when P_{in} is fixed, $m = 1$ and $n = 5$.

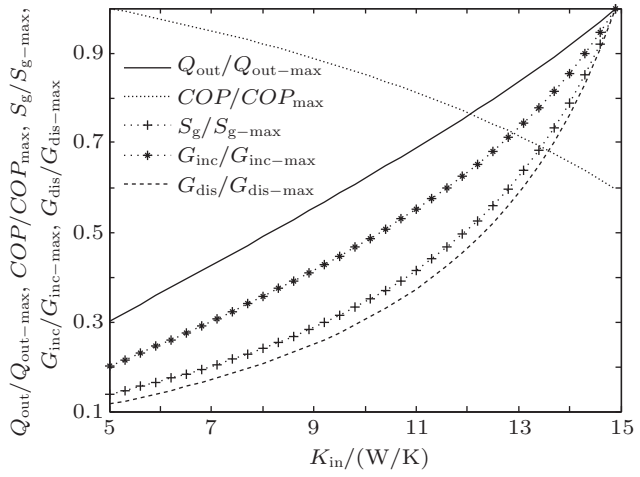


Fig. 8. Variations of COP, Q_{out}, S_g, G_{inc}, and G_{dis} with K_{in} when T_1 is fixed and $m = n = 1$.

In the third case, we assume that $T_H = 300$ K, $T_0 = 275$ K, and $T_1 = 265$ K. The three heat transfer laws are also discussed here. We assume that $K_{Leak} = 0.5$ W/K and $K_{in} + K_{out} = 20$ W/K for $m = n = 1$, $K_{Leak} = 5 \times 10^{-2}$ W/K$^{1.8}$ and $K_{in} + K_{out} = 2$ W/K$^{1.8}$ for $m = 1.2$ and $n = 1.5$, and $K_{Leak} = 5 \times 10^{-11}$ W/K^5 and $K_{in} + K_{out} = 2 \times 10^{-9}$ W/K^5 for $m = 1$ and $n = 5$, respectively. For the three heat transfer laws, the variations of COP, Q_{out}, S_g, G_{inc}, and G_{dis} with K_{in} can be shown in Figs. 8–10, respectively. The numerical results show that the variation tendencies of Q_{out}, S_g, G_{inc}, and G_{dis} are the same, and they all increase monotonically with increasing K_{in}, while COP decreases monotonically. For this case, if we take Q_{out} as the optimization objective, the numerical results

show that larger values of entransy increase rate and entransy dissipation rate lead to the larger $Q_{\rm out}$, while smaller entropy generation rate does not. If we take *COP* as the optimization objective, we can find that the entropy generation minimization, entransy increase minimization and entransy dissipation minimization all lead to a maximal *COP*.

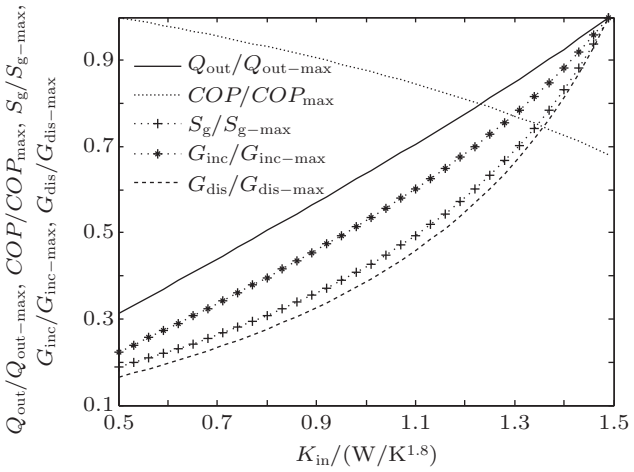


Fig. 9. Variations of *COP*, $Q_{\rm out}$, $S_{\rm g}$, $G_{\rm inc}$, and $G_{\rm dis}$ with $K_{\rm in}$ when T_1 is fixed, $m = 1.2$ and $n = 1.5$.

