Analyses of the endoreversible Carnot cycle with entropy theory and entransy theory*

Wang Wen-Hua(王文华), Cheng Xue-Tao(程雪涛)†, and Liang Xin-Gang(梁新刚)

Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, School of Aerospace, Tsinghua University, Beijing 100084, *China*

(Received 1 April 2013; revised manuscript received 21 May 2013)

The endoreversible Carnot cycle is analyzed based on the concepts of entropy generation, entropy generation number, entransy loss, and entransy loss coefficient. The relationships of the cycle output power and heat-work conversion efficiency with these parameters are discussed. For the numerical examples discussed, the preconditions of the application for these concepts are derived. When the inlet temperatures and heat capacity flow rates of hot streams and environment temperature are prescribed, the results show that the concepts of entropy generation and entransy loss are applicable. However, in the presence of various inlet temperatures of streams, larger entransy loss rate still leads to larger output power, while smaller entropy generation rate does not. When the heat capacity flow rates of hot streams are various, neither larger entransy loss rate nor smaller entropy generation rate always leads to larger output power. Larger entransy loss coefficient always leads to larger heat-work conversion efficiency for the cases discussed, while smaller entropy generation number does not always.

Keywords: entropy generation, entransy loss coefficient, heat-work conversion efficiency, endoreversible Carnot cycle

PACS: 05.70.Ln, 07.20.Pe **DOI:** 10.1088/1674-1056/22/11/110506

1. Introduction

The energy conservation has attracted more and more attention because of the energy crisis.[1–5] Heating or cooling objects and doing work are the main purposes of heat transport, which correspond to heat transfer and heat-work conversion, respectively. The optimization of these processes can benefit energy utilization and the reduction in energy consumption.

Researchers have done much work on the heat transfer optimization with the minimum entropy generation as a figure of merit.[6,7] However, there are limitations when using the entropy generation minimization in heat transfer optimization. Shah and Skiepko[8] analyzed 18 kinds of heat exchanger and showed that the heat exchanger effectiveness can be maximum, intermediate, or minimum at the maximum entropy generation. The concept of entransy was proposed in 2007 by the analogy between heat and electrical conductions.[9] Guo *et al.*[9] derived the extremum entransy dissipation principle and the minimum entransy-dissipation-based thermal resistance principle, which have been widely used to optimize heat conduction,[9–16] heat convection,[17,18] thermal radiation,[19,20] heat exchangers,[21–23] and thermal networks.[24,25] All the applications show that the entransy theory is effective for heat transfer optimization and can avoid the paradox similar to the entropy generation paradox.[8]

In the heat-work conversion optimization, the entropy generation minimization is usually used as the optimization criterion to thermodynamic cycles because the entropy generation represents the ability loss of doing work.[26] For instance, Myat *et al.*[27] demonstrated that the minimization of entropy generation in an absorption cycle leads to the maximization of the COP in their analyses of an absorption chiller. However, there are cases that are not in accordance with the entropy generation minimization in heat-work conversion optimization. The investigation of the refrigeration systems with entropy generation for heat-work conversion by Klein and Reindl[28] showed 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. Cheng *et al.*[29] revealed that the entropy generation could not be related to the net work change in the air standard cycle when the heat absorbed by the working fluid is from the combustion reaction of the gas fuel.

On the other hand, the entransy theory has been extended to the analyses of heat-work conversion processes.[27–37] Cheng *et al.*[30] defined the concept of entransy loss. For an endoreversible thermodynamic cycle, the entransy loss is the difference between entransy flow into the system and that out of the system, which is also the summation of the entransy dissipation due to heat transfer and the entransy variation (work entransy) resulting from the heat-work conversion. Researches demonstrated that the concept of entransy loss is suitable for heat-work conversion optimization with some preconditions,[29–37] while the entropy generation minimization is not always suitable.[29,33–35]

Furthermore, the concept of entransy loss coefficient is

*Project supported by the National Natural Science Foundation of China (Grant No. 51376101) and the Initiative Scientific Research Program of Tsinghua University, China.

†Corresponding author. E-mail: chengxt06@mails.tsinghua.edu.cn; chengxt02@gmail.com

© 2013 Chinese Physical Society and IOP Publishing Ltd

proposed based on the concept of entransy loss to optimize the heat-work conversion efficiency.[31] Zhou *et al.*[35] used this concept to optimize the heat-work conversion efficiency in irreversible Carnot cycle. In this paper, the preconditions for the application of these optimization methods are discussed with the endoreversible Carnot cycle.

