Physica A 453 (2016) 316–326

Contents lists available at ScienceDirect

Physica A

journal homepage: www.elsevier.com/locate/physa

Analysis of a quantum irreversible Otto cycle with exergetic sustainable index

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HIGHLIGHTS

- An irreversible quantum Otto cycle with -1/2 spin system is considered.
- Exergetic sustainability index is derived for quantum Brayton cycle.
- Calculation are conducted for irreversible cycles.
- Numerical results are presented and discussed.

ARTICLE INFO

Article history:
Received 8 October 2015
Received in revised form 14 January 2016
Available online 20 February 2016

Keywords:
Quantum Otto cycle
Irreversibility
-1/2 spin system
Exergetic sustainability index

ABSTRACT

In this study, exergetic sustainability index is applied to quantum irreversible Otto cycle with -1/2 spin system. Exergetic sustainability index in a quantum engine is used first time. This index is the ratio of exergy output (work output for a thermal engine) to total exergetic losses. It gives an opportunity to evaluate for all thermodynamic losses in the system, that is why, it is an important index. In addition, some thermodynamic parameters (work output, exergy destruction, first and second law efficiencies) are considered and their relationships between the exergetic sustainability index are determined.

1. Introduction

Developments in nano technology make possible to produce machines and engines in nano/micro scale. However, classical approaches in the physics and thermodynamics loss their validation in this scale. A new methodology called quantum thermodynamics should be applied to such systems.

Optimizing irreversible thermal cycles has become an important problem with respect to environmental progress and sustainable development issues. That is why, finite time thermodynamics (FTT) was proposed to investigate and determine the optimum operation conditions of the actual cycles. First study of the FTT conducted was the Curzon–Ahlborn–Novikov engine [1,2]. Quantum or nano/micro scaled thermodynamic cycles were studied by several authors. Firstly, nano scale thermal cycles are mentioned. These cycles can operate with ideal Bose and Fermi gases as well as ideal Maxwell–Boltzmann gas. Some of these papers including Otto, Diesel, Brayton and Dual engines can be found in open literature [3–33]. Several quantum heat engines with spin system were studied by several authors and some examples of them in the open literature are listed in Refs. [34–51].

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http://dx.doi.org/10.1016/j.physa.2016.02.051
0378-4371/

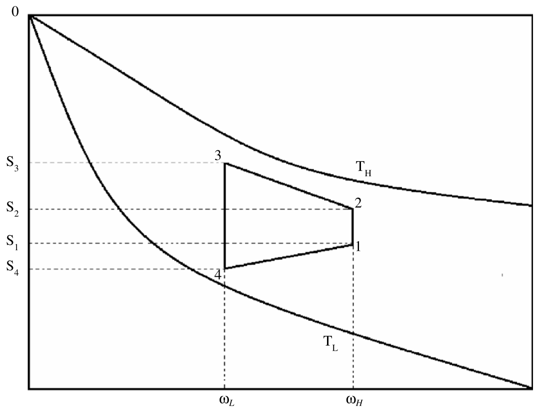

Fig. 1. S–ω diagram of the irreversible quantum cycle.

Exergetic sustainability index includes exergy output of the system and its waste exergy or exergy loss [52–58]. Exergy loss is the transport of exergy from the overall system to its surroundings and it is associated with the rejection of heat and streams of matter to the surroundings. These streams are not further used in any system [59]. Exergetic sustainability index is the rate of the exergy output (work output in this paper) to the total waste exergy that is difference of exergy input to the system and exergy output from the system. It provides an opportunity to assess sustainability of a system. Because, waste exergy affects directly using of the heat source, efficiency loss and economical parameters.

Environmental concerns and increasing energy need force scientist and engineers to improve more efficient and sustainable heat engines. In addition to that, quantum or atomic heat engines are popular research topic for now. We aimed to obtain more efficient and sustainable quantum heat engine cycle. Because of this reason, we present an irreversible quantum Otto cycle that represents the actual quantum Otto heat engine. In addition, we try to determine the effects of the parameters on the considered system. Furthermore, exergetic sustainability index is an important parameter to provide a balance between the technical, economical and environmental effects. In this paper, exergetic sustainability index is applied to a quantum heat engine (-1/2 spin irreversible Otto engine) first time. Other performance parameters (the work output, exergy destructions, first law efficiency and exergy efficiency) are investigated and relationships with the exergetic sustainability index are presented.

2. System description and analyses

System is assumed as contacts with hot and cold reservoirs at constant temperature. Quantum Otto studied in this paper is shown in Fig. 1. For the thermodynamic assessment, heat exchange conditions and systematic of the Otto cycle must be described at first. In the analysis applied in this paper, heat source and heat sink are assumed as infinite and they are kept at constant temperature. Heat input to the system and heat output from the system occur in isochoric steps. In addition, heat exchanges of the system are supposed to be similar to those via heat exchanger process. That is why effectiveness is used for the heat transfer processes. Finally, the system is considered as irreversible. Thermodynamic equations for the system are described as follows.

Throughout this paper "temperature" will refer top rather than T, if not stated otherwise ($\beta = l/k_B T$, where T is the absolute temperature in energy units). The temperature β of the working fluid is always well established for given S and ω because, for a two-level system, it is always well defined by the following relation [40]:

$$S = -\frac{1}{2}\tanh\left(\frac{\omega\beta}{2}\right), \tag{1}$$

where k_B is the Boltzmann coefficient and ω energy-level gap. Similar to Refs. [60–62], Boltzmann coefficient and Planck constant assume as 1. Consider a two-level system with a one-parameter Hamiltonian $H(\omega)$ such that the energy levels are $-\omega/2$ and $\omega/2$, for example a spin-1/2 system, in a magnetic field of intensity $B(T)$, with $\omega = 2\mu_B B$ and μ_B is the Bohr's magneton [46]. Heat input to the system is occurred from the high temperature heat source and it is assumed as if heat exchanger was used for this process. Transferred heat increases the temperature of the working fluid. Heat input (J) is calculated from Eq. (2) [46,47]:

$$Q_H = \frac{\omega_H}{2}\varepsilon_H\left[\tanh\left(\frac{\omega_H\beta_1}{2}\right) - \tanh\left(\frac{\omega_H\beta_H}{2}\right)\right], \tag{2a}$$

$$Q_H = \frac{\omega_H}{2}\left[\tanh\left(\frac{\omega_H\beta_1}{2}\right) - \tanh\left(\frac{\omega_H\beta_2}{2}\right)\right], \tag{2b}$$