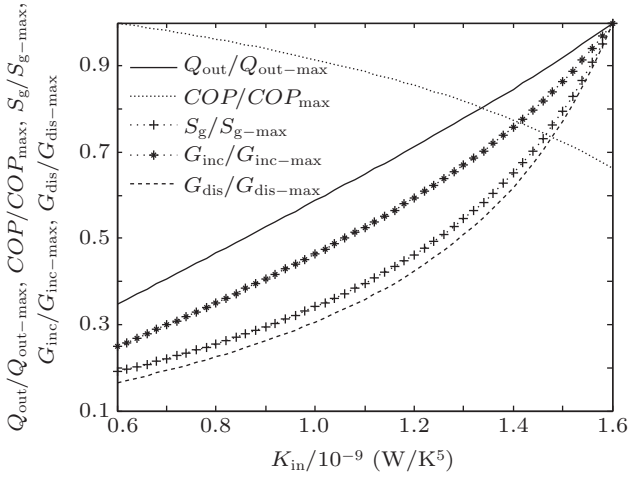


Fig. 10. Variations of *COP*, $Q_{\rm out}$, $S_{\rm g}$, $G_{\rm inc}$, and $G_{\rm dis}$ with $K_{\rm in}$ when T_1 is fixed, $m = 1$ and $n = 5$.

In the fourth case, we assume that $T_{\rm H} = 300$ K, $T_0 = 275$ K and $T_2 = 325$ K. For the three heat transfer laws, we assume that $K_{\rm Leak} = 1$ W/K and $K_{\rm in} + K_{\rm out} = 20$ W/K when $m = n = 1$, $K_{\rm Leak} = 0.1$ W/K$^{1.8}$ and $K_{\rm in} + K_{\rm out} = 2$ W/K$^{1.8}$ when $m = 1.2$ and $n = 1.5$, and $K_{\rm Leak} = 1 \times 10^{-10}$ W/K^5 and $K_{\rm in} + K_{\rm out} = 2 \times 10^{-9}$ W/K^5 when $m = 1$ and $n = 5$, respectively. The variations of *COP*, $Q_{\rm out}$, $S_{\rm g}$, $G_{\rm inc}$, and $G_{\rm dis}$ with $K_{\rm in}$ are also shown in Figs. 11–13, respectively. The results show that there is a maximum value for $G_{\rm dis}$, but there are no extremum values for *COP*, $Q_{\rm out}$, $S_{\rm g}$, and $G_{\rm inc}$. $Q_{\rm out}$, $S_{\rm g}$, and $G_{\rm inc}$all decrease monotonically with increasing $K_{\rm in}$, while *COP* increases monotonically. Therefore, if *COP* is our optimization objective, the entropy generation minimization and entransy increase minimization both lead to the maximum *COP*. If larger $Q_{\rm out}$ is our objective, only larger entransy increase rate results in larger $Q_{\rm out}$, while smaller entropy generation rate does not. The concept of entransy dissipation is not applicable for the analyses for this case, either.

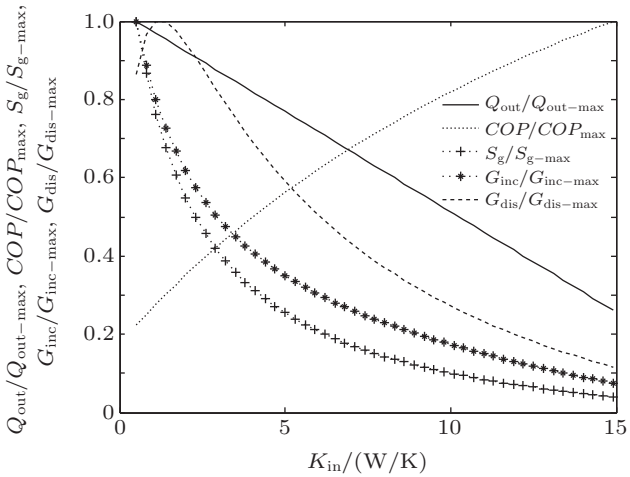


Fig. 11. Variations of *COP*, $Q_{\rm out}$, $S_{\rm g}$, $G_{\rm inc}$, and $G_{\rm dis}$ with $K_{\rm in}$ when T_2 is fixed and $m = n = 1$.

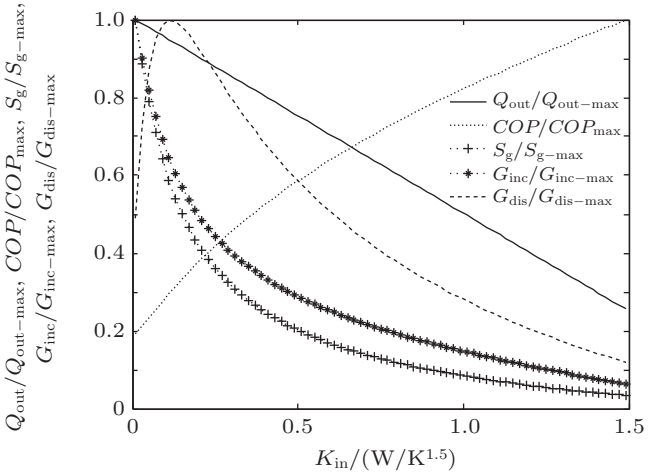


Fig. 12. Variations of *COP*, $Q_{\rm out}$, $S_{\rm g}$, $G_{\rm inc}$, and $G_{\rm dis}$ with $K_{\rm in}$ when T_2 is fixed, $m = 1.2$ and $n = 1.5$.