2. Entransy loss and entransy loss coefficient

Cheng *et al.*[30] proposed the concept of entransy loss, which is the difference between the entransy flow into and out of the system,

$$G_{\rm loss} = Q_{\rm in}T_{\rm in} - Q_{\rm out}T_{\rm out}, \tag{1}$$

where $Q_{\rm in}$ is the total heat flow rate into the system, $Q_{\rm out}$ is that out of the system, $T_{\rm in}$ is the equivalent temperature weighted by the heat flow rate into the system, and $T_{\rm out}$ is that weighted by the heat flow rate out of the system. They satisfy

$$T_{\rm in} = G_{\rm in}/Q_{\rm in} = \left(\int_{A_{\rm in}} q_{\rm in}T\,{\rm d}A_{\rm in} + \int_V Q_{\rm i}T\,{\rm d}V\right)/Q_{\rm in}, \tag{2}$$

$$T_{\rm out} = G_{\rm out}/Q_{\rm out} = \int_{A_{\rm out}} q_{\rm out}T\,{\rm d}A_{\rm out}/Q_{\rm out}, \tag{3}$$

where $G_{\rm in}$ is the total entransy flow rate into the system, $G_{\rm out}$ is that out of the system, $Q_{\rm i}$ is the inner heat source of the system, $A_{\rm in}$ is the boundary surface area through which the heat flux $q_{\rm in}$ comes in, and $A_{\rm out}$ is the boundary surface area through which the heat flux $q_{\rm out}$ goes out.

The entransy loss is the entransy decrease of the heat sources during the heat-work conversion process, which is also the utilized entransy for heat-work conversion. With the energy conservation, equation (1) can become[30]

$$G_{\rm loss} = Q_{\rm in}(T_{\rm in} - T_{\rm out}) + WT_{\rm out}, \tag{4}$$

where W is the output power. The maximum entransy loss corresponds to the maximum output power when $Q_{\rm in}$, $T_{\rm in}$, and $T_{\rm out}$ are prescribed.

The entransy loss coefficient $\eta_{\rm G}$ is defined as the ratio of entransy loss to the total entransy flow into the system,[31]

$$\eta_{\rm G} = G_{\rm loss}/G_{\rm in} = (Q_{\rm in}T_{\rm in} - Q_{\rm out}T_{\rm out})/Q_{\rm in}T_{\rm in}. \tag{5}$$

The heat-work conversion efficiency can be optimized with the entransy loss coefficient as a figure of merit.[31] Heat-work conversion efficiency is the ratio of the output power to the heat flow rate into the system,

$$\eta_{\rm t} = W/Q_{\rm in}. \tag{6}$$

Combining Eqs. (4) and (6), equation (5) is simplified into

$$\eta_{\rm G} = 1 - (1-\eta_{\rm t})T_{\rm out}/T_{\rm in}. \tag{7}$$

It can be found that the maximum entransy loss coefficient matches the maximum heat-work conversion efficiency when the ratio of the equivalent temperature weighted by the heat flow rate into the system to that weighted by the heat flow rate out of the system is prescribed. For a thermodynamic cycle working between two heat sources which have infinite heat capacities and temperatures $T_{\rm H}$ and $T_{\rm L}$, respectively, we have

$$T_{\rm in} = G_{\rm in}/Q_{\rm in} = T_{\rm H}, \tag{8}$$

$$T_{\rm out} = G_{\rm out}/Q_{\rm out} = T_{\rm L}. \tag{9}$$

Therefore, larger entransy loss coefficient is always related to larger heat-work conversion efficiency for the thermodynamic cycle system working between prescribed temperatures.

Another dimensionless criterion is the entropy generation number for heat-work conversion processes,[38] which is defined as

$$N_{\rm S_1} = S_{\rm g}/C_{\rm min}, \tag{10}$$

where $C_{\rm min}$ is the minimum heat capacity flow rate of the fluids in the system. The other definition of the entropy generation number is[39]

$$N_{\rm S_2} = S_{\rm g}/S_{\rm g,min}, \tag{11}$$

where $S_{\rm g,min}$ is the minimum entropy generation rate in the system. As $S_{\rm g,min}$ is a definite value, this entropy generation number has the same variation tendency as that of the entropy generation rate.

