Amirkabir Journal of Mechanical Engineering

Amirkabir J. Mech. Eng., 50(2) (2018) 127-130
DOI: 10.22060/mej.2016.713

# Performance Optimization of an Irreversible Brayton Cycle, and Proposing New Definitions for Second Law Efficiency and Exergy

M. M. Naserian, S. Farahat*, F. Sarhaddi

Mechanical Engineering Department, University of Sistan and Baluchestan, Zahedan, Iran

**ABSTRACT:** In this study, the optimal performance of an irreversible regenerative Brayton cycle is sought through power maximization using the finite-time thermodynamic concept in finite-size components. Optimization is performed on the maximum power as the objective function using a genetic algorithm. In order to take into account the time and the size constraints in the current problem, the dimensionless mass-flow parameter is used. The behavior of the system parameters, such as maximum output power, exergy, exergy destruction, first and second law efficiencies, and effectiveness of the heat exchangers are investigated using the dimensionless mass-flow rate parameter. The influence of the unavoidable exergy destruction due to finite-time constraint is taken into account by developing the definition of thermal exergy. According to the results, the external exergy destruction increases and consequently the second law efficiency and heat exchangers effectiveness decrease with an increment of the dimensionless mass-flow rate parameter. However, as the dimensionless mass-flow rate parameter tends to zero, the efficiency and the power of the system approaches Carnot efficiency and zero value, respectively. Finally, the improved definitions are proposed for the heat exergy and the second law efficiency which will be compared with the conventional definitions and then their cumulative effects on cycle's performance will be discussed.

**Review History:**

Received: 13 February 2016
Revised: 16 April 2016
Accepted: 29 May 2016
Available Online: 10 August 2016

**Keywords:**

Brayton cycle
Regenerative
Exergy
Optimization
Finite time

## 1- Introduction

The efficiency is defined as the ratio of net output power to the rate of inlet heat to the system. The efficiency of heat engines is restricted by Carnot efficiency. This efficiency is obtainable in the reversible range. Thus, in real systems, Carnot efficiency and performance coefficient are not of great importance, and they are poor guides to evaluate the performance of heat engines, heat pumps, and refrigerators. Practically, all thermodynamic processes take place in finite-size components during finite-time (for steady state condition, finite mass flow rate), which leads to irreversibility (exergy destruction). Accordingly, while Carnot cycle gives an upper bound for thermal efficiency, it cannot be a comparison standard for real heat engines. Analysis techniques have been developed in various studies to consider the internal and/or external irreversibility in heat engines.

Curzon and Ahlborn [1] studied the effect of external irreversibility, which accounted for irreversibilities in the heat-exchange processes between the power cycle and its heat sources, on Carnot cycle's output power and thermal efficiency. This system was entitled endoreversible due to the internal reversibility of cycle. In their research, thermal efficiency at the maximum power state was expressed in the form of Eq. (1). $T_L$ and $T_H$ are temperatures at cold and hot heat exchangers, respectively.

$$\eta_{CA} = 1 - \sqrt{\frac{T_L}{T_H}} \tag{1}$$

Gordon [2] analyzed heat engines considering finite rate heat transfer and finite-capacity thermal reservoirs. He showed that the efficiency at maximum power depends on the thermal reservoir temperatures and other system variables such as reservoir capacity or working fluid specific heats.

Vučković et al. [3] investigated an industrial plant using both conventional and advanced exergy analyses. They claimed that the highest exergy destruction was caused by the steam boiler. Moreover, 92.34% of the total exergy destruction in the boiler was unavoidable. Açıkkalp et al. [4] have analyzed a trigeneration system using an advanced exergy analysis. The results of their research indicated that the improvement potential of their system was low because 82% of the total exergy destruction cost rates were unavoidable.

## 2- Heat Engine Model

The schematic of the heat engine is shown in Fig. 1. The model represents an irreversible regenerative closed Brayton cycle. Heat reservoirs and heat exchangers have finite capacitance rates and finite total conductance, respectively. The system comprises of an irreversible adiabatic compressor, a heat regenerator, a pair of heat exchangers and an irreversible adiabatic turbine. Heat exchangers are used to transfer heat from high-temperature reservoir to the system and from the system to the low-temperature reservoir. The entire analysis of the system can be broken down into two sub-analyses: (i) Thermodynamic model and energy analysis (ii) exergy analysis.

A couple of fundamental assumptions are made to develop the thermodynamic model. The most important one is the heat capacity of the considered gas at constant pressure $C_{p,gas}$ varies with temperature as indicated in Eq. (2) [5].

Corresponding author, E-mail: said.farahat.usb@gmail.com

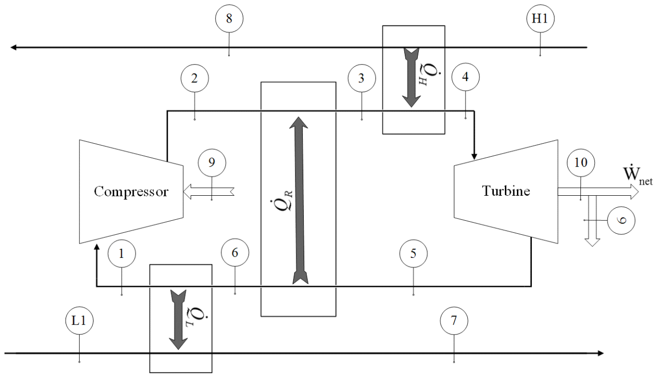


**Figure 1. The schematic of the heat engine**

$$C_{P,gas}(T) = 0.93750 + \frac{0.01215}{10^2} \times T + \frac{0.01670}{10^5} \times T^2 - \frac{0.07164}{10^9} \times T^3 \quad (2)$$

In order to enter the finite size constraint into the problem, the total thermal conductance of the system heat exchangers ($(U.A)_T$) is considered constant. Moreover, assuming that the mass flow rate is finite and non-zero, time will be constrained, as well. To take into account the time and the size constraints in current problem, using the dimensionless mass-flow parameter ($F$) is a perfect choice. The parameter was defined by Naserian et al. [6], as Eq. (3).

$$F = \frac{\dot{m}}{\left[\frac{(U.A)_T}{c_{P,\min}}\right]}, \quad 0 < F < 1 \quad (3)$$

## 3- Optimization Study

For certain values of F, the system is simulated in MATLAB, and the temperature and exergy of system streams are calculated. The outcome of this analysis is used in the genetic algorithm for optimization purposes. The net output power of the system is specified as the objective function for optimization.

