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Research paper

Assessment of nano-scale Stirling refrigerator using working fluid as Maxwell–Boltzmann gases by thermo-ecological and sustainability criteria

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ABSTRACT

Purpose of this paper is to investigate a nano scale irreversible Stirling refrigerator regarding size effects and presents one novel thermo-ecological criteria. System is researched by using four thermo-ecological and sustainable criteria. One novel criteria called modified ecological coefficient of performance (*MECOP*) is presented. Calculations are performed for irreversible cycle and results are obtained numerically. Finally, performance of the considered cycle is discussed and regarded criteria are compared. According to results, *ESI* is the most stable ecological criteria and *MECOP* is more stable than *ECOP* and *x* should be chosen as big as possible.

1. Introduction

Sustainable development is among the major issues in the World. Economical and environmental topics may be considered as two of the most important problems. Especially clean and sustainable energy should be crucially focused on because of the increasing energy need and environmental problems. Besides economical problems, environmental issues, such as global warming, have affected our life in last decade. Producing energy from the fossil fuels is the most important reason of the environmental pollution. For preventing the environmental problems as well as economic concerns, more efficient energy conversion tools are required.

Great efforts exist for designing more efficient thermal cycles. First studies about investigating actual thermal cycles, for more efficient systems, were conducted by Curzon–Ahlborn and Novikov [1,2]. They presented famous Curzon–Ahlborn–Novikov (CAN) engine that is endoreversible (internally reversible, however externally irreversible). These were first studies of Finite Time Thermodynamics (FTT). FTT is used for evaluating and optimizing endoreversible or irreversible thermal cycles, some examples for FTT might be seen in [3–8]. A lot of criteria based on FTT were submitted for the determining optimum performance of the actual thermal cycles. One of these is the ecological function (*ECF*) recommended by Angulo-Brown [9] and it was improved by Yan [10]. Some papers about the refrigeration and Stirling cycles instigated in terms of ecological function are listed in Refs. [11–26]. Another ecological criteria is the ecological coefficient of performance (*ECOP*) [27–38]. Exergetic sustainable index (*ESI*) is the final criteria and some applications of *ESI* in the open literature can be found in [39–49].

Development in nano technology may be an alternative for the energy need and the environmental concerns in the future. Nano technology has been focal point of the researchers and nano thermal cycles studies have been increasing. In addition to that, molecular or nano cycles offers us different applications in biophysics, biochemistry and biomedicine [50]. Thermal cycles considering size effects are recommended for the more accurate outputs. Because, gas behaviors are different from macro scale in the nano/micro scale in finite domain. Some papers about the nano gases considering nano scale effects in the open literature are shown in [51–69].

In this paper, a nano-scale irreversible Stirling refrigerator is investigated by using four different thermo-ecological and sustainability criteria. Size effects in the nano scale are considered in the investigation. The classical thermodynamic cycle models and corresponding results only deal with the macro scaled gas systems, in which the boundary effects are unimportant. In general, for a micro-/nanoscaled gas cycle system, reversible or irreversible cycle

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models in macro scale and corresponding performance results cannot predict its performance characteristics due to the various boundary effects of the system. Further, under reversible and irreversible conditions, the boundary effects on gas system may be different [69]. In addition to these, a novel criteria called as modified ecological coefficient of performance (*MECOP*) based on the *ECOP* are presented. Considered cycle is evaluated, numerical results are presented and discussed.

2. Thermodynamic modeling

Thermodynamic modeling of a nano-scale irreversible Stirling refrigeration cycle is presented in this section. Nano-scale effects are considered for an irreversible Stirling refrigerator, dimensions of the nano cylinder are (diameter is R and length is H) nanometer. Temperature – entropy diagram of the irreversible Stirling refrigerator is indicated in Fig. 1. Free energy of the Maxwell–Boltzmann gas considering nano-scale effects is [53,57]:

$$F = -NkT\left[\frac{(2\pi mk)^{3/2}T^{3/2}\pi R^2 H}{N} + 1\right] + Nk\frac{L_c(T)}{\sqrt{\pi}}\left(\frac{1}{R} + \frac{1}{H}\right) \tag{1}$$

where N is number of particles, L_c is half of the most probable Broglie's wave length, h is the Planck constant and k is Boltzmann constant. Using Eq. (1) Specific heats at constant volume (J K^{-1}) for ideal Maxwell–Boltzmann gas is [53,57]:

$$c_v = \frac{3}{2}Nk + Nk\frac{L_c(T)}{4\sqrt{\pi}}\left(\frac{1}{R} + \frac{1}{H}\right) \tag{2}$$

