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Multi-objective optimization of an irreversible Stirling cryogenic refrigerator cycle

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ABSTRACT

The main aim of this research article is a parametric demonstration of irreversible Stirling cryogenic refrigerator cycles that includes irreversibilities such as external and internal irreversibilities. In addition, through this study, finite heat capacities of external reservoirs are considered accordingly. To reach the addressed goal of this research, three objective functions that include the input power of the Stirling refrigerator, the coefficient of performance (COP) and cooling load (R_L) have been involved in optimization process simultaneously. The first aforementioned objective function has to minimize; the rest objective functions, on the other hand, have to maximize in parallel optimization process. Developed multi objective evolutionary approaches (MOEAs) based on NSGA-II algorithm is implemented throughout this work. Moreover, cold-side's effectiveness of the heat exchanger, hot-side's effectiveness of the heat exchanger, heat source's heat capacitance rate, heat sink's capacitance rate, temperature ratio $\left(\frac{T_h}{T_c}\right)$, temperature of cold side are assigned as decision variables for decision making procedure. To gain a robust decision, different decision making approaches that include TOPSIS, LINMAP and fuzzy Bellman–Zadeh are used. Pareto optimal frontier was determined precisely and then three final outputs have been gained by means of the mentioned decision making approaches.

1. Introduction

Stirling engine producing low temperature stream, is one of the crucial refrigeration cycle approaches. More description about coefficient of performance (COP) of the refrigeration systems are presented in Ref. [1]. Stirling engine producing low temperature stream also have relevant outputs [1] for the COP of the refrigeration systems.

Leff and Teeters [2] have mentioned that since there is no 'normal peak' in these systems, the straight-forward Curzon–Ahlborn [1] determination will not cover for the reversed Carnot cycle. The Lagrangian approach of unknown multiplier has been utilized by Blanchard [3] to determine the endoreversible Carnot heat pump's COP operating at lowest input power for a specific heating load. Recently, the efficiency of other refrigeration cycles such as Carnot, Brayton, Stirling and Ericsson has been investigated, by employing the context of the finite time thermodynamics approach [4–9], the criteria of ecological [10–17] and thermo-economic model [18–21] for various working situations.

Finite time thermodynamic (FTT) is one of the basic methods to analyze thermodynamic systems, though the Carnot cycle's endo-reversible approach has been presented and progressed for 20 years from 1950s and 1970s [22]. The FTT approaches are utilized through the actual apparatus and processes optimization, related to finite-time and finite-size limitations [23]. In recent years, utilizing FTT concepts for the optimization and evaluate of heat engines and refrigeration systems for various objectives optimizations have made considerable advance [24–30]. Hints for the optimum design of different actual refrigerators have prepared by these developments.

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Nomenclature

A	area
b_1	related to Eqs. (15)–(17)
C	heat capacitance
C_V	molar specific heat capacity, J mol^{-1} K^{-1}
d	Index of deviation
d_{i+}	deviation of ith solution from the ideal solution
d_{i-}	deviation of ith solution from the non-ideal solution
COP	coefficient of performance
F_1	related to Eqs. (15)–(17)
i	ith objective
j	jth solution
n	working fluid's mole number, mol
p	power, W
Q	heat transfer, J
R	universal gas constant, J mol^{-1} K^{-1}
T	temperature, K
t	cyclic period, s
U	overall heat transfer coefficient
x	temperature ratio of the Stirling cryogenic refrigerator
X	decision variable's vector

Greek letter

λ	ratio of volume through the regenerative processes (volumetric ratio)
ε_H	hot-side heat exchanger's effectiveness
ε_R	regenerator's effectiveness
ε_L	cold-side heat exchanger's effectiveness

Subscripts

c	sink side/cold side
H, h	heat source/hot side
L	cooling/heat sink
R	regenerator
s	isentropic/ideal
1,2,3,4	states points

To involve all of the above-proposed objects three objective functions counting input power, the coefficient of performance (COP) and cooling load (R_L) have been investigated. Furthermore, Six decision parameters that contains the heat capacitance rates of heat sink and heat source, the cold- and hot-side heat exchangers effectiveness, ratio of temperatures $\left(\frac{T_h}{T_c}\right)$ and temperature of sink side (T_c) have been used in the multi-objective optimization process.

