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Performance analysis and optimum criteria of an irreversible Braysson heat engine

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Abstract

An irreversible cycle model of a Braysson heat engine operating between two heat reservoirs is used to investigate the performance of the cycle affected by the finite-rate heat transfer between the working fluid and the heat reservoirs, heat leak loss between the heat reservoirs and irreversibility inside the cycle. The specific power output is maximized with respect to the cycle temperatures along with the isobaric temperature ratio. The specific power output is found to be a decreasing function of the internal irreversibility parameter and isobaric temperature ratio while there exist the optimal values of the state point temperatures at which the specific power output attains its maximum value for a typical set of operating parameters. Moreover, the maximum specific power output and other cycle parameters are calculated for different sets of operating conditions. The optimally operating regions of the important parameters in the cycle are determined. The results obtained here may provide some useful criteria for the optimal design and performance improvement of a realistic Braysson heat engine.

Keywords: Braysson heat engine; Multi-irreversibilities; Specific power output; Thermal efficiency; Optimally operating region; Optimum criterion

1. Introduction

The Braysson cycle is a hybrid power cycle based on a conventional Brayton cycle for the high temperature heat addition while adopting the Ericsson cycle for the low temperature heat rejection as proposed and investigated by Frost et al. [1] using the first law of thermodynamics. Very recently, some workers have investigated the performance of an endoreversible Braysson cycle [2–4] and a mirror cycle [5] based on the analysis of Brayton [6–23] and Ericsson [24–28] cycles by using the concept of finite time thermodynamics [29–38] for a typical set of operating conditions and obtained some significant results.

In real thermodynamic cycles, there often exist other irreversibilities besides finite-rate heat transfer between the working fluid and the heat reservoirs. For example, the heat leak loss between the heat reservoirs and internal dissipation of the working fluid are also two main sources of irreversibility. In the present paper, we will study the influence of multi-irreversibilities on the performance of a Braysson heat engine cycle.

2. An irreversible Braysson cycle

An irreversible Braysson cycle working between a source and a sink of infinite heat capacities is shown on the T–S diagram of Fig. 1. The external irreversibilities are due to the finite temperature difference between the heat engine and the external reservoirs and the direct heat leak loss from the source to the sink while the internal irreversibilities are due to nonisentropic processes in the expander and compressor devices as well as due to other entropy generations within the cycle. The working fluid enters the compressor at state point 4 and is compressed up to state point $1S/1$ in an ideal/real compressor, and then it comes into contact with the heat source and is heated up to state point 2 at constant pressure. After that the working fluid enters the turbine at state point 2 and expands up to state point $3S/3$ in an ideal/real expander/turbine, it rejects the heat to the heat sink at constant temperature and enters the compressor at state point 4, thereby, completing the cycle. Thus we study

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Nomenclature

A	area	m^2
c_P	specific heat	$kJ \cdot kg^{-1} \cdot K^{-1}$
k_0	heat leak coefficient	$kW \cdot K^{-1}$
$\dot{m}$	mass flow rate of the working fluid	$kg \cdot s^{-1}$
P	specific power output	$kW \cdot m^{-2}$
P^*	dimensionless specific power output	
Q	heat transfer rate	kW
Q_0	heat leak loss	kW
R	internal irreversibility parameter	
S	entropy	$kJ \cdot K^{-1}$
T	temperature	K
U	overall heat transfer coefficient	$kW \cdot m^{-2} \cdot K^{-1}$
x	isobaric temperature ratio	
1, 2, 3, 4	state points	

Greeks symbol

η	efficiency

Subscripts

H	heat source/hot-side
L	sink/cold-side
max	maximum
m	optimum
η	at maximum thermal efficiency

the 4–1–2–3–4 closed cycle of an irreversible Braysson heat engine coupled with the heat reservoirs of infinite heat capacities at temperature T_H and T_L, respectively.

