

The Application of Entransy Dissipation Theory on the Performance Analysis of an Irreversible Atkinson Cycle

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Abstract Several techniques on the Second Law of Thermodynamics have been used in the past for the analysis of Air standard Cycles. The terms used for these techniques include irreversibility analysis, entropy generation minimization, exergy analysis and thermodynamic efficiency. Entransy is a recently developed concept reflecting the heat transfer potential, rather than the ability to convert heat to work. This paper extends this concept to optimize thermodynamic processes of an irreversible Atkinson cycle. The entransy balance equation of thermodynamic processes is introduced, with which the concept of entransy dissipation is developed. For the irreversible Atkinson cycle where the working fluid is heated by the streams with prescribed inlet temperatures and specific capacity flow rates, it is found that the maximum entransy dissipation leads to the maximum output work, which is the maximum principle of entransy dissipation in thermodynamic processes. At the same time, it is found that minimum entropy generation alone could not describe change of the output work for the Atkinson cycle. The operation parameters are optimized for evaluating the maximum output work of Atkinson cycle by incorporating maximum entransy dissipation and minimum entropy generation when both, entransy dissipation and entropy generation, are induced by dumping the used streams into the environment is considered.

Keywords Entransy Dissipation, Entropy Generation, Irreversible Atkinson Cycle, Maximum Output Work, Environment

1. Introduction

The Atkinson cycle is named after its inventor James Atkinson in 1882 Pulkrabek [1]. As the worldwide energy crisis is becoming more and more serious, effective energy utilization and exchange are receiving more and more attention. Considering that nearly 80% of the total energy consumption is related to heat transfer Chen Q [2]. The

improvement of heat transfer is of great significance to reduce energy consumption. A series of achievements has been made, since finite-time thermodynamics was used to analyze and optimize the performance of real thermodynamic processes, devices and cycles Bejan [3], Chen L [4], Ge Y [5], Lin JC [6], I. Prigogine [7]. A. Bejan [8-9] developed the entropy generation minimization (EGM) approach in thermodynamic optimization. The total entropy production rate denoted by S_{gen} is the sum of entropy production associated with heat conduction and fluid friction. However, among all the variational principles in thermodynamics, Prigogine's minimum entropy generation principle is still the most debated one V. Bertola [10]. Accordingly the entropy generation minimization approach, widely applied to modeling and optimization of thermal system that owe their thermodynamics imperfection to heat transfer, mass transfer, and fluid flow irreversibility's, demonstrates some inconsistencies and paradoxes in the application of thermodynamic system. This is because the focus of the entropy generation minimization is on the heat-work conversion processes, while in thermodynamic cycles the rate and efficiency of heat transfer are more concerned. A. Bejan [11] related the best heat transfer process to the minimum entropy generation. The minimum principle of entropy generation may be not always applicable to heat transfer optimization.

Nomenclature

- C heat capacity flow rate (WK-1)
- C_p heat capacity flow rate at constant pressure (WK-1)
- C_v heat capacity flow rate at constant volume (WK-1)
- G_{dis} entransy dissipation not induced by environment (WK)
- $G_{dis,e}$ entransy dissipation induced by environment (WK)
- Q heat transfer rate (W)
- S_g entropy generation not induced by environment (WK-1)

- $S_{g,e}$ entropy generation induced by environment (WK-1)
- T temperature (K)
- W output work (W)
- Greek symbols
- ε effectiveness of heat exchanger
- γ reversible adiabatic index
- Subscripts
- H hot fluid
- in inlet
- L cold fluid
- max maximum
- min minimum
- out outlet

For this purpose, Guo et al [12] introduced a new physical quantity, entransy that describes the heat transfer ability by the analogy between heat and electrical conduction. For body whose internal energy is U and temperature is T , its entransy is defined as,

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

Cheng et al. proved that this concept could be used to describe the irreversibility of heat transfer. X.T. Cheng [13] developed a microscopic expression of entransy for a monatomic ideal gas system. X.G. Liang [14] related the entransy to the microstate number and indicated the microscopic physical meaning of entransy to some extent. Guo et al derived the minimum entransy dissipation principle for prescribed heat flux boundary conditions and the maximum entransy dissipation principle for prescribed temperature boundary conditions. These two principles are referred to as the extreme entransy dissipation principle. Furthermore, Guo et al defined an equivalent thermal resistance of the system based on the entransy dissipation and heat flux. Then, the extreme entransy dissipation principle is equivalent to the minimum thermal resistance principle that is much easier for understanding. These principles are used to optimize heat conduction H.Y. Zhu [15], Z.H. Xie [16], Q.H. Xiao [17]; heat convection Q. Chen [18], Q. Chen [19], J. Wu [20]; thermal radiation J. Wu [21], X.T. Cheng [21]; transport networks X.B. Liu [23]. It is found that the maximum entransy dissipation corresponds to the maximum heat transfer rate when the heat transfer temperature difference is prescribed, while the minimum entransy dissipation corresponds to the minimum heat transfer temperature difference when the heat transfer rate is prescribed.

