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Maximum power of a multistage Rankine cycle in low-grade thermal energy conversion

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HIGHLIGHTS

- A method for evaluating the maximum power output was derived for multistage LTEC.
- At most, maximum power increased approximately twice compared with a single-stage heat engine.
- The thermal efficiency of the cycle for the maximum power was constant, regardless of the number of stages.

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ABSTRACT

As energy and environmental problems worsen on a global scale, enthusiasm has grown for the use of low-grade thermal energy conversion (LTEC), which utilizes unused low-temperature heat sources. The majority of these unused low-temperature heat sources are difficult to recover owing to their low temperature; thus, the thermal efficiency of the cycle in LTEC is, in principle, smaller than for the standard power generation cycle. Therefore, improving the performance of the LTEC system by using a multistage heat engine to mitigate the irreversible loss in heat exchange has often been studied. However, little is known about the properties of this system and its effectiveness. This study used a multistage heat engine to analyze the maximum power usable by LTEC and proposed an evaluation formula based on the maximum power. The evaluation formula derived for the maximum power of a multistage heat engine revealed that, compared with a single-stage engine, the power increases approximately twofold at its maximum, and that the thermal efficiency of the cycle for the maximum power is constant, regardless of the number of stages.

1. Introduction

As energy and environmental problems worsen on a global scale, enthusiasm has grown for the use of low-grade thermal energy conversion (LTEC), which utilizes unused low-temperature heat sources. LTEC is a power generation system with low energy density but enormous availability, which utilizes temperature differences between low heat sources such as hot spring water, waste heat, and ocean thermal energy conversion (OTEC). Unused low-temperature heat sources include gas and waste heat from hot water or from high-temperature areas, and cover a wide range of temperatures. However, waste heat is often low in temperature and difficult to recover. As a result, the thermodynamic cycle of LTEC is not as efficient, in principle, as a standard power generation cycle.

The thermal efficiency of cycles is used as one of the most important criteria for evaluating power generation systems that utilize fossil fuels, such as thermal power generation. On the other hand, LTEC targets unused thermal energy, such as hot spring water and waste heat, as an added heat (that is, energy input), so the thermal efficiency of the cycle cannot adequately evaluate the system during optimization. To determine the available power for a power generation system, Curzon and Ahlborn [1] defined the maximum power of a Carnot heat engine by using a proportional constant for the time required for an isothermal process per cycle, in which heat exchange by the heat source was considered. In this state, they derived the thermal efficiency of the cycle. This evaluation was summarized by Chen et al. [2]. Wu [3] derived the maximum power for an infinite use of warm and cold heat sources (with constant heat source and heat sink temperatures for the

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Nomenclature

C	heat capacity rate, [W/K]
c_p	specific heat, [J/(kg K)]
m	mass flow rate, [kg/s]
Q	heat flow, [W]
s	specific entropy, [J/(kg K)]
T	temperature, [K], [°C]
ΔT	temperature difference, [K], [°C]
Greek symbols	
η	efficiency, [%]
Subscripts	
H	high temperature
I	inlet
L	low temperature
m	maximized
M	between cycles 1 and 2 in double-stage heat engine
n	number of stages
O	outlet
opt	optimal
th	thermodynamic

evaporator and the condenser). Wu and Kiang [4] expanded the results by Curzon and Ahlborn [1] on the internally reversible Carnot heat engine and calculated the maximum power for this engine by using the ratio of entropic differences between high and low temperature areas. Some studies have evaluated the maximum power for fluid mixtures [5,6]. The authors have proposed various evaluation methods to optimize a power generation system for unused heat energies [7–10].

Other methods have been proposed to improve system performance, such as a conversion to the Lorenz cycle using mixed media [11–17], or a decrease in the irreversible loss in a heat exchange process by employing a multistage heat engine (multistage Rankine cycle). The mixed-medium method is expected to mitigate irreversible loss and system pressure, but with a compromise in heat transfer at the heat exchanger [18–20], so balancing these two characteristics is critical. In a multistage Rankine cycle, independent heat engines are aligned serially against the heat source. Irreversible thermal energy losses the heat source and working fluid in the heat exchange process is mitigated by passing the heat source through each exchanger, one after another. Many studies have evaluated the performance of this multistage Rankine cycle and suggested improvements [21–25]. However, these studies are restricted to assessments under fixed heat source temperatures or ideal conditions such as thermodynamically infinite cycles or single-stage condensers. Currently, the performance and effectiveness of multistage heat engines are barely understood. A multistage heat engine is a complex system in which each stage is composed of components that are independent of each other. Additionally, the temperature range of the working fluid is different at each stage. Thus, no evaluations have been established regarding the performance, effectiveness, and optimization of this system.