Multi-objective optimization has extreme presence in different engineering problems such as skyline computation, vehicle routing issues and so forth [31–33]. Simultaneous consent of various objective functions through for gaining optimum solution through the multi-objective optimization is a highly difficult target. The background of the Evolutionary algorithms (EA) referred to 18th century in a stochastically effort to gain a solution of this type while this approach was evolved and applied gradually [34]. An acceptable route to a multi-objective quandary is summarized to prepare an assortment of routes, each of them consents the objectives at a reasonable degree without being overcome by the rest solutions [35]. Generally, Multi-objective optimization issues represent an uncounted collection of outputs which is called Pareto frontier, who examined vectors illustrating the prior feasible solution in the space of the objective function. Multi-objective optimization of system of energies and various thermodynamic have been the focus of many studies these days [36–43]. Recently, Ahmadi et al. [44,45] have developed a multi-objective optimization method for designing a power Stirling engine by applying the Genetic Algorithm (GA) which is known as a branch of evolutionary algorithm.

In the current study, multi-objective optimization algorithms have been executed to maximize the coefficient of performance (COP) and cooling load (R_L) and minimize the input power. To obtain the optimum solution, three robust decision making methods were used and error analysis of the outcomes gained from each decision making techniques was employed to determine effectiveness and accuracy of each optimum route that obtained from the mentioned decision making methods.

2. System description

Magnetic material or a gas can play role of working fluids in the Stirling cycle while various working fluids have various effectiveness properties. If the implemented working fluids assumed ideal gas in the cycle the referred cycle separates into two isochoric and two isothermal processes as displayed schematically in Fig. 1. The expansion stroke of an actual cycle can be determined in the addressed cycle as an isothermal process 1–2 join irreversible isothermal heat addition owing to the finite heat capacity's heat source that temperature differ from T_{L1} to T_{L2} at temperature T_c. Adding of the heat into the working fluid from the regenerator is assumed as an isochoric process like as process 2–3. Isothermal processes 3–4 assumed for the compression stroke join irreversible heat declining to the finite heat capacity's heat sink that temperature changes in interval of T_{H1} to T_{H2} at temperature T_h. Moreover, isochoric process 4–1 represents the heat declination from the working fluid to the regenerator. As mentioned earlier, the heat transfer in the mentioned processes such as 1–2 and 3–4 in an actual cycle have to happen in finite time. To reach this, these mentioned heat processes have to be preceded throughout a finite temperature variation and consequently introduced as external irreversibilities.

3. Thermodynamic analysis

The value of the absorbed heat of the cycle at temperature T_c from the source represent by Q_c and the value of the released heat of the cycle at temperature T_h from the sink represent Q_h therefore:

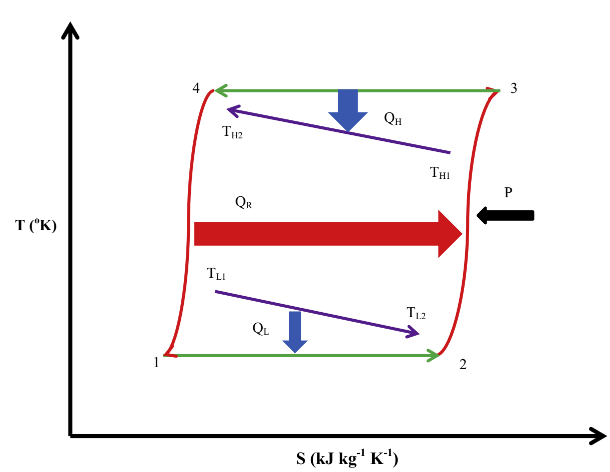

Fig. 1. Qualitative scheme of an irreversible Stirling refrigerator cycle [9].