For the design optimization of thermodynamic cycles the entransy theory is also applicable. In the present work, the entransy balance equations for thermodynamic processes of an irreversible Atkinson cycle are introduced and the

expressions for entransy dissipation and entropy generation are derived. In addition, the operation parameters are optimized for obtaining maximum output work from an irreversible Atkinson cycle by incorporating principles of maximum entransy dissipation and minimum entropy generation

2. Thermodynamic Analysis of the Atkinson Cycle with Irreversible Processes

The Atkinson cycle with irreversible processes is shown in Fig. 1, where Q_H is the heat absorbed by the working fluid from the high temperature stream through the counter flow heat exchanger whose number of heat transfer units is NTU_H , Q_L is the heat released to the low temperature fluid through the counter flow heat exchanger with the number of heat transfer units NTU_L , and the output work is W . The heat capacity flow rate, the inlet and outlet temperature of the high temperature stream are C_H, T_{H-in} and T_{H-out} , respectively, while those of the low temperature stream are C_L, T_{L-in} and T_{L-out} respectively. For the working fluid, the heat capacity flow rate at constant volume is C_V and the heat capacity flow rate at constant pressure is C_P . The temperature of the working fluid is T_1 at state 1 and it gets increased to T_2 at state 2 by isentropic compression. The working fluid is heated by the high temperature stream from state 2 to 3 under constant volume and its temperature gets increased to T_3 . The next process is the second isentropic process during which the mechanical work output is obtained and subsequently the temperature of the working fluid decreases to T_4 at state 4. Finally, the working fluid is cooled by the low temperature fluid from state 4 to 1 under constant pressure and returns to its initial state.

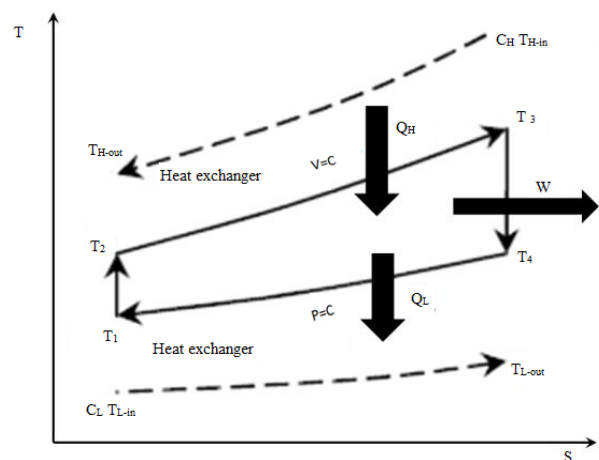


Figure 1. T-s diagram for the cycle model

For the irreversible Atkinson cycle as shown in Fig. 1, the heat transfer rate (Q_H) between the working fluid and the high temperature stream is given as :

$$Q_H = C_H (T_{H-in} - T_{H-out}) = C_{H-min} (T_{H-in} - T_2) \varepsilon_H$$

$$= C_{H-min} (T_{H-in} - T_2) \frac{1 - \exp\left[\frac{-NTU_H(1-C^{H*})}{1-C^{H*} \exp\left[\frac{-NTU_H(1-C^{H*})}{1-C^{H*}}\right]}\right]}{1-C^{H*} \exp\left[\frac{-NTU_H(1-C^{H*})}{1-C^{H*}}\right]}, \quad (2)$$

where, C_{H-min} is the smaller one between C_H and C_V , ε_H is the effectiveness, and C^{H*} is the capacity ratio of the high temperature stream. One can write the expression of C^{H*} as:

$$C^{H*} = \frac{\min\{C_H, C_V\}}{\max\{C_H, C_V\}}, \quad (3)$$

Similarly, the heat transfer rate (Q_L) between the working fluid and the low temperature stream is