This study aims to evaluate the maximum power available to the LTEC system, propose an evaluation method for a power generation system utilizing a multistage heat engine, and gain insights into the evaluation of the LTEC system through analysis and comparison with mathematical models.

2. Maximum power output of an LTEC system

2.1. Maximum power output of a single-stage Carnot heat engine

Ikegami and Bejan [7] derived the maximum power of a Carnot heat engine, a reversible cycle shown in Fig. 1, in a power generation system such as that shown in Fig. 2. The maximum power output, $W_{m,1}$, for the system is calculated by the following equation [7] for given values of the temperatures of high-temperature and low-temperature heat sources, T_{HI} and T_{LI}, and heat capacity rates, $C_H = (m \cdot c_P)_H$ and $C_L = (m \cdot c_P)_L$. It is assumed that the outlet temperature of the heat source and the temperature of the working fluid are the same ($T_{\mathrm{HC}} = T_{\mathrm{HO}}$, $T_{\mathrm{LC}} = T_{\mathrm{LO}}$).

$$W_{m,1} = \frac{\left(\sqrt{T_{\mathrm{HI}}} - \sqrt{T_{\mathrm{LI}}}\right)^2}{C_H^{-1} + C_L^{-1}} \tag{1}$$

T_{HO} and T_{LO}, the temperatures of high-temperature and low-temperature heat source outlets, for maximum power, $W_{m,1}$, are calculated by the following equations:

$$T_{\mathrm{HO,opt},1} = \frac{C_H \cdot T_{\mathrm{HI}} + C_L\sqrt{T_{\mathrm{HI}} \cdot T_{\mathrm{LI}}}}{C_H + C_L} \tag{2}$$

$$T_{\mathrm{LO,opt},1} = \frac{C_H\sqrt{T_{\mathrm{HI}} \cdot T_{\mathrm{LI}}} + C_L \cdot T_{\mathrm{LI}}}{C_H + C_L} \tag{3}$$

Thermal efficiency of cycle efficiency, $\eta_{\mathrm{th,opt},1}$, and heat flows, $Q_{H,\mathrm{opt},1}$ and $Q_{L,\mathrm{opt},1}$, are expressed as follows:

$$\eta_{\mathrm{th,opt},1} = 1 - \sqrt{\frac{T_{\mathrm{LI}}}{T_{\mathrm{HI}}}} \tag{4}$$

$$Q_{\mathrm{H,opt},1} = \frac{T_{\mathrm{HI}} - \sqrt{T_{\mathrm{HI}} \cdot T_{\mathrm{LI}}}}{C_H^{-1} + C_L^{-1}} \tag{5}$$

$$Q_{\mathrm{L,opt},1} = \frac{\sqrt{T_{\mathrm{HI}} \cdot T_{\mathrm{LI}}} - T_{\mathrm{LI}}}{C_H^{-1} + C_L^{-1}} \tag{6}$$

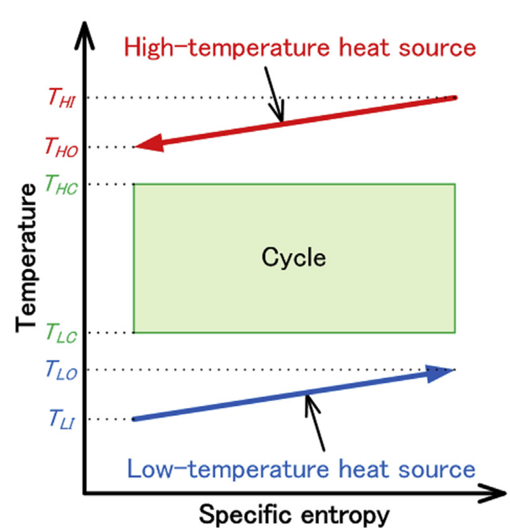

Fig. 1. Conceptual T–s diagram of Carnot cycle.