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Finite-time thermodynamic analysis for endoreversible Lenoir cycle coupled to constant-temperature heat reservoirs

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Abstract
A thermodynamic model of a steady-flow endoreversible Lenoir heat engine cycle (a "three point" cycle) coupled to constant-temperature heat reservoirs is established in this paper by using finite time thermodynamic theory. The cycle consists of one isochoric heating branch, one adiabatic expansion branch and one isobaric cooling branch. The analytical formulae about power output and thermal efficiency of the cycle are derived. The optimal performance of the cycle is obtained with the fixed total thermal conductance of heat exchangers. Moreover, the effects of the heat reservoir temperature ratio and the total thermal conductance of heat exchangers on the general and optimal performances are analyzed. The results show that the power and efficiency performance curve of the cycle is a fixed "point" with constant thermal conductance of hot- and cold-side heat exchangers, and there exist optimal thermal conductance distributions, which lead to maximum power and maximum efficiency, respectively, with changeable thermal conductances of hot- and cold-side heat exchangers. Both the power and efficiency will be enhanced with the increase of thermal conductance ratio between high- and low-temperature heat reservoirs, or the total thermal conductance of heat exchangers.

Keywords: Finite time thermodynamics; Endoreversible Lenoir heat engine cycle; Power and efficiency characteristics.

1. Introduction

Since the analysis and optimization of various heat engine cycles for various objectives have been made by using the finite time thermodynamics theory [1-10], it has made tremendous progress in different periods. The endoreversible model for heat engine cycles, which is originally used by NoviKov [11], Chambadal [12], Curzon and Ahlborn [1], is the basic model of finite time thermodynamics. Sun et al. [13] and Chen et al. [14] derived the fundamental optimal formulae of power and efficiency for endoreversible Carnot heat engine with the fixed total heat-transfer area of heat exchangers, and made some performance optimizations. Chen et al. [15, 16] investigated performances of steady-flow thermodynamic cycles coupled to constant- and variable-temperature heat reservoirs, derived the optimum performance characteristics of endoreversible Carnot and Brayton heat engines with fixed total thermal conductance of heat exchangers, obtained the optimum power output and the thermal efficiency limit, and made a comparison between the two cycles. Zhang et al. [17] established a relatively universal endoreversible steady-flow heat engine cycle model, which consists of two adiabatic branches, two constant thermal-capacity heating branches and a constant thermal-capacity cooling branch, and studied power, efficiency and their optimal relationship, and the exergy-based ecological performance. Yang et al. [18] built an endoreversible model of an intercooled regenerated Brayton heat and power cogeneration plant coupled to variable-temperature heat reservoirs, and optimized the heat conductance distributions and the choice of intercooling pressure ratio on the basis of the exergetic analysis.

Early in the 1860, Lenoir developed an atmospherically compressive engine, the progenitor of the Otto one. The Lenoir cycle is based on the engine [19]. By using the classical thermodynamic method, Georgiou [20] made some analysis on the formulae of thermal efficiency, temperature ratio and adiabatic coefficient for the simple Lenoir cycle, the version with straightforward regenerative preheating process, and the modified (double) Lenoir cycle with regenerative preheating, and compared the thermal efficiency with Carnot's. On the basis of Ref. [20], the focus of this paper is to study power output and thermal efficiency characteristics of endoreversible Lenoir heat engine cycle with heat-transfer loss, and optimize the heat conductance distribution by using finite time thermodynamics.

2. Cycle model

The model of endoreversible Lenoir heat engine cycle coupled to constant-temperature heat reservoirs T_H and T_L is shown in Figure 1 (a) and (b). The "three point" cycle consists of three processes. The heating process is isochoric 1–2. The expansion process is adiabatic 2-3. The cooling process is isobaric 3–1. It is assumed that the working fluid is an ideal gas.

According to the law of heat transfer, properties of working fluid and the theory of heat exchangers [21, 22], the rate of heat transfer (Q_H) supplied by the heat source, and the rate of heat transfer (Q_L) released to the heat sink are, respectively

$$\begin{aligned} Q_H &= U_H (T_2 - T_1) / \ln\left[(T_H - T_1)/(T_H - T_2)\right] \\ &= \dot{m} C_V (T_2 - T_1) = \dot{m} C_V E_H (T_H - T_1) \end{aligned} \tag{1}$$

$$\begin{aligned} Q_L &= U_L (T_1 - T_3) / \ln\left[(T_1 - T_L)/(T_3 - T_L)\right] \\ &= \dot{m} C_P (T_3 - T_1) = \dot{m} C_P E_L (T_3 - T_L) \end{aligned} \tag{2}$$