3. Optimization of the endoreversible Carnot cycle

The Carnot cycle is an ideal one composed of two reversible isothermal processes and two reversible adiabatic processes. Considering that time is an important parameter, the maximum output power should be the optimization objective. Therefore, the finite time thermodynamics attracts more and more researchers.[40–43] Chen applied the entransy theory to the finite time thermodynamic optimization.[44] The endoreversible Carnot cycle has been widely used in the finite time thermodynamic investigations.[45–47] It was first proposed by Curzon and Ahlborn,[48] in which the working medium undergoes the Carnot cycle.

3.1. Cycle working between a hot stream with finite heat capacity and the environment

Consider an endoreversible Carnot cycle working between a hot stream with finite heat capacity and the environment, as shown in Fig. 1. We assume that the inlet temperature and outlet temperature of the hot stream are $T_{\rm H-in}$ and $T_{\rm H-out}$, the heat capacity flow rate is $C_{\rm H}$, and the environment temperature is T_0. The thermal conductance of the heat exchangers

between the hot stream and cycle fluid and that between the cycle fluid and the environment are UA_h and UA_l, respectively. The temperatures of the working medium on the hot side and cold side are T_h and T_l, respectively.

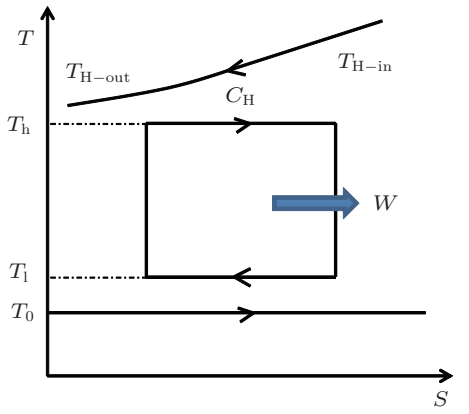


Fig. 1. (color online) The schematic of the endoreversible Carnot cycle.

The heat flow rate from the hot stream is

$$Q_H = C_H \varepsilon_H (T_{H-in} - T_h), \tag{12}$$

where ε_H is the effectiveness of the hot side heat exchanger,

$$\varepsilon_H = 1 - \exp(-UA_h/C_H). \tag{13}$$

The released heat flow rate to the environment is

$$Q_L = UA_l (T_l - T_0). \tag{14}$$

The heat flow rates and temperatures of the Carnot cycle satisfy

$$Q_H/T_h = Q_L/T_l. \tag{15}$$

The absorbed and released heat flow rates, Q_H and Q_L, and the working medium temperature on the cold side T_l can be determined by Eqs. (12)–(15) with prescribed T_h. According to the first law of thermodynamics, the output power is

$$W = Q_H - Q_L. \tag{16}$$

Treating the thermodynamic cycle and the environment as a whole system, the total heat flow rate from the hot stream into the whole system is

$$Q_{in} = C_H(T_{H-in} - T_0). \tag{17}$$

Substituting Eqs. (16) and (17) into Eq. (6) makes the heat-work conversion efficiency become

$$\eta_t = (Q_H - Q_L)/[C_H(T_{H-in} - T_0)]. \tag{18}$$

When the concept of entropy generation is used to optimize thermodynamic cycles, the entropy generation rate due to the release of the waste streams into the environment should be considered. Based on the first law of thermodynamics for the whole system and Eq. (17), the heat flow rate transferred from the system into the environment Q_0 is

$$Q_0 = C_H(T_{H-in} - T_0) - W. \tag{19}$$

The differential entropy balance equation for the whole endoreversible Carnot cycle is

$$dS = \delta S_g + dS_f, \tag{20}$$

where dS is the entropy change rate, dS_f is the entropy flow rate, and δS_g is the entropy generation rate. As the whole system is steady, the entropy change rate $dS = 0$, and then the entropy generation rate is

$$S_g = \int \delta S_g = -\int dS_f = C_H \ln(T_0/T_{H-in}) + Q_0/T_0, \tag{21}$$

where the first term on the right side is the entropy flow rate from the hot stream, and the second term is the entropy flow rate into the environment.