Assuming the working fluid as an ideal/prefect gas and the heat exchangers as counter flow configurations, the heat transfer to and from the heat engine following Newton's Law of heat transfer will be

$$Q_H = \frac{U_H A_H (T_2 - T_1)}{\ln((T_H - T_1)/(T_H - T_2))} = \dot{m} c_P (T_2 - T_1) \tag{1}$$

and

$$Q_L = U_L A_L (T_3 - T_L) \tag{2}$$

where U_J and A_J ($J = H, L$) are the overall heat transfer coefficients and areas on their respective heat exchangers, T_i ($i = 1, 2, 3$) are the temperatures of the working fluid at state points 1, 2 and 3, and $\dot{m}$ and c_P are, respectively, the mass flow rate and specific heat of the working fluid.

According to Fig. 1, it is reasonable to consider some heat leak loss directly from the source to the sink, which may be expressed as [26,27,30]

$$Q_0 = k_0 (T_H - T_L) \tag{3}$$

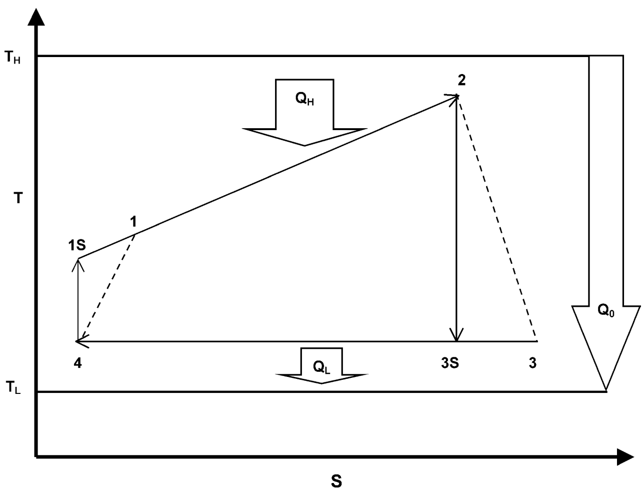

Fig. 1. The T–S diagram of an irreversible Braysson heat engine cycle.

where k_0 is the heat leak coefficient. In addition, it is very significant to further consider the influence of irreversible adiabatic processes and other entropy generations within the cycle. Using the second law of thermodynamics for this cycle model, we have

$$\dot{m} c_P \ln(x) - U_L A_L (T_3 - T_L)/T_3 < 0$$
$$\Longrightarrow \dot{m} c_P R T_3 \ln(x) = U_L A_L (T_3 - T_L) \tag{4}$$

where $x = T_2/T_1$ is the isobaric temperature ratio and R is the internal irreversibility parameter which is greater than unity for a real cycle and defined as

$$R = \frac{S_3 - S_4}{S_2 - S_1} = \frac{U_L A_L (T_3 - T_L)/T_3}{\dot{m} c_p \ln(x)} > 1 \tag{5}$$

where S_1, S_2, S_3 and S_4 are the entropy of the working fluid at state point 1, 2, 3 and 4, respectively. When the adiabatic processes are reversible and other entropy generations within the cycle are negligible, $R = 1$ and the cycle becomes an endoreversible cycle, in which the irreversibility is only due to finite temperature differences between the heat engine and the external reservoirs and the heat leak loss between the heat reservoirs. When $R = 1$ and the heat leak loss is negligible, the cycle model is directly simplified as that adopted in Refs. [2,3].

3. The expressions of several parameters

Using Eqs. (1)–(3) and (5), we can derive the expressions of the specific power output and thermal efficiency, which are, respectively, given by

$$P = \frac{Q_H - Q_L}{A} = \frac{U_H[(x-1)T_1 - R T_3 \ln x]}{a T_3/(T_3 - T_L) + b} \tag{6}$$

and

$$\eta = \frac{Q_H - Q_L}{Q_H + Q_0} = \frac{[(x-1)T_1 - R T_3 \ln x]}{(x-1)T_1 + \frac{k_0(T_H - T_L)}{U_H A}[a T_3/(T_3 - T_L) + b]} \tag{7}$$