where $\dot{m}$ is mass flow rate of the working fluid, E_H and E_L are the effectivenesses of the hot- and cold-side heat exchangers. The relationships of the effectivenesses (E_H and E_L), the numbers of heat transfer units (N_H and N_L), and the heat conductance (U_H and U_L) of the hot- and cold-side heat exchangers are as following:

$$E_H = 1 - \exp(-N_H), E_L = 1 - \exp(-N_L) \tag{3}$$

$$N_H = U_H / (\dot{m} c_V), N_L = U_L / (\dot{m} c_P) \tag{4}$$

and the heat conductance (U_H and U_L) is the product of heat-transfer coefficient α and heat transfer surface area F, that is, $U_H = \alpha_H F_H$ and $U_L = \alpha_L F_L$.

Within an endoreversible cycle, according to the second law of thermodynamics, the working fluid obeys:

$$\Delta s = c_V \ln\left(T_2/T_1\right) - c_P \ln\left(T_3/T_1\right) = 0 \tag{5}$$

3. Performance analysis

According to properties of ideal working fluid, Eq. (5) can be rearranged as:

$$T_2 / T_1 = \left(T_3 / T_1\right)^k \tag{6}$$

The power output and the thermal efficiency of the cycle are:

$$P = Q_H - Q_L \tag{7}$$

$$\eta = 1 - Q_L / Q_H \tag{8}$$

Eqs. (1) and (2) give the relations among the temperatures of three state points:

$$T_2 = E_H T_H + (1 - E_H) T_1 \tag{9}$$

$$T_3 = \frac{\left(T_1 - E_L T_L\right)}{\left(1 - E_L\right)} \tag{10}$$

Combining Eqs. (1), (2), (9) and (10) gives:

$$Q_H = \dot{m} c_V E_H (T_H - T_1) \tag{11}$$

$$Q_L = \frac{\dot{m} k c_V E_L \left(T_1 - T_L\right)}{\left(1 - E_L\right)} \tag{12}$$

Combining Eqs. (7), (8), (11) and (12) gives power output and the thermal efficiency as follows:

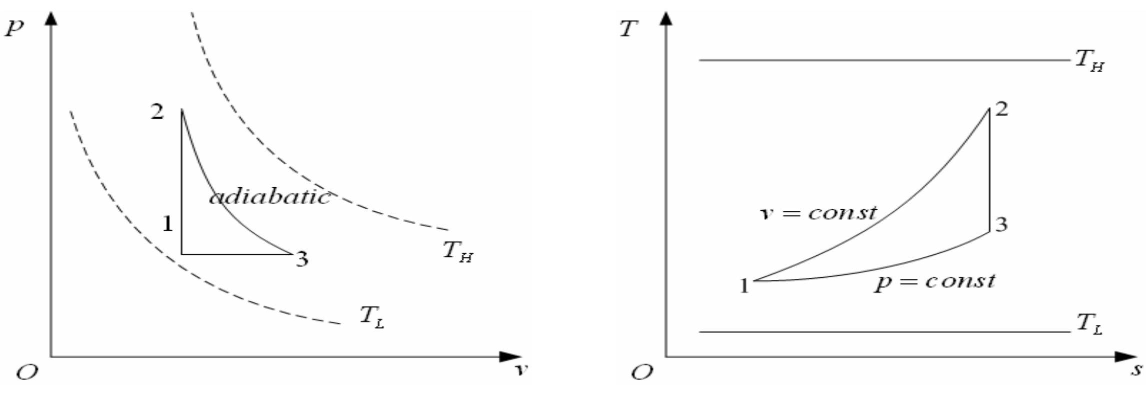
$$P = \dot{m} c_V \left[\left(E_H T_H + \frac{k E_L T_L}{1 - E_L} \right) - \left(E_H + \frac{k E_L}{1 - E_L} \right) T_1 \right] \tag{13}$$

$$\eta = \left(\frac{T_H}{(T_H - T_1)} + \frac{k E_L T_L}{E_H \left(1 - E_L\right)(T_H - T_1)} \right) - \left(\frac{1}{(T_H - T_1)} + \frac{k E_L}{E_H \left(1 - E_L\right)(T_H - T_1)} \right) T_1 \tag{14}$$

Combining Eqs. (6), (9) and (10) gives what the temperature T_1 obeys:

$$T_1 - E_L T_L = \left(1 - E_L\right) \left[E_H T_H + (1 - E_H) T_1 \right]^{\frac{1}{k}} T_1^{1 - \frac{1}{k}} \tag{15}$$

The value of T_1 can be obtained by numerical calculation method from Eq. (15). Substituting T_1 into Eqs. (9) and (10), one can obtain the value of T_2 and T_3. Substituting T_1 into Eqs. (13) and (14), one can obtain the power output and the thermal efficiency of the endoreversible Lenoir cycle.