Similarly, the entransy loss rate into the environment should also be considered when the concept of entransy loss is used to optimize the endoreversible Carnot cycle. The whole system including the endoreversible Carnot cycle and the environment is an open system. The entransy loss is the difference between the entransy flow into the system from the hot stream and those induced by dumping the used hot stream and the released heat from the cycle into the environment. According to Eq. (1), the total entransy loss rate is

$$G_{loss} = C_H(T_{H-in}^2 - T_0^2)/2 - Q_0T_0, \tag{22}$$

where the first term on the right hand side of the equation is the net entransy flow rate brought into the system by the hot stream, and the second term is that into the environment.

The total entransy flow rate taken into the system is

$$G_{in} = C_H(T_{H-in}^2 - T_0^2)/2. \tag{23}$$

Substituting Eqs. (22) and (23) into Eq. (5), the entransy loss coefficient of the endoreversible Carnot cycle is expressed as

$$\eta_G = [C_H(T_{H-in}^2 - T_0^2) - 2Q_0T_0]/[C_H(T_{H-in}^2 - T_0^2)]. \tag{24}$$

According to Eqs. (2), (3), and (23), we have

$$Q_{in} = C_H(T_{H-in} - T_0), \tag{25}$$

$$T_{in} = (T_{H-in} + T_0)/2, \tag{26}$$

$$T_{out} = T_0. \tag{27}$$

Considering Eqs. (19), and (23)–(27), we find that larger entransy loss rate leads to larger output power, and larger entransy loss coefficient leads to larger heat-work conversion efficiency when the inlet temperature T_{H-in} and the heat capacity

flow rate $C_{\rm H}$ of the hot stream are prescribed. Furthermore, as $T_{\rm in}$ in Eq. (26) and $T_{\rm out}$ in Eq. (27) are fixed for different $C_{\rm H}$, larger entransy loss coefficient is still related to larger thermal efficiency.

For a specific example, assume that $C_{\rm H} = 3$ W/K, $T_{\rm H-in} = 400$ K, $T_0 = 300$ K, the thermal conductances of heat exchangers $UA_{\rm h} = 100$ W/K, and $UA_{\rm l} = 80$ W/K. The variations of the output power, entropy generation rate, entransy loss rate, heat-work conversion efficiency, and entransy loss coefficient with $T_{\rm h}$ are shown in Fig. 2. The heat capacity flow rate of the fluid remains constant, and then $C_{\rm min}$ remains constant when $T_{\rm h}$ changes. Based on the two definitions of the entropy generation number, the variation tendencies of the entropy generation numbers and the entropy generation rate are consistent. It is found that both the minimum entropy generation rate and the maximum entransy loss rate correspond to the maximum output power, while both the minimum entropy generation numbers and the maximum entransy loss coefficient correspond to the maximum heat-work conversion efficiency with prescribed inlet temperature and heat capacity flow rate of the stream. As the inlet temperature $T_{\rm H-in}$ and the heat capacity flow rate $C_{\rm H}$ of the hot stream are fixed, $Q_{\rm in}$, $T_{\rm in}$, and $T_{\rm out}$ in Eqs. (25)–(27) are fixed. According to Eq. (4), larger output power corresponds to larger entransy loss rate. According to Eq. (7), larger heat-work conversion efficiency corresponds to larger entransy loss coefficient.

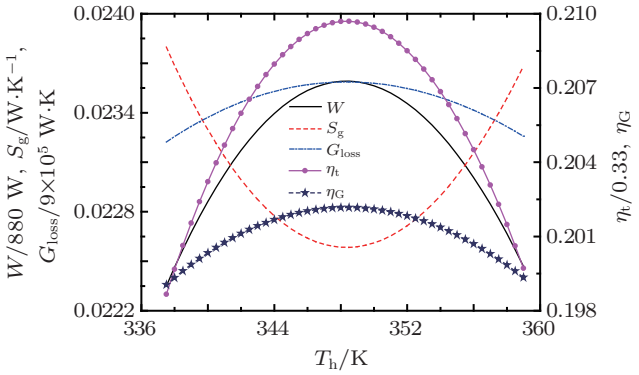


Fig. 2. (color online) The variations of the output power, entropy generation rate, entransy loss rate, heat-work conversion efficiency, and entransy loss coefficient with $T_{\rm h}$.

