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Thermodynamic optimization of Stirling heat pump based on multiple criteria

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ABSTRACT

In this research work, a connectionist investigation of irreversible Stirling heat pump cycles that includes both internal and external irreversibilities together finite heat capacities of external reservoirs was carried out. Finite temperature difference between the external fluids and the working fluids through the heat sink and heat source causes an external irreversibility. On the other hand, regenerative heat loss and entropy generation through the cycle are the main source of the internal irreversibilities generation. Three objective functions including the heating load (R_H) and coefficient of performance (COP) have been considered simultaneously maximized, on the other hand at the same time the input power of the Stirling heat pump is minimized. To assess this idea, Multi-objective optimization approach be founded on NSGA-II method has been utilized which following variables have been considered as decision variables such as 1 – the effectiveness of the hot-side heat exchanger, 2 – the performance of the cold-side heat exchanger, 3 – the rate of heat capacitance through the heat sink, temperature ratio $(\frac{T_h}{T_c})$, 4 – rate of the heat capacitance through the heat source and 5-temperature of cold side. By applying addressed multi-objective optimization approach, Pareto optimal frontier determined and utilizing different decision-making techniques that includes the LINMAP, TOPSIS and fuzzy Bellman–Zadeh approaches help us to figure out a final optimal solution.

1. Introduction

Throughout cycle approaches of refrigerators, air conditioning and heat pump (RAC & HP) systems, Stirling and Ericsson cycles play vital role which have been used by a different experts in the approach of realistic frameworks to determine the generation of desired temperatures. Recently huge amounts of attentions have been made by various Scientists on the addressed cycles. Curzon and Ahlborn were introduced the concept of finite time thermodynamics [1] by performing a new work on Carnot heat engine whereas they highlighted the effectiveness of addressed engine that operates at maximum power is calculated with their introduced formula $\left[\eta_m = 1 - \sqrt{\frac{T_L}{T_H}}\right]$. It should be noted that the output of their proposed formula is always lower than the routine formula of Carnot $\left[\eta_c = 1 - \frac{T_L}{T_H}\right]$ while closed more appropriate with the actual efficiencies of operating systems given by them. In addition the same theory on the finite time Carnot heat engine with limited external reservoirs heat capacities was also performed by Wu [2]. Based on his work, the inlet temperatures of the external fluids are the most important variables in the highest power output and the performance at highest power. Due to loose of "Natural Maximum" in the reversed Carnot cycle, the simple C–A are calculations unable to perform as noted previously by Leff and Teeters [3]. Determination of the COP of endoreversible Carnot heat pump that operates at lowest power input for a desired heating load by implementing the Lagrangian approach of indefinite factor was conducted by Blankard [4]. Wu has been effectively implemented the theorem of finite time thermodynamics to indicate the optimal

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Nomenclature

C	rate of heat capacitance (W K^{-1})
C_v	specific heat capacity (J mol^{-1} K^{-1})
Cl_i	decision index in TOPSIS method (–)
COP	the coefficient of performance (W m^{-2})
i	ith objective (–)
j	jth solution (–)
n	number of mole (–)
R_H	heating load (W)
P	Output power (W)
Q	heat (J)
R	the gas constant (J mol^{-1} K^{-1})
S	entropy (J K^{-1})
T	temperature (K)
t	time (s)
X	vector of decision variables (–)
x	temperature ratio (–)
W	output work (J)

Subscripts

1, 2, 3, 4	state points
c	cold side
dis	distance
H	heat source
h	hot side
L	cold side/heat sink
R	regenerator

Greek

η	thermal efficiency (-)
ε	effectiveness (–)
ϕ	internal irreversibility parameter (–)
λ	the volume ratio (–)
α	proportionality constant (J K^{-1})

performance of the various cycles such as endo-reversible Carnot, Stirling RAC & HP and Brayton systems for various situations [5,6]. Nova days, optimum performance parameters of the Stirling refrigerators and Stirling heat pumps have been investigated systematically by performing finite time thermodynamics as a function of operating conditions [7–17]. Chen et al. developed mathematical and thermodynamic models for the coefficient of performance, heating load and cooling load for heat pumps and refrigerators with finite heat transfer efficiency [7–12]. Kaushik et al and Feidt et al investigated the impacts of irreversibilities in heat pump cycles [13–17].