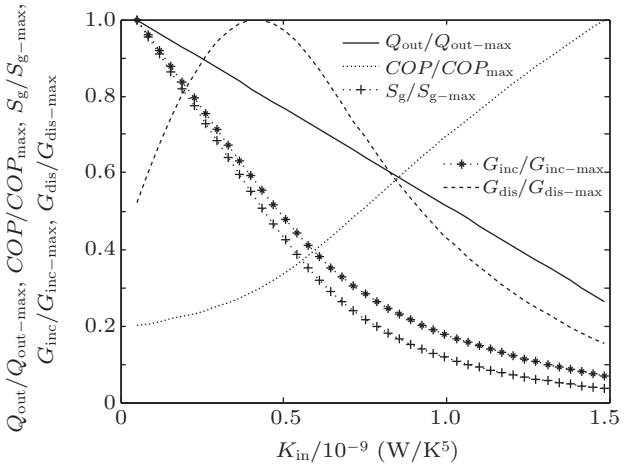


Fig. 13. Variations of *COP*, $Q_{\rm out}$, $S_{\rm g}$, $G_{\rm inc}$, and $G_{\rm dis}$ with $K_{\rm in}$ when T_2 is fixed, $m = 1$ and $n = 5$.

In the fifth case, we assume that $T_H = 300$ K, $T_0 = 265$ K, $T_1 = 263$ K, and $T_2 = 320$ K. According to Eqs. (5) and (6), we can obtain

$$\frac{Q_{out}}{Q_{in}} = \frac{Q_{in}+P_{in}}{Q_{in}} = 1+\frac{P_{in}}{Q_{in}} = \frac{T_2}{T_1}. \tag{11}$$

Then, we have

$$\frac{P_{in}}{Q_{in}} = \frac{T_2 - T_1}{T_1}. \tag{12}$$

Therefore, with Eqs. (7) and (12), there is

$$COP = \frac{Q_{out}}{P_{in}} = 1+\frac{Q_{in}}{P_{in}} = 1+\frac{T_1}{T_2 - T_1}. \tag{13}$$

It can be seen that COP is constant in this case. For the three heat transfer laws, we assume that $K_{Leak} = 2$ W/K when $m = n = 1$, $K_{Leak} = 6 \times 10^{-2}$ W/K$^{1.8}$ when $m = 1.2$ and $n = 1.5$, and $K_{Leak} = 1.7 \times 10^{-10}$ W/K^5 when $m = 1$ and $n = 5$, respectively. The variations of COP, Q_{out}, S_g, G_{inc}, and G_{dis} with K_{in} can be shown in Figs. 14–16, respectively.

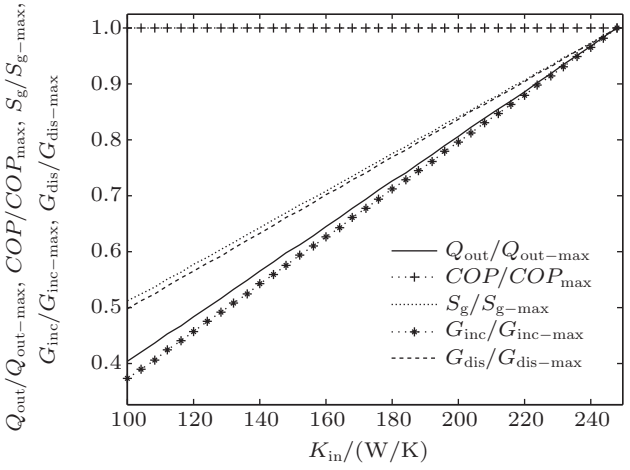


Fig. 14. Variations of COP, Q_{out}, S_g, G_{inc}, and G_{dis} with K_{in} when T_1 and T_2 are fixed and $m = n = 1$.