According to Eq. (10), the minimum heat capacity flow rate $C_{\rm min}$ is just $C_{\rm H}$. Hence, the entropy generation number has the same variation tendency as the entropy generation rate when $C_{\rm H}$ is constant. Assuming $T_{\rm h}$ = 350 K, the variations of the output power, entropy generation rate, and entransy loss rate with $C_{\rm H}$ for the whole system are shown in Fig. 3. The variations of the heat-work conversion efficiency, entropy generation number, and entransy loss coefficient with $C_{\rm H}$ for the whole system are shown in Fig. 4. It is shown that neither smaller entropy generation rate nor larger entransy loss rate always leads to larger output power, while both smaller entropy generation numbers and larger entransy loss coefficient lead to larger heat-work conversion efficiency when the heat capacity flow rate of the hot stream $C_{\rm H}$ is unfixed. As the inlet temperature of the hot stream is fixed, $T_{\rm in}$ and $T_{\rm out}$ in Eqs. (26) and (27) are fixed while $Q_{\rm in}$ varies. According to Eq. (7), larger heat-work conversion efficiency always leads to larger entransy loss coefficient. For Eq. (4), larger entransy loss may not always lead to larger output power.

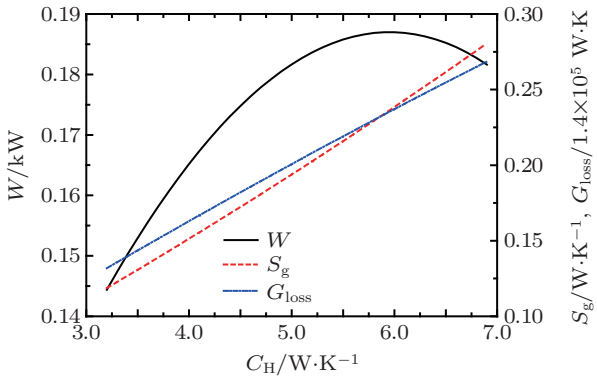


Fig. 3. (color online) The variations of the output power, entropy generation rate, and entransy loss rate with $C_{\rm H}$.

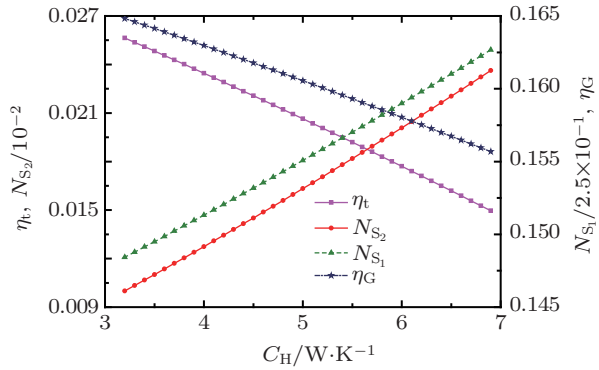


Fig. 4. (color online) The variations of the heat-work conversion efficiency, entropy generation number, and entransy loss coefficient with $C_{\rm H}$.

When the inlet temperature of the hot stream $T_{\rm H-in}$ is changeable and $T_{\rm h} = 350$ K, the variations of the output power, entropy generation rate, entransy loss rate, heat-work conversion efficiency, and entransy loss coefficient with $T_{\rm H-in}$ for the whole system are shown in Fig. 5. According to Eq. (10), the minimum heat capacity flow rate $C_{\rm min}$ is just $C_{\rm H}$. Therefore, the entropy generation numbers have the same variation tendencies as that of the entropy generation rate for constant $C_{\rm H}$. It is shown that larger entransy loss rate leads to larger output power while smaller entropy generation rate does not, and larger entransy loss coefficient leads to larger heat-work conversion efficiency while smaller entropy generation numbers do not when the inlet temperature of the hot stream is unfixed. When the inlet temperature increases, the output power

and the heat-work conversion efficiency both increase. Meanwhile, $Q_{\rm in}$ and $T_{\rm in}$ increase, which results in the increase in $G_{\rm loss}$ and $\eta_{\rm G}$.

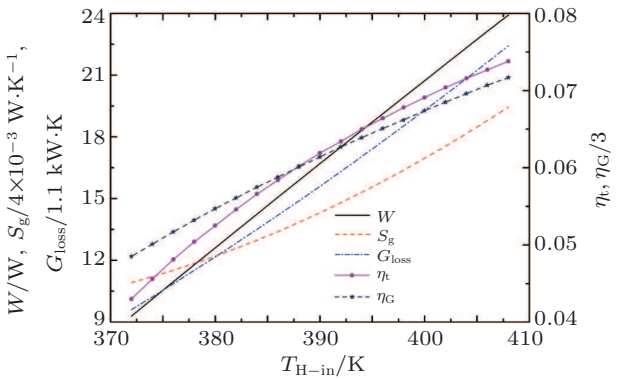


Fig. 5. (color online) The variations of the output power, entropy generation rate, entransy loss rate, heat-work conversion efficiency, and entransy loss coefficient with $T_{\rm H-in}$.