(a) (b)

Figure 1. p-v and T-s diagrams for endoreversible Lenoir heat engine cycle model.

4. Discussion

4.1 Performance with constant thermal conductance of hot- and cold-side heat exchangers

When the thermal conductances of hot- and cold-side heat exchangers (U_H and U_L) are fixed as constants, the effectivenesses (E_H and E_L) are constants, too. Coupled to constant-temperature heat reservoirs T_H and T_L, Eqs. (13)-(15) give both the power output and the thermal efficiency of the endoreversible Lenoir cycle to be also constants. That is, the $T-s$ curve of the cycle is completely fixed, and the $P-\eta$ curve of the cycle is a fixed "point".

This makes performance of the endoreversible Lenoir cycle very different from those of other typical endoreversible heat engine cycles studied before, such as endoreversible Carnot [5-10], Diesel [23], Otto [24], Atkinson [25], Brayton [26], Dual [27], Stirling [28] and Miller [29] cycles, as well as some universal heat engine cycle models [30-34]. The $P-\eta$ characteristic curve of the endoreversible Lenoir cycle is a fixed "point", while the characteristic curves of the other endoreversible cycles are almost all parabolic-like ones. Making some comparisons between them, one can see that, as there is no (adiabatic) compression process in the Lenoir cycle, the thermal efficiency loses the variability dimension adapted to the temperature or ratio of pressure of state points. Therefore, there does not exist the fundamental optimal formulae of power and thermal efficiency for the cycle, and when the thermal conductances of hot- and cold-side heat exchangers (U_H and U_L) are fixed as constants, the state of each point is fixed.

4.2 Performance with variable thermal conductances of hot- and cold-side heat exchangers

When the thermal conductances of hot- and cold-side heat exchangers (U_H and U_L) are changeable, the heat conductance distribution can be optimized with a fixed total thermal conductance of heat exchangers. The optimum power output or the optimum thermal efficiency will be obtained. For a fixed total thermal conductance U_T, one can define:

$$U_L + U_H = U_T \tag{16}$$

and set $u_L = U_L / U_T \; (0 < u_L < 1)$. Combining it with Eqs. (3) and (4) gives the effectivenesses (E_H and E_L):

$$E_H = 1 - \exp\left(-\frac{(1-u_L)U_T}{\dot{m}c_V}\right), E_L = 1 - \exp\left(-\frac{u_L U_T}{\dot{m}kc_V}\right) \tag{17}$$

From Eqs. (13)-(17), one can obtain the characteristics of power output and the thermal efficiency versus thermal conductance distribution, and the optimal thermal conductance distribution of the endoreversible Lenoir cycle.

5. Numerical examples

Numerical examples are provided to illustrate the preceding analyses. According to Ref. [17], take the working fluid as ideal gas, and it is set that: $T_L = 320\mathrm{K}$, $\dot{m} = 1.1165\mathrm{kg/s}$, $C_V = 0.7165\mathrm{kJ/(kg \cdot K)}$, and $k = 1.4$.

When the thermal conductances of hot- and cold-side heat exchangers (U_H and U_L) are fixed as constants, the effectivenesses (E_H and E_L) are constants, and set them as $E_H = E_L = 0.8$ or 0.9. The power output and the thermal efficiency of endoreversible Lenoir cycle can be obtained by using numerical calculation method.

When the thermal conductances of hot- and cold-side heat exchangers (U_H and U_L) are changeable, the values of total thermal conductance are set as $U_T =$ $2.5\mathrm{kW/K}$, $5\mathrm{kW/K}$, $7.5\mathrm{kW/K}$ and $10\mathrm{kW/K}$. Take the thermal conductance distribution (u_L) as a variable, one can obtain power and efficiency versus thermal conductance distribution by using numerical calculation method, and analyze the effects of design parameters on the performance.

Figure 2 shows power output and the thermal efficiency of endoreversible Lenoir cycle when the thermal conductances of hot- and cold-side heat exchangers (U_H and U_L) are fixed as constants. In that condition, the power output and the thermal efficiency of the cycle are completely fixed, that means, the

$P-\eta$ characteristic curve of the cycle is a fixed "point". It is the distinct characteristic which makes Lenoir cycle differ from the other cycles. Both the power output and the thermal efficiency will increase with the increase of the temperature ratio between heat source and heat sink, or the effectivenesses (E_H and E_L) of heat exchangers.