$$\begin{aligned} Q_L &= C_L(T_{L-out} - T_{L-in}) = C_{L-min}(T_4 - T_{L-in})\varepsilon_L \\ &= C_{L-min}(T_4 - T_{L-in}) \frac{1 - \exp\left[\frac{-NTU_L(1-C^{L*})}{1-C^{L*} \exp\left[\frac{-NTU_L(1-C^{L*})}{1-C^{L*}}\right]}\right]}{1-C^{L*} \exp\left[\frac{-NTU_L(1-C^{L*})}{1-C^{L*}}\right]}, \end{aligned} \quad (4)$$

where C_{L-min} is the smaller one between C_L and C_P , ε_L is the effectiveness, and C^{L*} is the capacity ratio of the low temperature stream. One can write the expression of C^{L*} as:

$$C^{L*} = \frac{\min\{C_L, C_P\}}{\max\{C_L, C_P\}}, \quad (5)$$

Based on Eqs. (2) and (4), one can get:

$$T_3 = T_2 + \frac{Q_H}{C_V}, \quad (6)$$

$$T_1 = T_4 - \frac{Q_L}{C_P}, \quad (7)$$

The output work rate (W) can be written as:

$$W = Q_H - Q_L, \quad (8)$$

For the thermodynamic states 3 and 4, one can write:

$$T_3 v_3^{\gamma-1} = T_4 v_4^{\gamma-1}, \quad (9)$$

Equation (9) can be rearranged as:

$$T_3 = T_4 r_e^{\gamma-1}, \quad (10)$$

Where, r_e is the expansion ratio $= v_4/v_3$ and γ is reversible adiabatic index $= C_P/C_V$

Similarly for thermodynamic states 1 and 2, one can write:

$$T_1 v_1^{\gamma-1} = T_2 v_2^{\gamma-1}, \quad (11)$$

Equation (11) can be rearranged as:

$$T_1 = \frac{T_2}{r_k^{\gamma-1}}, \quad (12)$$

Where, r_k is the compression ratio $= v_1/v_2$

On combining equation (10) and (12), one can get:

$$T_3 = T_2 * r_e^{\gamma} * \frac{1}{r_k^{\gamma}}, \quad (13)$$

And consequently,

$$T_4 = T_1 * \frac{r_e}{r_k}, \quad (14)$$

2.1. Entropy Generation and Entropy Dissipation when Used Stream is not Dumped into the Environment

The total entropy generation rate (S_g) in gas-gas heat exchanger, when used stream is not dumped into the environment, can be written as Chen Q [24].

$$S_g = \left(C_H \ln \frac{T_{H-out}}{T_{H-in}} + C_V \ln \frac{T_3}{T_2}\right) + \left(C_L \ln \frac{T_{L-out}}{T_{L-in}} + C_P \ln \frac{T_1}{T_4}\right), \quad (15)$$

Equation (15) can be rearranged as:

$$S_g = \left(C_H \ln \frac{T_{H-out}}{T_{H-in}} + \frac{C_P}{\gamma} \ln \frac{T_3}{T_2}\right) + \left(C_L \ln \frac{T_{L-out}}{T_{L-in}} + C_P \ln \frac{T_1}{T_4}\right), \quad (16)$$

By using Eqs. (2) and (4), one can get:

$$T_{H-out} = T_{H-in} - \frac{Q_H}{C_H}, \quad (17)$$

$$T_{L-out} = T_{L-in} + \frac{Q_L}{C_L}, \quad (18)$$

The entropy dissipation (G_{dis}), induced by dumping the used stream into the environment is not taken into account, can be calculated as:

$$G_{dis} = G_{inlet} - G_{outlet}, \quad (19)$$

Where G_{inlet} is the entropy that flow out of the hot stream and G_{outlet} is the entropy into the cold stream

For any heat exchanger with one dimensional steady flow, the energy balance equation of the hot fluid can be written as:

$$C_H \frac{dT_H(x)}{dx} = -Q(x), \quad (20)$$

Where C_H is the heat capacity flow rate, $Q(x)$ is the heat transfer rate at x , $T_H(x)$ is the temperature of the hot fluid at x . Multiplying both side of eq. (20) by the hot fluid temperature $T_H(x)$, the entropy balance equation of the hot fluid can be written as:

$$\begin{aligned} C_H \int_{T_{H-out}}^{T_{H-in}} T_H dT_H &= \int Q(x) T_H(x) dx, \\ \frac{1}{2} C_H T_{H-in}^2 - \frac{1}{2} C_H T_{H-out}^2 &= \int Q(x) T_H(x) dx, \end{aligned} \quad (21)$$