3.2. Cycle working between heat sources with infinite heat capacity

Figure 6 is an endoreversible Carnot cycle working between temperatures $T_{\rm H}$ and $T_{\rm L}$. The heat capacities of the heat sources are infinite. The thermal conductances of heat exchangers on each side are $UA_{\rm h}$ and $UA_{\rm l}$, respectively. When the working medium temperature on the hot side $T_{\rm h}$ changes, there is

$$Q_{\rm in} = UA_{\rm h}(T_{\rm H} - T_{\rm h}). \tag{28}$$

According to Eqs. (8) and (9), $T_{\rm in}$ and $T_{\rm out}$ are prescribed for the endoreversible Carnot cycle working between the heat sources with infinite heat capacity. Equation (28) indicates that $Q_{\rm in}$ changes with $T_{\rm h}$. Therefore, the maximum entransy loss coefficient always corresponds to the maximum heat-work conversion efficiency according to Eq. (7).

For the endoreversible Carnot cycle in Fig. 6, the entropy generation rate is

$$S_{\rm g} = \frac{Q_{\rm L}}{T_{\rm L}} - \frac{Q_{\rm H}}{T_{\rm H}}. \tag{29}$$

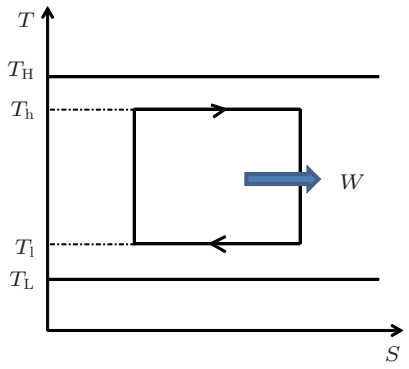


Fig. 6. (color online) The schematic of the endoreversible Carnot cycle working between heat sources with infinite heat capacity.

The entransy loss rate and the entransy loss coefficient are

$$G_{\rm loss} = Q_{\rm H}T_{\rm H} - Q_{\rm L}T_{\rm L}, \tag{30}$$

$$\eta_{\rm G} = \frac{Q_{\rm H}T_{\rm H} - Q_{\rm L}T_{\rm L}}{Q_{\rm H}T_{\rm H}}. \tag{31}$$

Consider a specific example in which $T_{\rm H} = 400$ K, $T_{\rm L} = 300$ K, $UA_{\rm h} = 100$ W/K, and $UA_{\rm l} = 80$ W/K. The variations of the output power, entropy generation rate, entransy loss rate, heat-work conversion efficiency, and entransy loss coefficient with $T_{\rm h}$ are shown in Fig. 7. The definition of entropy generation number in Eq. (11) is not applicable for this case. Based on the other definition, the minimum entropy generation number remains constant, and then the entropy generation number has the same variation tendency as that of the entropy generation rate. The results show that larger entransy loss coefficient as well as smaller entropy generation number leads to larger heat-work conversion efficiency, while neither smaller entropy generation rate nor larger entransy loss rate leads to larger output power. According to Eqs. (7)–(9), larger heat-work conversion efficiency always leads to larger entransy loss coefficient, but larger entransy loss rate may not lead to larger output power as $Q_{\rm in}$ is variational in Eq. (4).

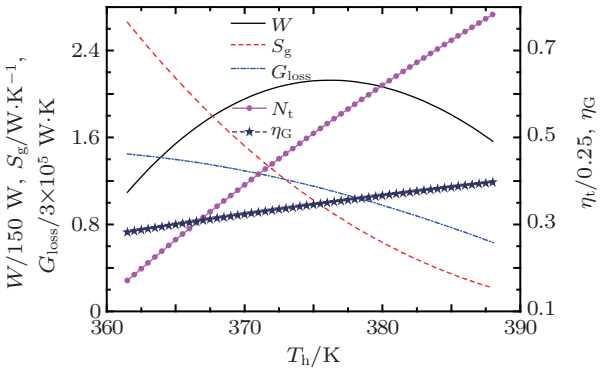


Fig. 7. (color online) The variations of the output power, entropy generation rate, entransy loss rate, heat-work conversion efficiency, and entransy loss coefficient with $T_{\rm h}$.