## 4- Results and Discussion

The variation of dimensionless net power with parameter $F$ is depicted in Fig. 2 at the maximum power state. Hereafter, all results are investigated at the maximum state even though it is not stated. The slope of the power increases gradually with $F$ up to the maximum of maximum power value at $F$=0.3. Afterward, the dimensionless net power slopes down sharply. Therefore, the maximum of maximum net power is located between the two limits.

Fig. 3 depicts the effect of $F$ on mean temperature of passing streams through high-temperature and low-temperature heat exchangers. The mean temperature difference increases between the hot and cold streams for the heat exchangers, while the difference reduces between the high and low temperature working fluids. Therefore, the exergy destruction in the heat exchangers and hence total external exergy destruction is due to the large temperature difference between the heat sources flows and corresponding working fluid.

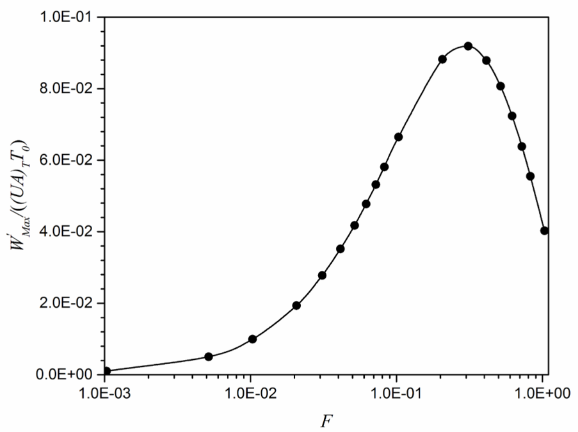


**Figure 2. Variation of dimensionless maximum net power with parameter *F***

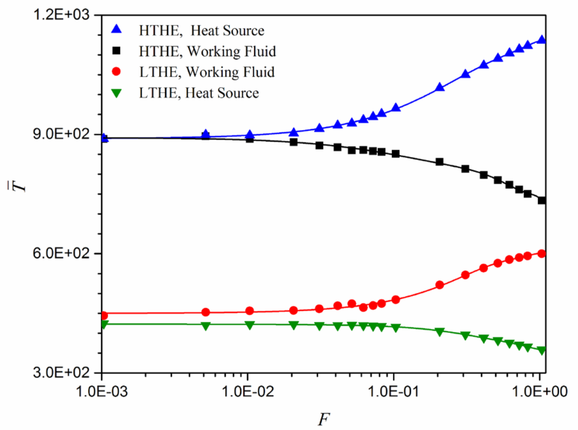


**Figure 3. Effect of *F* on mean temperature of streams passing through heat exchangers**

## 5- Conclusion

By inserting the concept of finite time thermodynamic into the problem, the system performance was evaluated thermodynamically and exergetically. The influence of the unavoidable exergy destruction due to finite-time constraint is taken into account. Finally, the improved definitions are proposed for heat exergy and the second law efficiency. New definitions for the heat exergy and second law efficiency are as follows:

- Heat exergy: The maximum amount of useful power that can be produced as a specified Finite size system undergoes a finite time process between the specified initial and dead state.
- Second law efficiency: The ratio of actual net output power of a specified finite size system undergoes a finite time process, to the new definition of supplied heat exergy.

## References

[1] FL. Curzon, and B. Ahlborn, Efficiency of a Carnot engine at maximum power output, *Am J Phys*, 43(1) (1975) 22-24.

[2] JM.Gordon, Observations on efficiency of heat engines operating at maximum power, *Am J Phys* 58(4) (1990) 370-375.

[3] G. D. Vučković, M. V. Vukić, M. M. Stojiljković, and D. D. Vučković, Avoidable and unavoidable exergy destruction and exergoeconomic evaluation of the thermal processes in a real industrial plant, *Thermal Science* 16 (2012) 433-446.

[4] E. Açıkkalp, H. Aras, and A. Hepbasli, Advanced exergoeconomic analysis of a trigeneration system using a diesel-gas engine Modeling and optimization of combined cycle power plant based on exergoeconomic and environmental analyses, *Applied Thermal Engineering* 67 (2014) 388-395.

[5] P. Ahmadi, and I. Dincer, Thermodynamic and exergoe nvironmental analyses, and multi-objective optimization of a gas turbine power plant, *Applied Thermal Engineering* 31 (2011) 2529-2540.

[6] M. M. Naserian, S. Farahat, and F. Sarhaddi, Finite time exergy analysis and multi-objective ecological optimization of a regenerative Brayton cycle considering the impact of flow rate variations, *Energy Conversion and Management* 103 (2015) 790-800.

Please cite this article using:

M. M. Naserian, S. Farahat, F. Sarhaddi, Performance Optimization of an Irreversible Brayton Cycle, and Proposing New Definitions for Second Law Efficiency and Exergy, *Amirkabir J. Mech. Eng.*, 50(2) (2018) 385-398.

DOI: 10.22060/mej.2016.713