Similarly, the entropy balance equation of the cold fluid can be written as:

$$\frac{1}{2} C_L T_{L-out}^2 - \frac{1}{2} C_L T_{L-in}^2 = \int Q(x) T_L(x) dx, \quad (22)$$

Equation (21) and (22) in equation (19), one can get:

$$G_{dis} = \left[\frac{1}{2} C_H T_{H-in}^2 + \frac{1}{2} C_L T_{L-in}^2 \right] - \left[\frac{1}{2} C_H T_{H-out}^2 + \frac{1}{2} C_L T_{L-out}^2 \right] = \int Q(x) [T_H(x) - T_L(x)] dx, \quad (23)$$

Equation (23) can be rearranged as:

$$G_{dis} = G_{inlet} - G_{outlet} = \frac{1}{2} C_H (T_{H-in}^2 - T_{H-out}^2) - \frac{1}{2} C_L (T_{L-out}^2 - T_{L-in}^2), \quad (24)$$

2.2. Entropy Generation and Entropy Dissipation when Used Stream is Dumped into the Environment

The total entropy generation rate ($S_{g,e}$) in gas-gas heat exchanger when used stream is dumped into the environment can be written as:

$$S_{g,e} = \left(C_H \ln \frac{T_{H-out}}{T_{H-in}} + C_V \ln \frac{T_3}{T_2} \right) + \left(C_L \ln \frac{T_{L-out}}{T_{L-in}} + C_P \ln \frac{T_1}{T_4} \right) + \frac{Q_{e1}}{T_0} + \frac{Q_{e2}}{T_0}, \quad (25)$$

Where Q_{e1} and Q_{e2} are the heat exchanges between the used streams and the environment, whose expressions are

$$Q_{e1} = C_H (T_{H-out} - T_0), \quad (26)$$

$$Q_{e2} = C_L (T_{L-out} - T_0), \quad (27)$$

Using Equation (26) and (27) in equation (25), one can get:

$$S_{g,e} = \left(C_H \ln \frac{T_{H-out}}{T_{H-in}} + C_V \ln \frac{T_3}{T_2} \right) + \left(C_L \ln \frac{T_{L-out}}{T_{L-in}} + C_P \ln \frac{T_1}{T_4} \right) + \frac{C_H (T_{H-out} - T_0)}{T_0} + \frac{C_L (T_{L-out} - T_0)}{T_0}, \quad (28)$$

Using Equation (17) and (18) in Equation (28), one can get:

$$S_{g,e} = \left(C_H \ln \frac{T_{H-out}}{T_{H-in}} + C_V \ln \frac{T_3}{T_2} \right) + \left(C_L \ln \frac{T_{L-out}}{T_{L-in}} + C_P \ln \frac{T_1}{T_4} \right) + \frac{C_H \left(T_{H-in} - \frac{Q_H}{C_H} - T_0 \right)}{T_0} + \frac{C_L \left(T_{L-in} + \frac{Q_L}{C_L} - T_0 \right)}{T_0}, \quad (29)$$

Equation (29) can be rearranged as:

$$S_{g,e} = \left(C_H \ln \frac{T_{H-out}}{T_{H-in}} + C_V \ln \frac{T_3}{T_2} \right) + \left(C_L \ln \frac{T_{L-out}}{T_{L-in}} + C_P \ln \frac{T_1}{T_4} \right) + \frac{C_H (T_{H-in} - T_0)}{T_0} + \frac{C_L (T_{L-in} - T_0)}{T_0} - \frac{(Q_H - Q_L)}{T_0}, \quad (30)$$

Using Equation (8) in Equation (30), one can get:

$$S_{g,e} = \left(C_H \ln \frac{T_{H-out}}{T_{H-in}} + C_V \ln \frac{T_3}{T_2} \right) + \left(C_L \ln \frac{T_{L-out}}{T_{L-in}} + C_P \ln \frac{T_1}{T_4} \right) + \frac{C_H (T_{H-in} - T_0) + C_L (T_{L-in} - T_0)}{T_0} - \frac{W}{T_0}, \quad (31)$$