In another case, the heat-work conversion efficiency $\eta_{\rm t}$ is set as 0.15, and $T_{\rm H} = 400$ K, $T_{\rm L} = 300$ K, $UA_{\rm l} = 80$ W/K. The variations of the output power, entropy generation rate, entransy loss rate, and entransy loss coefficient with $UA_{\rm h}$ are shown in Fig. 8. The results show that the entransy loss coefficient remains constant while the entropy generation rate increases with increasing $UA_{\rm h}$ when the heat-work conversion efficiency $\eta_{\rm t}$ remains constant. The entropy generation number has the same variation tendency as that of the entropy generation rate. Larger entransy loss rate is related to larger output power, while smaller entropy generation rate is not. The entransy loss coefficient has the same variation tendency as that of the heat-work conversion efficiency, while the entropy generation number does not. As $T_{\rm H}$ and $T_{\rm L}$ are fixed, $T_{\rm in}/T_{\rm out}$ is then fixed in Eq. (7). According to Eq. (7), the entransy loss

coefficient η_G always corresponds to the heat-work conversion efficiency η_t. In this case, the entransy loss coefficient is constant when the heat-work conversion efficiency remains constant.

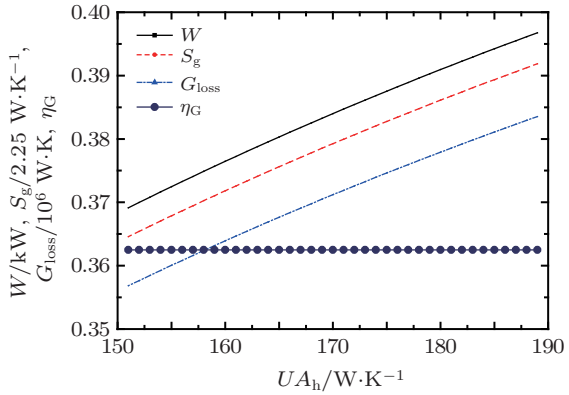


Fig. 8. (color online) The variations of the output power, entropy generation rate, entransy loss rate, and entransy loss coefficient with UA_h.

4. Conclusions

For the endoreversible Carnot cycle discussed, the output power, entropy generation rate, entransy loss rate, thermal efficiency, entropy generation number, and entransy loss coefficient are analyzed for some conditions. When the inlet temperatures and heat capacity flow rates of streams are prescribed, both smaller entropy generation rate and larger entransy loss rate lead to larger output power, while both smaller entropy generation number and larger entransy loss coefficient lead to larger thermal efficiency. When the inlet temperatures of streams are not given, larger entransy loss rate leads to larger output power while smaller entropy generation rate does not, and larger entransy loss coefficient leads to larger heat-work conversion efficiency while smaller entropy generation number does not. When the heat capacity flow rates of streams are not fixed or the heat capacities of heat sources are infinite, larger entransy loss coefficient is always related to larger heat-work conversion efficiency, while smaller entropy generation number is not. Neither smaller entropy generation rate nor larger entransy loss rate always leads to larger output power.