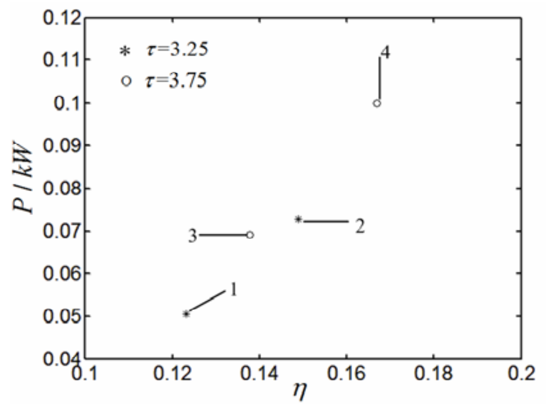


Figure 2. Power and efficiency of endoreversible Lenoir cycle with constant thermal conductance; (1) τ=3.25, $E_H = E_L = 0.8$; (2) τ=3.25, $E_H = E_L = 0.9$; (3) τ=3.75, $E_H = E_L = 0.8$; (4) τ=3.75, $E_H = E_L = 0.9$.

Figure 3 shows the characteristic of power output (P) versus thermal conductance distribution (u_L) of endoreversible Lenoir cycle, and the effects of the temperature ratio (τ) and the total thermal conductance (U_T) on the characteristic. One can see that taking heat-transfer loss into consideration, the $P-u_L$ characteristic curve is parabolic-like one, and there exists an optimal thermal conductance distribution (u_{LP}) leading to the maximum power output (P_m). The power output (P) will increase with the increase of the temperature ratio (τ) between heat source and heat sink, or the total thermal conductance (U_T). But the optimal thermal conductance distribution (u_{LP}) will decrease with the increase of the total thermal conductance (U_T). To a certain range the total thermal conductance (U_T) increases, the maximum power output (P_m) will not increase obviously. Moreover, the neighborhood of the thermal conductance distribution ($u_{LP} - \Delta u,\ u_{LP} + \Delta u$) that makes the power output (P) approach very near the maximum (P_m) extends. From the perspective of engineering, when the total thermal conductance (U_T) increases to that range, one can obtain the maximum power output (P_m) even thermal conductance distribution (u_L) departure the optimal one (u_{LP}) in some extent.

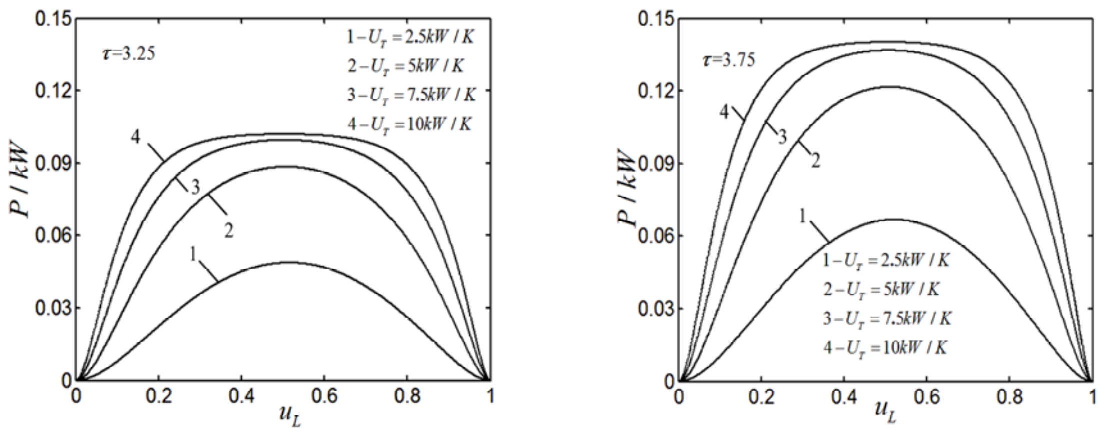


Figure 3. Power versus thermal conductance distribution of endoreversible Lenoir cycle.

Figure 4 shows the characteristic of thermal efficiency (η) versus thermal conductance distribution (u_L) of endoreversible Lenoir cycle, and the effects of the temperature ratio (τ) and the total thermal conductance (U_T) on the characteristic. One can see that there exists an optimal thermal conductance distribution ($u_{L\eta}$) leading to the maximum thermal efficiency (η_m). The $\eta - u_L$ characteristic curve is also parabolic-like one, and the effects of τ and U_T on the $\eta - u_L$ characteristic are similar to those on $P - u_L$ characteristic.

