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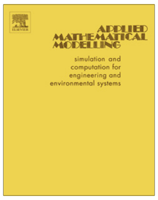

Ecological optimization of an irreversible Brayton cycle with regeneration, inter-cooling and reheating

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ABSTRACT

A mathematical model is developed for an irreversible Brayton cycle with regeneration, inter-cooling and reheating. The irreversibility are from the thermal resistance in the heat exchangers, the pressure drops in pipes, the non-isentropic behavior in the adiabatic expansions and compressions and the heat leakage to the cold source. The cycle is optimized by maximizing the ecological function, which is achieved by the search for optimal values for the temperatures of the cycle and for the pressure ratios of the first stage compression and the first stage expansion. The advantages of using the regenerator, intercooler and reheater are presented by comparison with cycles that do not incorporate one or more of these processes. Optimization results are compared with those obtained by maximizing the power output and it is concluded that the point of maximum ecological function has major advantages with respect to the entropy generation rate and the thermal efficiency, at the cost of a small loss in power.

1. Introduction

Brayton cycle is the ideal thermodynamic cycle used for the gas turbine analysis. Its usefulness varies from stationary power generation to applications in transport, and also presents an advantageous relationship between high power output and low weight of machinery. Due to its high applicability the search for improving its performance has been the goal of several papers, specially the optimizations based on the finite time thermodynamics.

Curzon and Ahlborn [1] conducted one of the first studies in this area, finding that the thermal efficiency of an endoreversible Carnot cycle at maximum power is equal to $1 - \sqrt{T_L/T_H}$. Leff [2] expanded this same analysis for Brayton, Otto, Diesel and Atkinson cycles, and found that the efficiencies at maximum work to these cycles are equal to that obtained by Curzon and Ahlborn [1]. Bejan [3] studied the optimum distribution of the conductance between heat exchangers for a Brayton cycle when the power is maximized and introduced a model to quantify the heat leakage. Ibrahim et al. [4] optimized the power output for the Carnot and Brayton cycles considering both thermal reservoirs with finite and infinite thermal capacitance rates. Wu and Kiang [5] studied the effects of incorporating non-isentropic processes in compressor and turbine for the power output optimization of a Brayton cycle. Chen [6] observed that the addition of other kinds of

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Nomenclature

A	heat transfer area [m^2]
$\dot{C}_I$	internal conductance rate of the heat engine [W/K]
$\dot{C}_p$	heat capacity rate at constant pressure of the working fluid [W/K]
$\dot{E}$	ecological function [W]
$\overline{\dot{E}}$	dimensionless ecological function
k	specific heat ratio [dimensionless]
N	number of transfer units [dimensionless]
p	pressure [Pa]
Δp	pressure drop [Pa]
$\dot{Q}$	heat transfer rate [W]
$\overline{\dot{Q}}$	dimensionless heat transfer rate
$\mathrm{r_P}$	pressure ratio [dimensionless]
$\dot{S}_g$	entropy generation rate [W/K]
$\overline{\dot{S}}_g$	dimensionless entropy generation rate
T	temperature [K]
$\overline{T}$	dimensionless temperature
U	overall heat transfer coefficient [W/m^2 K]
v	specific volume [m^3/kg]
$\dot{W}$	power output [W]
$\overline{\dot{W}}$	dimensionless power output
x	isentropic temperature ratio for the low pressure compressor [dimensionless]
y	isentropic temperature ratio for the high pressure turbine [dimensionless]

Greek letters

ε	heat exchanger effectiveness [dimensionless]
η	thermal efficiency, isentropic efficiency [dimensionless]
ρ	pressure drop parameter [dimensionless]

Subscripts

0	environment
C	compressor
Carnot	Carnot cycle
E	corresponding to ecological optimization
G	global
H	hot side
I	heat leakage
L	cold side
max	maximum
R	regenerator
s	isentropic
T	turbine
W	corresponding to power optimization

irreversibility, in addition to the thermal resistance between working fluid and reservoirs, makes appear a point of maximum thermal efficiency which has a finite amount of power, unlike the endoreversible cycles [1,2,7].

Angulo-Brown [8] introduced an ecological criterion, $E = \dot{W} - T_L\dot{S}_g$, for the optimization of a Carnot cycle, where $\dot{W}$ is the power output and $\dot{S}_g$ is the entropy generation rate, and obtained the efficiency under conditions of maximum ecological function is close to the average between the Carnot efficiency and the Curzon and Ahlborn efficiency [1]. Yan [9] suggested that the proposed ecological function would make more sense if the expression was $\dot{E} = \dot{W} - T_0\dot{S}_g$, in case the temperature of the cold reservoir T_L is different from the environment T_0, and this modification was accepted by subsequent authors. The ecological function was used for optimization of endoreversible and irreversible Carnot and Brayton cycles by several authors [10–14]. Ust et al. [15] also utilized this criterion for the analysis of a Brayton heat engine with regeneration. In all these studies it is observed that such optimization leads to greater thermal efficiencies along with lower entropy generation rates, at the cost of a small drop in power, when compared with the same cycle operating at maximum power conditions.