References

[1] Zhang Z J, Zeng Y H and Kusiak A 2012 *Energy* **47** 505
[2] Tu Z C 2012 *Chin. Phys. B* **21** 020513
[3] Frank E D, Sullivan J L and Wang M Q 2012 *Environ. Res. Lett.* **7** 034030
[4] Wang X W, Cai G B and Gao Y S 2011 *Chin. Phys. B* **20** 064701
[5] Wang H and Wu G X 2012 *Chin. Phys. B* **21** 010505
[6] Grazzini G and Gori F 1988 *Int. J. Heat Mass Transfer* **31** 2547
[7] Johannessen E, Nummedal L and Kjelstrup S 2002 *Int. J. Heat Mass Transfer* **45** 2649
[8] Shah R K and Skiepko T 2004 *J. Heat Transfer ASME* **126** 994
[9] Guo Z Y, Zhu H Y and Liang X G 2007 *Int. J. Heat Mass Transfer* **50** 2545
[10] Chen L G, Wei S H and Sun F R 2008 *J. Phys. D: Appl. Phys.* **41** 195506
[11] Xie Z H, Chen L G and Sun F R 2009 *Sci. China Ser. E* **52** 3413
[12] Xiao Q H, Chen L G and Sun F R 2011 *Chin. Sci. Bull.* **56** 102
[13] Chen L G, Xiao Q H, Xie Z H and Sun F R 2012 *Int. Commun. Heat Mass Trans.* **39** 1556
[14] Feng H J, Chen L G, Xie Z H and Sun F R 2012 *Sci. China Tech. Sci.* **55** 3322
[15] Feng H J, Chen L G and Sun F R 2012 *Sci. China Tech. Sci.* **55** 515
[16] Feng H J, Chen L G, Xie Z H and Sun F R 2013 *Sci. China Tech. Sci.* **56** 299
[17] Chen Q and Ren J X 2008 *Chin. Sci. Bull.* **53** 3753
[18] Yuan F and Chen Q 2011 *Energy* **36** 5476
[19] Cheng X T and Liang X G 2011 *Int. J. Heat Mass Transfer* **54** 269
[20] Cheng X T, Xu X H and Liang X G 2011 *Sci. China Tech. Sci.* **54** 2446
[21] Guo Z Y, Liu X B, Tao W Q and Shah R K 2010 *Int. J. Heat Mass Transfer* **53** 2877
[22] Qian X D and Li Z X 2011 *Int. J. Thermal. Sci.* **50** 608
[23] Xia S J, Chen L G and Sun F R 2009 *Chin. Sci. Bull.* **54** 3587
[24] Cheng X T, Xu X H and Liang X G 2011 *Sci. China Tech. Sci.* **54** 964
[25] Wang W H, Cheng X T and Liang X G 2013 *Sci. China Tech. Sci.* **56** 529
[26] Zeng D L, Ao Y, Zhang X M and Liu C 2002 *Engineering Thermodynamics* (Beijing: High Education Press) (in Chinese)
[27] Myat A, Thu K and Kim Y D 2011 *Appl. Therm. Eng.* **31** 2405
[28] Klein S A and Reindl D T 1998 *J. Energy Resour. Technol.* **120** 172
[29] Cheng X T, Wang W H and Liang X G 2012 *Chin. Sci. Bull.* **57** 2934
[30] Cheng X T and Liang X G 2012 *Energy* **44** 964
[31] Cheng X T and Liang X G 2012 *Energy* **47** 421
[32] Cheng X T, Wang W H and Liang X G 2012 *Sci. China Tech. Sci.* **55** 2847
[33] Zhou B, Cheng X T and Liang X G 2013 *Sci. China Tech. Sci.* **56** 228
[34] Wang W H, Cheng X T and Liang X G 2013 *Energy Convers. Manage.* **68** 82
[35] Zhou B, Cheng X T and Liang X G 2013 *J. Appl. Phys.* **113** 124904
[36] Cheng X T and Liang X G 2013 *J. Thermal Sci. Tech.* **8** 337
[37] Cheng X T, Chen Q, Hu G J and Liang X G 2013 *Int. J. Heat Mass Transfer* **60** 180
[38] Bejan A 1997 *Advanced Engineering Thermodynamics* (2nd edn.) (New York: John Wiley & Sons)
[39] Bejan A 1996 *J. Appl. Phys.* **79** 1191
[40] Chen L G, Wu C and Sun F R 2005 *J. Non-Equilibrium Thermodynamics* **24** 327
[41] Wu C, Chen L G and Chen J C 1999 *Recent Advances in Finite Time Thermodynamics* (New York: Nova Science Publishers)
[42] Chen L G and Sun F R 2004 *Advances in Finite Time Thermodynamics: Analysis and Optimization* (New York: Nova Science Publishers)
[43] Chen L G, Ma K, Ge Y L and Sun F R 2013 *Arab J. Sci. Eng.* **38** 341
[44] Chen L G 2012 *Chin. Sci. Bull.* **57** 4404
[45] Li J, Chen L G and Sun F R 2008 *Appl. Energy* **85** 96
[46] Qin X Y, Chen L G, Sun F R and Wu C 2005 *Appl. Energy* **81** 365
[47] Wu C, Chen L G and Sun F R 1998 *Energy Convers. Manage.* **39** 579
[48] Curzon F L and Ahlborn B 1975 *Am. J. Phys.* **43** 22