The entropy dissipation ($G_{dis,e}$), induced by dumping the used stream into the environment is taken into account, can be calculated as:

$$G_{dis,e} = G_{inlet,e} - G_{outlet,e}, \quad (32)$$

Where $G_{inlet,e}$ is the entransy that flows out of the hot stream into the environment and $G_{outlet,e}$ is the entransy of the cold stream into the environment:

$$G_{inlet,e} = \frac{1}{2}C_H(T_{H-in}^2 - T_0^2) + \frac{1}{2}C_L(T_{L-in}^2 - T_0^2), \quad (33)$$

$$G_{outlet,e} = (Q_{e1} + Q_{e2})T_0, \quad (34)$$

Using Equation (33) and (34) in equation (32), one can get:

$$\begin{aligned} G_{dis,e} &= \frac{1}{2}C_H(T_{H-in}^2 - T_0^2) + \frac{1}{2}C_L(T_{L-in}^2 - T_0^2) - Q_{e1}T_0 - Q_{e2}T_0 \\ &= \frac{1}{2}C_H(T_{H-in}^2 - T_0^2) + \frac{1}{2}C_L(T_{L-in}^2 - T_0^2) - [Q_{e1} + Q_{e2}]T_0, \end{aligned} \quad (35)$$

Using Equation (26) and (27) in Equation (35), one can get:

$$G_{dis,e} = \frac{1}{2}C_H(T_{H-in}^2 - T_0^2) + \frac{1}{2}C_L(T_{L-in}^2 - T_0^2) - [C_H(T_{H-out} - T_0) + C_L(T_{L-out} - T_0)]T_0, \quad (36)$$

Using Equation (17) and (18) in Equation (36), one can get:

$$G_{dis,e} = \frac{1}{2}C_H(T_{H-in}^2 - T_0^2) + \frac{1}{2}C_L(T_{L-in}^2 - T_0^2) - \left[C_H \left(T_{H-in} - \frac{Q_H}{C_H} - T_0 \right) + C_L \left(T_{L-in} + \frac{Q_L}{C_L} - T_0 \right) \right] T_0, \quad (37)$$

Equation (37) can be rearranged as:

$$G_{dis,e} = \frac{1}{2}C_H(T_{H-in}^2 - T_0^2) + \frac{1}{2}C_L(T_{L-in}^2 - T_0^2) - C_H T_0 (T_{H-in} - T_0) - C_L T_0 (T_{L-in} - T_0) + (Q_H - Q_L)T_0, \quad (38)$$

Using Equation (8) in Equation (38), one can get:

$$G_{dis,e} = \frac{1}{2}C_H(T_{H-in}^2 - T_0^2) + \frac{1}{2}C_L(T_{L-in}^2 - T_0^2) - C_H T_0 (T_{H-in} - T_0) - C_L T_0 (T_{L-in} - T_0) + WT_0, \quad (39)$$

3. Results and Discussion

The derived expressions above are used and plotted in order to compare performance parameters of the Atkinson cycle with T_2 . For the numerical calculations in the present work, the following values are used [25].

$$C_H = 3 \text{ W/K}, C_L = 2 \text{ W/K}, \gamma = 1.4, r_k = 8, T_{H-in} = 400 \text{ K}, T_{L-in} = T_0 = 300 \text{ K}, NTU_H = 3 \text{ and } NTU_L = 2.$$

Variations of the normalised output work, normalised entropy generation and normalised entransy dissipation with different values of T_2 , when the entropy generation and the entransy dissipation induced by dumping the used stream into the environment is not considered, are shown in Fig.2. As can be seen from the figure, values of normalised output work (W/W (max)) goes on increasing with T_2 and attains its maximum value at $T_2 = 350\text{K}$. On the other hand, values of normalised entropy generation (Sg/Sg (max)) and normalised entransy dissipation (Gdis/Gdis (max)) go on decreasing with T_2 . The normalised entropy generation (Sg/Sg (max)) attains its minimum value at temperature $T_2 > 375 \text{ K}$ while normalised entransy dissipation (Gdis/Gdis (max)) has its maximum value at $T_2 = 325 \text{ K}$. The above observations can also be drawn by evaluating Equations (8), (16) and (24). Hence, the minimum entropy generation and the maximum entransy dissipation both does not correspond to the maximum output work when dumping the used stream into the environment is not considered