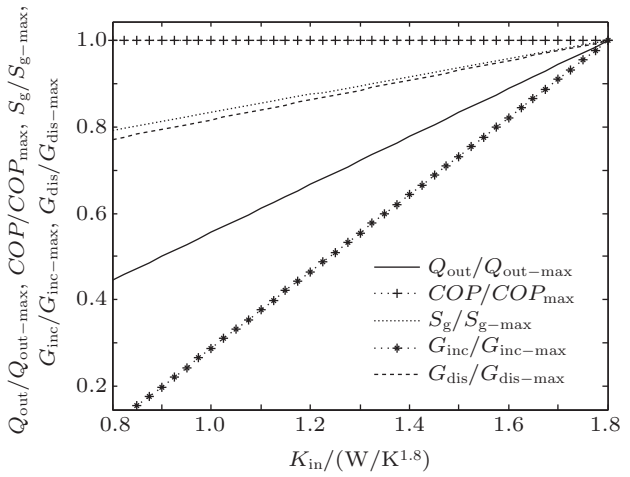


Fig. 15. Variations of COP, Q_{out}, S_g, G_{inc}, and G_{dis} with K_{in} when T_1 and T_2 are fixed, $m = 1.2$ and $n = 1.5$.

The results show that Q_{out}, S_g, G_{inc}, and G_{dis} all increase monotonically with increasing K_{in}. Therefore, larger entransy dissipation rate, larger entropy generation rate, and larger entransy increase rate all lead to larger Q_{out}. For the analyses of COP, none of the concepts of entransy dissipation, entransy increase and entropy generation are applicable.

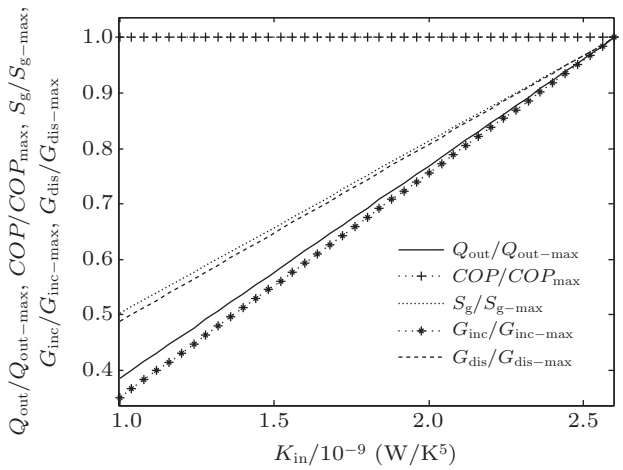


Fig. 16. Variations of COP, Q_{out}, S_g, G_{inc}, and G_{dis} with K_{in} when T_1 and T_2 are fixed, $m = 1$ and $n = 5$.

5. Conclusions

In this paper, the applicabilities of the entropy generation minimization and the entransy theory to the optimization analysis of an air conditioning system are discussed. Three different heat transfer laws and five cases are analyzed numerically.

The applicabilities of the entransy theory and the entropy generation minimization to the discussed air conditioning system are conditional. If larger Q_{out} is the objective, larger G_{inc} always leads to larger Q_{out}, while smaller entropy generation does not. If COP is taken as the optimization objective, neither the entropy generation minimization, nor the entransy increase minimization (or maximization) nor the entransy dissipation minimization (or maximization) always leads to the maximum COP.

For the five discussed cases, the concept of entransy dissipation is not applicable for the optimizations of COP nor Q_{out}.

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References

[1] Wang H and Wu G X 2013 *Chin. Phys. B* **22** 087501
[2] Cheng X T and Liang X G 2015 *Chin. Phys. B* **24** 060510
[3] Wang W H, Cheng X T and Liang X G 2013 *Chin. Phys. B* **22** 110506
[4] Cheng X T, Zhang Q Z, Xu X H and Liang X G 2013 *Chin. Phys. B* **22** 020503
[5] Zhao X L, Fu L and Zhang S G 2011 *Energy Convers. Manage* **52** 494
[6] Chen L G, Feng H and Sun F R 2011 *J. Energy Institute* **84** 105
[7] Bi Y, Chen L G and Sun F R 2009 *Int. J. Exergy* **6** 550
[8] Cheng X T and Liang X G 2013 *Chin. Sci Bull.* **58** 4696

