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Determining of the optimum performance of a nano scale irreversible Dual cycle with quantum gases as working fluid by using different methods

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HIGHLIGHTS

- Nano scale irreversible dual cycle is investigated.
- Ideal Bose and Fermi gases are used as working fluid.
- Different methods are used and compared to each other.
- Numerical results are presented and discussed.

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ABSTRACT

In this paper, a nano scale irreversible Dual cycle working with ideal Bose and Fermi gases is examined. Degeneracy conditions and thermo-size effects on the quantum gases are researched. Thermodynamic analyses of the cycle are conducted by considering irreversibilities. Different thermodynamic assessment methods are applied and then compared to each other. The obtained results are presented numerically. It concluded that *ECF* is the most convenient method for the Bose gas under weak degeneracy condition and *x* should be chosen as biggest as possible for all other conditions.

1. Introduction

Both engineers and scientists have been trying to determine the optimum conditions, when first steam engine was invented. The first research determined the upper bound of the efficiency thermal engines was conducted by Sadi Carnot. This engine was totally reversible. This means that there were no losses based on entropy generation (irreversibilities). After more than a century, Finite Time Thermodynamics (FTT) was considered for the irreversibilities in the system. The initial studies regarding FTT were conducted by Curzon, Ahlborn [1] and Novikov [2]. They proposed an endoreversible cycle, which is internally reversible and externally irreversible, is called as Curzon–Ahlborn–Novikov (CAN) engine. Novel thermodynamic evaluation parameters were submitted by using FTT. Its ecological function (*ECF*) was first proposed by Angulo-Brown, [3] and was modified by Yan [4]. An ecological function is described as $ECF = W - T_o S_{gen}$ where W is the work output, T_o is environmental temperature and S_{gen} is the entropy generation. There have been several papers written

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in the open literature regarding *ECF* and some of these are listed in Refs. [5–36]. Ust et al. submitted two new criteria called the ecological performance coefficient (*ECOP*) and the exergetic performance coefficient (*EPC*) [37–51]. They are defined as $ECOP = \frac{W}{T_o S_{gen}}$ and $EPC = \frac{Ex}{T_o S_{gen}}$ respectively where *Ex* is exergy output of the system. In addition, Açıkkalp and Yamık proposed a maximum available work (*MAW*), which is $MAW = Ex - T_o S_{gen}$ [52].

Many nano machines have been developed over the last few decades. This is the reason why nano scale thermal cycles should be focused on. However, nano scale cycles adhere to the principles of both statistical physics and quantum physics. Some of the researches into operating quantum gases are listed in Refs. [53–75]. In addition to that, quantum thermo-size effects have important influence on the thermodynamic properties of the quantum gases. Some references can be found about quantum thermo-size effect of the quantum gasses in Refs. [76–78,60,79–85]. FTT analysis is applied to nano scale Dual cycle in this paper and some papers about the finite-time analysis of the classical Dual cycle is listed in Refs. [86–91]. Some papers about quantum thermodynamic cycles and microscopic energy conversion systems are listed in Refs. [92–113]. Further investigations about these cycles might gain importance in the future.

In this paper, an irreversible nano scale Dual cycle operating with quantum gases are investigated. In the analyses, quantum thermo-size effects are considered because of their important effects in nano scale. In the analyses, firstly, thermodynamic properties of the quantum gases are described. Secondly, thermodynamic analysis of the Dual cycle operating quantum gases are obtained. After that, the different thermodynamics evaluation methods mentioned first paragraph are applied and then they are compared. Finally, the most convenient method is tried to suggest for determining the optimum operating conditions for the nano scale irreversible Dual cycle.

2. Thermodynamic analysis of the nano scale irreversible Dual cycle

Thermodynamic analyses for an irreversible nano scale Dual cycle using ideal Fermi and Bose gases as working fluids are performed. For the quantum gases, both statistical and quantum physics must be considered, in addition, thermo—size effects in the nano scale as well. Free energy of the ideal Fermi gas for degeneracy conditions including thermo—size effects is [76]:

$$F_F = \frac{3}{5}NkT_F\left[1 - \frac{5\pi^2}{12}\left(\frac{T}{T_F}\right)^2 + \frac{5\sqrt{\pi}}{32}\lambda_F\frac{A}{V} - \frac{3\pi^2}{16}\left(\frac{T}{T_F}\right)^2\left(\frac{\sqrt{\pi}\lambda_F}{4}\frac{A}{V}\right)\right] \tag{1}$$

using Eq. (1), internal energy and enthalpy for the ideal Fermi gas is described as following respectively [76]:

$$U_F = \frac{3}{5}NkT_F\left[1 + \frac{5\pi^2}{12}\left(\frac{T}{T_F}\right)^2 - \frac{9\pi^{5/2}}{64}\lambda_F\frac{A}{V} + \frac{25\sqrt{\pi}}{96}\lambda_F\frac{A}{V}\right] \tag{2}$$

$$H_F = \frac{3}{5}NkT_F\left[1 + \frac{5\pi^2}{12}\left(\frac{T}{T_F}\right)^2 + \frac{25\sqrt{\pi}}{96}\lambda_F\frac{A}{V} - \frac{9\pi^{5/2}}{64}\left(\frac{T}{T_F}\right)^2\lambda_F\frac{A}{V}\right] - \left[\frac{3Nk\sqrt{\pi}\left(3\pi^2T^2 - 10T_F^2\right)\lambda_F}{320T_F}\frac{A}{V}\right] \tag{3}$$

where, N is the number of particles, and k is Boltzmann constant, A is the area of the considered system, V is the volume of the system, T_F is the Fermi temperature and λ_F represents wave length of particles at Fermi temperature. Free energy for the ideal Bose gas for degeneracy conditions can be written as Eq. (4) [76]:

$$F_B = \frac{3}{5}N_{cl}kT\frac{\zeta(5/2)}{\zeta(3/2)}\left[1 - \frac{\lambda_c}{3\zeta(3/2)}\frac{A}{V}\ln\left(\lambda_c\frac{A}{V}\right)\right] \tag{4}$$

where λ_C is the wave length at the critical temperature, N_{cl} is the classical number of particles and it can be defined as [76]:

$$N_{cl} = Vn_q\zeta(3/2) \tag{5}$$

where n_q is the quantum density. Using Eq. (4), internal energy and enthalpy of an ideal Bose gas can be obtained as:

$$U_B = \frac{kT\left[(kmT)^{3/2}\left(253.535V - 32.351A\lambda_c\ln\left(\lambda_c\frac{A}{V}\right)\right)\right]}{h^3} \tag{6}$$

$$H_B = \frac{kT\left[(kmT)^{3/2}\left(422.558V + 21.567A\lambda_c - 32.351A\lambda_c\ln\left(\lambda_c\frac{A}{V}\right)\right)\right]}{h^3} \tag{7}$$

where m is the rest mass of the gas. Properties of the system considered in Fig. 1 can be given as following.

The heat input to the system is:

$$Q_H = (U_3 - U_2) + (H_4 - H_3). \tag{8}$$

The heat output from the system is:

$$Q_L = (U_5 - U_1). \tag{9}$$