Variations of the normalised output work, normalised entropy generation and normalised entransy dissipation with different values of T_2 , when the entropy generation and the entransy dissipation induced by dumping the used stream into the environment is considered, are shown in Fig.3. As can be seen from the figure, values of normalised output work (W/W (max)) goes on increasing with T_2 and attains its maximum value at $T_2 = 350\text{K}$. On the other hand, values of normalised entropy generation (Sg, e/Sg, e (max)) goes on decreasing and normalised entransy dissipation (Gdis, e/Gdis, e (max)) goes on increasing with T_2 . The normalised entropy generation (Sg, e/Sg, e (max)) attains its minimum value at temperature $T_2 = 350 \text{ K}$ while normalised entransy dissipation (Gdis, e/Gdis, e (max)) has its maximum value at $T_2 = 350 \text{ K}$. The above observations can also be drawn by evaluating Equations (8), (31) and (39). Hence, the minimum entropy generation and the maximum entransy dissipation both correspond to the maximum output work when dumping the used stream into the environment is considered.

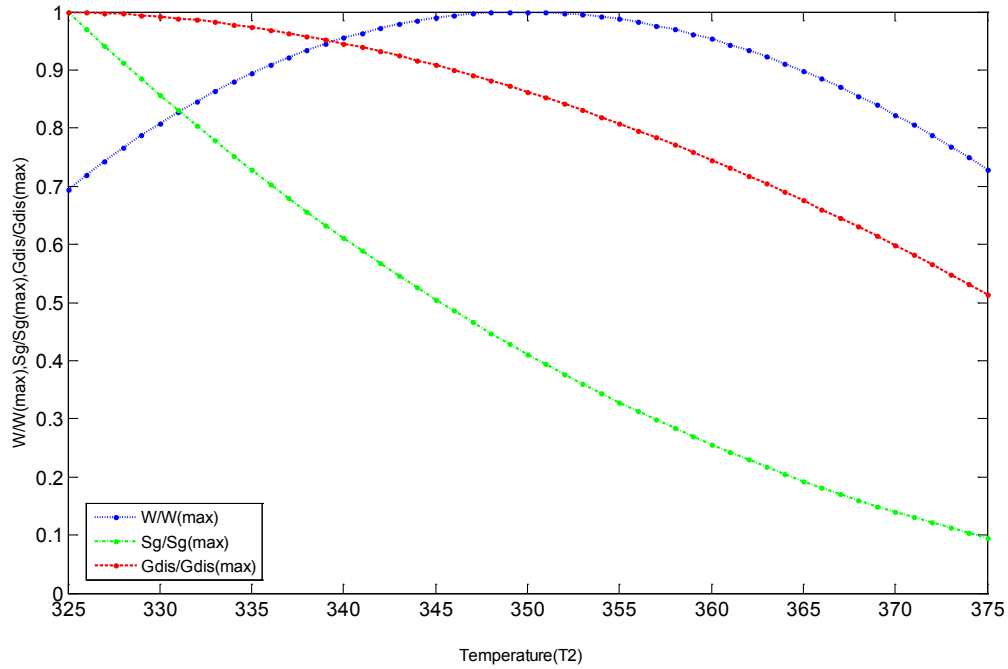


Figure 2. Variations of output work, the entropy generation and the entransy dissipation with T_2 when the entropy generation and the entransy dissipation induced by dumping the used stream into the environment are not considered