[9] Li J, Chen L G, Ge Y L and Sun F R 2013 *Acta Phys. Sin.* **62** 130501 (in Chinese)
[10] Cheng X T and Liang X G 2014 *Energy Convers. Manage* **80** 238
[11] Myat A, Thu K and Kim Y D 2011 *Appl. Therm. Engineering* **31** 2405
[12] Cheng X T and Liang X G 2013 *Chin. Phys. B* **22** 010508
[13] Adavbiele A S 2010 *Int. J. Energy Research Africa* **1** 67
[14] Chen L G, Wu C H and Sun F R 1999 *J. Non-Equil. Thermody.* **24** 327
[15] Wu C H, Chen L G and Chen J C 1999 *Recent Advances in Finite Time Thermodynamics* (New York: Nova Science Publishers)
[16] Chen L G and Sun F R 2004 *Advances in Finite time thermodynamics: Analysis and Optimization* (New York: Nova Science Publishers)
[17] Myat A, Thu K and Kim Y D 2011 *Appl. Thermal Eng.* **31** 2405
[18] Chen L G, Feng H and Sun F R 2011 *J. Energy Institute* **84** 105
[19] Cheng X T and Liang X G 2013 *Energy Buildings* **67** 387
[20] Klein S A and Reindl D T 1998 *J. Energy Resources Technology* **120** 172
[21] Guo Z Y, Zhu H Y and Liang X G 2007 *Int. J. Heat Mass Transfer* **50** 2545
[22] Cheng X T and Liang X G 2011 *Int. J. Heat Mass Transfer* **54** 269
[23] Cheng X T, Zhang Q Z and Liang X G 2012 *Appl. Thermal Eng.* **38** 31
[24] Cheng X T and Liang X G 2012 *Energy Convers. Manage* **58** 163
[25] Chen L G, Xiao Q H, Xie Z H and Sun F R 2012 *Int. Comm. Heat. Mass Transfer* **39** 1556
[26] Chen L G, Feng H J, Xie Z H and Sun F R 2013 *Int. J. Heat Mass Transfer* **67** 704
[27] Chen L G, Xiao Q H, Xie Z H and Sun F R 2013 *Int. J. Heat Mass Transfer* **67** 506
[28] Chen L G, Wei S H and Sun F R 2014 *Int. J. Low-Carbon Tech.* **9** 20
[29] Feng H J, Chen L G and Sun F R 2012 *Sci. China: Tech. Sci.* **55** 779
[30] Feng H J, Chen L G, Xie Z H and Sun F R 2014 *Sci. China: Tech. Sci.* **57** 784
[31] Feng H J, Chen L G, Xie Z H and Sun F R 2014 *Chin. Sci. Bull.* **59** 2470
[32] Liu W, Liu Z C, Jia H, Fana A W and Nakayama A 2011 *Int. J. Heat Mass Transfer* **54** 3049
[33] Cheng X T and Liang X G 2012 *Energy* **44** 964
[34] Cheng X T, Chen Q, Hu G J and Liang X G 2013 *Int. J. Heat Mass Transfer* **60** 180
[35] Açıkkalp E 2014 *Energy Convers. Manage* **86** 792
[36] Hu G J, Cao B Y and Guo Z Y 2011 *Chin. Sci. Bull.* **56** 2974
[37] Cheng X T and Liang X G 2014 *Chin. Sci. Bull.* **59** 5309
[38] Cheng X T, Liang X G and Guo Z Y 2011 *Chin. Sci. Bull.* **56** 847
[39] Xia S J, Chen L G and Sun F R 2010 *Appl. Math. Model.* **34** 2242
[40] Chen L G 2012 *Chin. Sci. Bull.* **57** 4404
[41] Chen L G 2014 *Sci. China: Tech. Sci.* **57** 2305
[42] Feng H J, Chen L G, Xie Z H and Sun F R 2015 *Sci. China: Tech. Sci.* **58** 1084
[43] Feng H J, Chen L G, Xie Z H and Sun F R 2015 *Int. J. Heat Mass Transfer* **84** 848
[44] Feng H J, Chen L G, Xie Z H and Sun F R 2015 *Int. J. Heat Mass Transfer* **89** 24
[45] Yang A B, Chen L G, Xia S J and Sun F R 2014 *Chin. Sci. Bull.* **59** 2031
[46] Zhu Y, Hu Z, Zhou Y, Jiang L and Yu L 2014 *Energy Convers. Manage* **88** 267
[47] Li T, Fu W and Zhu J 2014 *Energy* **72** 561
[48] Kim K H and Kim K 2015 *Int. J. Heat Mass Transfer* **84** 80
[49] Bejan A 2014 *ASME J. Heat Transfer* **136** 055501
[50] Oliveira S R and Milanez L F. 2014 *Int. J. Heat Mass Transfer* **79** 518
[51] Wu Y Q 2015 *Chin. Phys. B* **24** 070506
[52] Cheng X T and Liang X G 2013 *Energy Convers. Manage* **73** 121
[53] Chen LG, Li J and Sun F R 2008 *Appl. Energy* **85** 52
[54] Xia S J, Chen L G and Sun F R 2008 *J. Therm. Sci. Tech.* **7** 226
[55] Cheng X T, Wang W H and Liang X G 2012 *Sci. China: Tech. Sci.* **55** 2847
[56] Cheng X T and Liang X G 2014 *Energy Convers. Manage* **87** 1052