And using Eq. (1) Pressure of the Maxwell–Boltzmann gas (Pa) is [53,57]:

$$P = \frac{NkT(L_c(T)R + H(L_c(T) + R))}{\pi H^2 R^3} \tag{3}$$

Cooling load of the refrigeration is (J) [71,72]:

$$Q_L = -\left(\int_3^4 c_v dT + \frac{P_4V_4 - P_3V_3}{1 - n_e}\right) \tag{4}$$

where n_e is the polytrophic coefficient of the expansion process. Heat output from the cycle (J) is [71,72]:

$$Q_H = \int_1^2 c_v dT + \frac{P_2V_2 - P_1V_1}{1 - n_c} \tag{5}$$

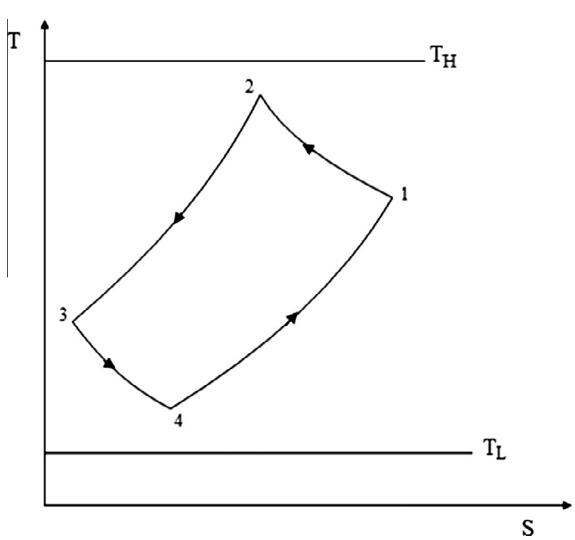

Fig. 1. *T–S* diagram of the system (adapted from [70]).

From the first law of the thermodynamics, work input to the system (J) is:

$$W = Q_H - Q_L \tag{6}$$

Entropy generation (J K^{-1}) is the measurement of the irreversibilities of any cycle and it can be described by using second law of the thermodynamics as:

$$S_{gen} = \left(\frac{Q_H}{T_H} - \frac{Q_L}{T_L}\right) \tag{7}$$

Using polytrophic equations temperatures of the system can be defined as following;

$$T_1 = T_2 x^{1-n_c}, \quad T_3 = T_4 x^{n_e - 1}, \quad T_4 = \alpha T_2 \tag{8}$$

where x is the compression ratio and it is defined as $\left(\frac{V_1}{V_2} = \frac{V_4}{V_3} = x\right)$. Stroke volume of the cylinder is the:

$$V_1 = \pi R^2 H_s \tag{9}$$

where H_s is the stroke length. In this paper, ecological function is modified for the refrigeration cycles. It can be seen in Eq. (10). Purpose of this modification is to obtain maximum cooling load (Q_L) when sum of the work input (W) and exergy destruction (T_oS_{gen}) is minimum. Because, cooling load is the objective function for any refrigeration system and increasing at work input and exergy destruction cause to decrease in the performance. Modified ecological function is (J) [51]:

$$MECF = Q_L - (W + T_oS_{gen}) \tag{10}$$

ECOP is the rate of the cooling load to exergy destruction and it is written as:

$$ECOP = \frac{Q_L}{T_oS_{gen}} \tag{11}$$

New criterion we proposed in this study is the modified ecological coefficient of performance. Similar to *MECF*, we consider cooling load as objective parameter and try to maximize it. *MECOP* can be defined as rate of the cooling load to sum of the work input and the exergy destruction.

$$MECOP = \frac{Q_L}{(W + T_oS_{gen})} \tag{12}$$

Last criterion we researched is the exergetic sustainability index. It is defined as the rate of the reversible work to difference of the exergy inlet and useful exergy. It can be seen in Eq. (13):

$$ESI = \frac{Q_H\left(1 - \frac{T_o}{T_H}\right) - Q_L\left(1 - \frac{T_o}{T_L}\right)}{W - Q_L\left(1 - \frac{T_o}{T_L}\right)} \tag{13}$$

In this paper, analyses are conducted for the dimensionless parameters that are expressed following:

$$w = \frac{W}{NkT_H}, \quad q_L = \frac{Q_L}{NkT_H}, \quad mecf = \frac{MECF}{NkT_H}, \quad s_{gen} = \frac{S_{gen}}{Nk} \tag{14}$$

3. Results and discussion

This paper is about performance of an irreversible nano-scale Stirling refrigerator operating with ideal Maxwell–Boltzmann gas. Mentioned system is investigated by using four different thermo-ecological criteria. Analyses are calculated numerically and compared with each other. Fixed parameters used in the calculations are listed in Table 1.

In this paragraph, considered parameters are researched for x and results are indicated in Figs. 2–5. Fig. 2 represents changes of