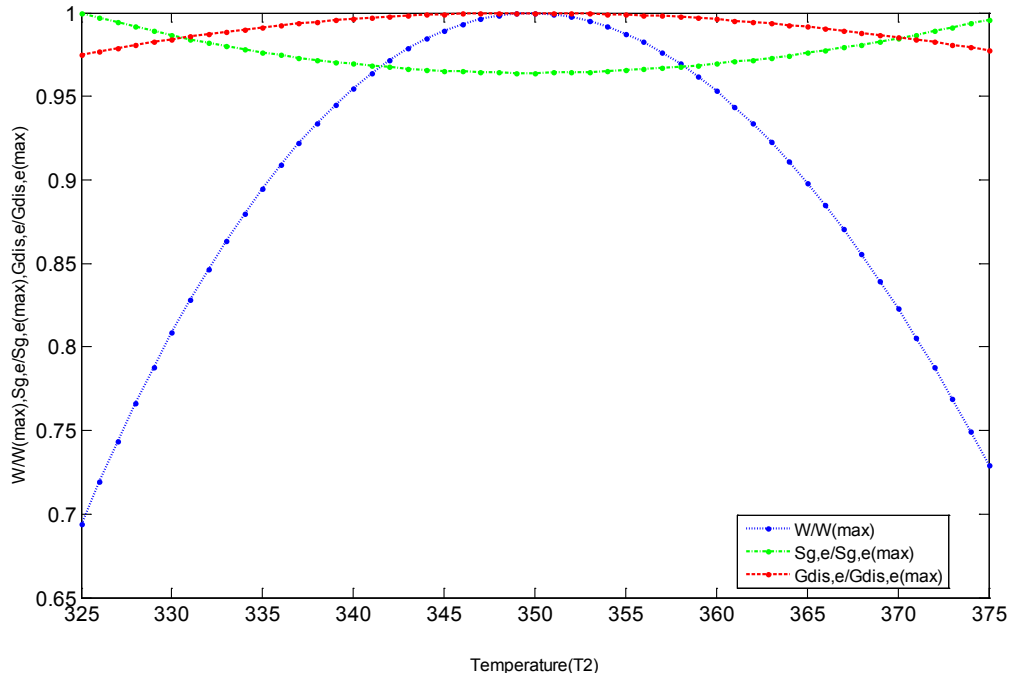


Figure 3. Variations of the output work, the entropy generation and the entransy dissipation with T_2 when the entropy generation and the entransy dissipation induced by dumping the used stream into the environment are considered.

Variations of the normalised output work, normalised entropy generation and normalised entransy dissipation with different values of heat capacity flow rate (C_p), when the entropy generation and the entransy dissipation induced by dumping the used stream into the environment is not considered, are shown in Fig.4. As can be seen from the figure, values of normalised output work ($W/W_{(max)}$), normalised entropy generation ($S_g/S_{g(max)}$) and normalised entransy dissipation ($G_{dis}/G_{dis(max)}$) go on increasing with C_p but attains their maximum values at different values C_p . The maximum value of normalised output work is at $C_p = 1.7$ W/K, maximum value of normalised entropy generation is at $C_p = 3$ W/K and maximum value of normalised entransy dissipation is at $C_p = 2.5$ W/K. The above observations can also be drawn by evaluating Equations (8), (16) and (24). Hence, the minimum entropy generation and the maximum entransy dissipation both does not correspond to the maximum output work when dumping the used stream into the environment is not considered.

Variations of the normalised output work, normalised entropy generation and normalised entransy dissipation with different values of heat capacity flow rate (C_p), when the entropy generation and the entransy dissipation induced by dumping the used stream into the environment is considered, are shown in Fig.5. As can be seen from the figure, values of normalised output work ($W/W_{(max)}$) goes on increasing with T_2 and attains its maximum value at $C_p = 1.7$ W/K. On the other hand, the normalised entropy generation ($S_{g,e}/S_{g,e(max)}$) attains its minimum value at temperature $C_p = 1.7$ W/K while normalised entransy dissipation ($G_{dis,e}/G_{dis,e(max)}$) has its maximum value at $C_p = 1.7$ W/K. The above observations can also be drawn by evaluating Equations (8), (31) and (39). Hence, the minimum entropy generation and the maximum entransy dissipation both correspond to the maximum output work when dumping the used stream into the environment is considered.