Table 1 lists the optimal thermal conductance distributions (u_{LP} for P_m and $u_{L\eta}$ for η_m) of the cycle with different heat reservoir temperature ratios (τ) and total thermal conductances (U_T). One can find that for the fixed heat reservoir temperature ratio (τ) and total thermal conductance (U_T), the optimal thermal conductance distributions obey $u_{LP} < u_{L\eta}$ rule, namely, the optimal thermal conductance distribution for maximum power output (P_m) differs from that for (η_m), the former is less than the latter one.

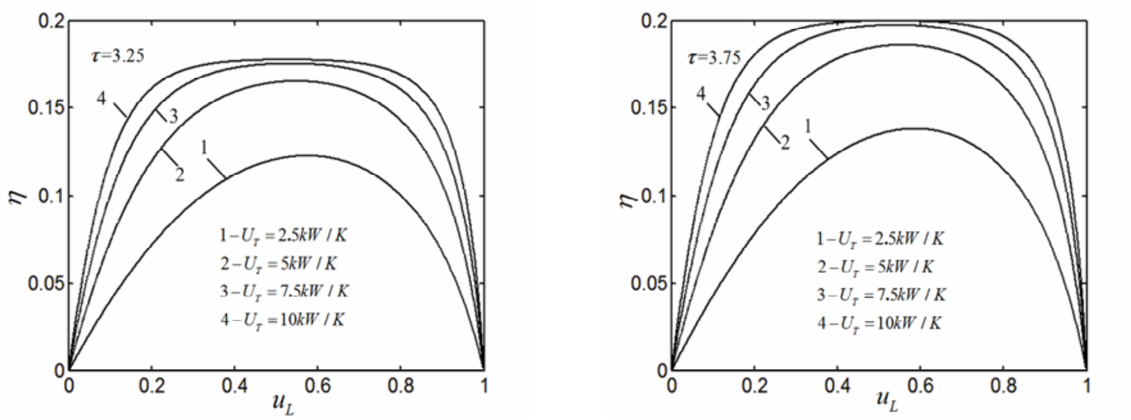


Figure 4. Efficiency versus thermal conductance distribution of endoreversible Lenoir cycle.

Table 1. Optimal thermal conductance distributions of the cycle with different heat reservoir temperature ratio and total thermal conductance.

$U_T/(kW/K)$		2.5	5	7.5	10
τ=3.25	u_{LP}	0.515	0.507	0.504	0.503
	$u_{L\eta}$	0.574	0.548	0.534	0.526
τ=3.75	u_{LP}	0.521	0.511	0.507	0.505
	$u_{L\eta}$	0.587	0.557	0.540	0.530

6. Conclusion

Based on the finite time thermodynamic theory, this paper establishes a thermodynamic model of a steady-flow endoreversible Lenoir heat engine cycle (a "three point" cycle) coupled to constant-temperature heat reservoirs, derives the formulae about power and thermal efficiency of the cycle, and obtains the optimal performance of the cycle with the fixed total thermal conductance of heat exchangers. The characteristic of power output versus thermal conductance distribution and that of thermal efficiency versus thermal conductance distribution are obtained using numerical examples. The results obtained herein show that there exist optimal thermal conductance distributions, which lead to maximum power and maximum efficiency (u_{LP} for P_m and $u_{L\eta}$ for η_m), respectively, with variable thermal conductance of hot- and cold-side heat exchangers. Moreover, both the heat reservoir temperature ratio and the total thermal conductance have obvious effects on the characteristics of cycle. The model, method and results can provide some theoretical guidelines for the improvement of practical performance of Lenoir heat engine.

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Nomenclature

c	specific heat (kJ/(kg·K))	η	thermal efficiency
E	effectiveness of the heat exchanger	τ	temperature ratio
F	heat transfer surface area (m^2)	*Subscripts*	
k	ratio of the specific heats	H	high temperature side
$\dot{m}$	mass flow rate (kg/s)	L	low temperature side
P	pressure (kPa); power (kW)	LP	maximum power output
Q	heat flow rate (kJ/s)	$L\eta$	maximum thermal efficiency
s	specific entropy (kJ/(kg·K))	m	maximum
T	temperature (K)	P	pressure
u	thermal conductance distribution	V	volume
Greek symbols		$1-3$	state point/sequence number
α	heat-transfer coefficient		

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