To consider all above-mentioned declares, in this research three objective functions counting input power, the coefficient of performance (COP) and heating load (R_H) have been studied. Furthermore, the multi-objective optimization method was performed with Six decision variables that includes rates of the heat capacitance through heat sink and heat source, the cold-side and hot- and heat exchangers performance's, ratio of temperatures ($\frac{T_h}{T_c}$) and temperature of sink side (T_c).

Multi-objective optimization is useful way for solving engineering problems at various fields for research [18–20].

Solving the optimization of multi-objective issues is a severely hard target and needs simultaneous satisfaction of various and often contradicting objectives. Owing to this fact, evolutionary algorithms (EAs) have been established and developed through the 18th century in an endeavor to randomly solve multi-objective issues [21]. An acceptable route to a multi-objective quandary is to inquiry an assortment of routes, each of them convinces the objectives at a satisfactory degree away being overcome by another route [22]. Multi-objective optimization quandaries universally represent a feasibly innumerable group of ways which called Pareto frontier, whose assessed vectors show the foremost feasible exchanges throughout the objective function area. By the way, multi-objective optimization of energy systems and diverse themodynamic have been applied in different field of science these days [23–31].

Throughout this communication, multi-objective optimization algorithms has been utilized to maximize the coefficient of performance (COP_H) and heating load (R_H) and minimize the input power. To assess this valuable goal, three robust, cheap and fast decision making approaches have been used to determine the optimum solutions through the multi-objective optimization process. Moreover, error analysis has been carried out indicate statistical analysis of the gained solutions of various decision making techniques. More details about the mentioned decision making that includes LINMAP, TOPSIS and Fuzzy methods are demonstrated in the following sections.

2. System description

Gas or a magnetic material can be used as a working fluids of the Stirling cycle (Nickel-based super alloys are the primary materials used in the Stirling-cycle portion of the Engine). Also, different working fluids lead to different performance characteristic of Stirling systems.

As depicted in Fig. 1, the cycle comprises two isochoric and two isothermal processes when the addressed working fluids of the cycle are the ideal gas. The mentioned cycle proximate the expansion stroke of an actual cycle as an isothermal process 1–2 while an irreversible isothermal heat added from a heat source of finite heat capacity at temperature T_c that the temperature changes in range of T_{L1} to T_{L2}.

Addition of the heat from the regenerator to the addressed working fluid was considered as an isochoric process 2–3. The compression stroke was considered as isothermal processes 3–4 with an irreversible heat rejection to the heat sink of finite heat capacity at temperature T_h that temperature changes in range of T_{H1} to T_{H2}: Lastly, rejection of the heat from the working fluid that comes to the regenerator was considered as an isochoric process 4–1. As expressed previously, the heat transfer processes 1–2 and 3–4 in an actual cycle must happen throughout finite time. This needs the addressed heat processes would be preferred in the finite temperature difference and consequently, specified as stand hardly irreversible.

In addition, the change of entropy through process 3–4 is greater than the change of entropy through process 1–2. So, for each cycle, there are some net entropy generation as well as internal irreversibility parameter (ϕ); which defined as the rate of entropy change throughout the expansion process to the rate entropy change in the compression process. Furthermore, some heat losses entire the regenerator, as a perfect regeneration needs unlimited regeneration area or time. Therefore, it is necessary to study an actual regenerator. Involving all the above mentioned aspects, the addressed heat pumps approaches turn irreversible. As mentioned previously, the external irreversibility is caused by difference of limited temperature between the external reservoirs and the cycle and on the other hand, regenerative loss and entropy generation results internal irreversibilities.