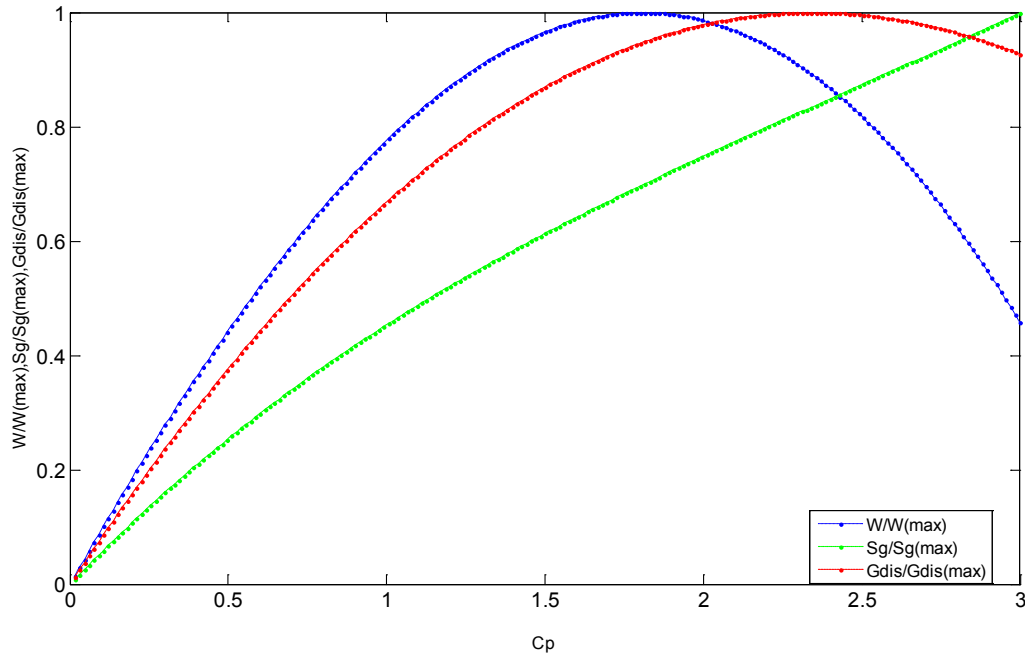


Figure 4. Variations of the output work, the entropy generation and the entransy dissipation with C_p when the entropy generation and the entransy dissipation induced by dumping the used stream into the environment are not considered

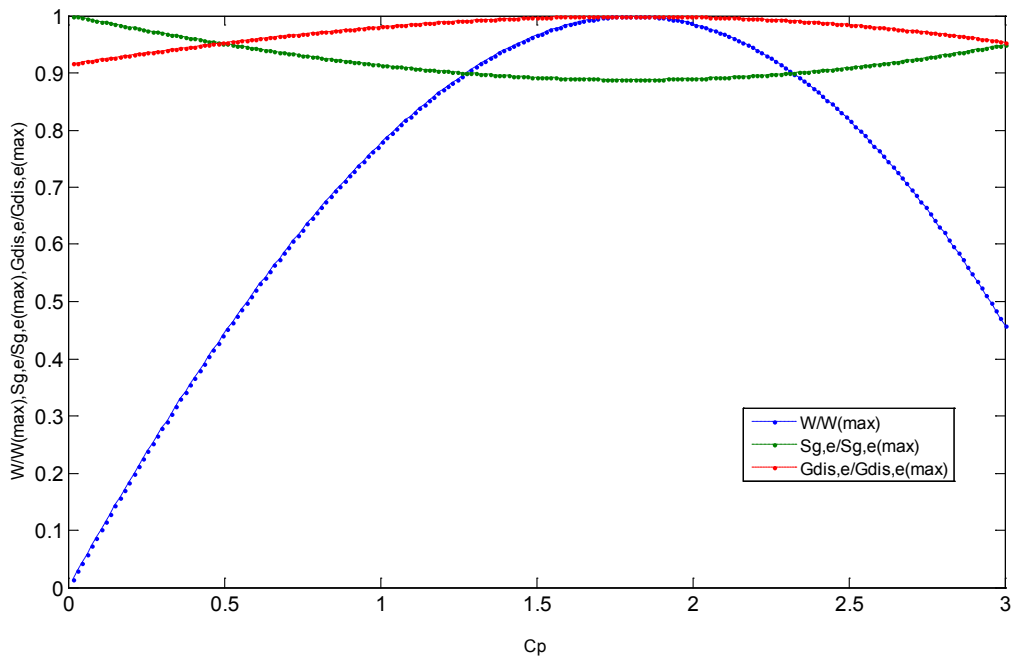


Figure 5. Variations of the output work, the entropy generation and the entransy dissipation with C_p when the entropy generation and the entransy dissipation induced by dumping the used stream into the environment are considered

4. Conclusion

In this paper, the entransy balance equation of thermodynamic processes is introduced for the first time in Atkinson cycle. For any thermodynamic process, it is found that some of the net entransy flow from the heat sources is dissipated during the heating and the cooling processes of the working fluid, while the rest is lost in the process of doing work. For the Atkinson cycle and the irreversible thermodynamic processes where the working fluid is heated by the streams with prescribed inlet temperatures and specific capacity flow rates, it is found that the maximum entransy dissipation corresponds to the maximum output work. Since entropy generation, being point function, is zero for reversible cycle hence, the concept of entransy dissipation could be used to describe the performance of thermodynamic processes. With the maximum principle of entransy dissipation and the minimum principle of entropy generation, the thermodynamic optimization design of the irreversible Atkinson cycle are analyzed and discussed. It is found that the operation parameters could be optimized to get the maximum output work by calculating the maximum entransy dissipation and the minimum entropy generation when the entropy generation and the entransy dissipation induced by dumping the used stream into the environment are considered.

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