Energy Conversion and Management 89 (2015) 147–155

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Thermodynamic analysis and optimization of an irreversible Ericsson cryogenic refrigerator cycle

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ARTICLE INFO

Article history:
Received 19 August 2014
Accepted 21 September 2014

Keywords:
Decision making
Ericsson refrigerator
Cooling load
Power input
Optimization

ABSTRACT

Optimum ecological and thermal performance assessments of an Ericsson cryogenic refrigerator system are investigated in different optimization settings. To evaluate this goal, ecological and thermal approaches are proposed for the Ericsson cryogenic refrigerator, and three objective functions (input power, coefficient of performance and ecological objective function) are gained for the suggested system. Throughout the current research, an evolutionary algorithm (EA) and thermodynamic analysis are employed to specify optimum values of the input power, coefficient of performance and ecological objective function of an Ericsson cryogenic refrigerator system. Four setups are assessed for optimization of the Ericsson cryogenic refrigerator. Throughout the three scenarios, a conventional single-objective optimization has been utilized distinctly with each objective function, nonetheless of other objectives. Throughout the last setting, input power, coefficient of performance and ecological function objectives are optimized concurrently employing a non-dominated sorting genetic algorithm (GA) named the non-dominated sorting genetic algorithm (NSGA-II). As in multi-objective optimization, an assortment of optimum results named the Pareto optimum frontiers are gained rather than a single ultimate optimum result gained via conventional single-objective optimization. Thus, a process of decision making has been utilized for choosing an ultimate optimum result. Well-known decision-makers have been performed to specify optimized outcomes from the Pareto optimum results in the space of objectives. The outcomes gained from aforementioned optimization setups are discussed and compared employing an index of deviation presented in this work.

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1. Introduction

Among the different models for refrigeration systems, the Ericsson cycle is one of the most important ones which have been utilized in various engineering designs. Several engineering companies have used the Ericsson cycle to manufacture practical systems in order to produce very low temperatures. These efforts have led to the development of novel designs for these cycles. Walker and colleagues [1], Leff and Teeters [2] have mentioned that in the study by Curzon and Ahlborn [3] and Wu [4], the straightforward calculation made by the authors is not applicable for a reversed Carnot cycle since there is no 'Natural Maxima' in these cycles.

Blanchard [5] utilized the Lagrangian approach of undetermined multiplier for a given heating load to obtain the COP of an endoreversible Carnot heat pump operating at minimum power input. In recent years, Wu [6,7], Wu and colleagues [4], Chen and colleagues [8], Chen [9], Ahmadi and colleagues [10], Chen and Yan [11], Kaushik [12], Tyagi [13–15] demonstrated the optimal performance as a function of working circumstances by employing the concept of finite time thermodynamics following the work of Curzon and Ahlborn [3] on the different irreversible and endoreversible cycles for various operating circumstances. Angulo-Brown [16] introduced the ecological function as $E_p = P_o - T_L\dot{S}_{gen}$ (T_L is the sink temperature, P_o is the power output, and $\dot{S}_{gen}$ is the entropy generation rate) for a finite time Carnot heat engine. The author obtained that at the maximum power output, the thermal efficiency is nearly the average of the Carnot efficiency and the C–A efficiency. When the heat sink temperature T_L is not equivalent to the environmental temperature T_0, Yan [17] suggested that it is more appropriate to utilize the ambient temperature in the ecological function. The study of ecological optimization of different

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http://dx.doi.org/10.1016/j.enconman.2014.09.064
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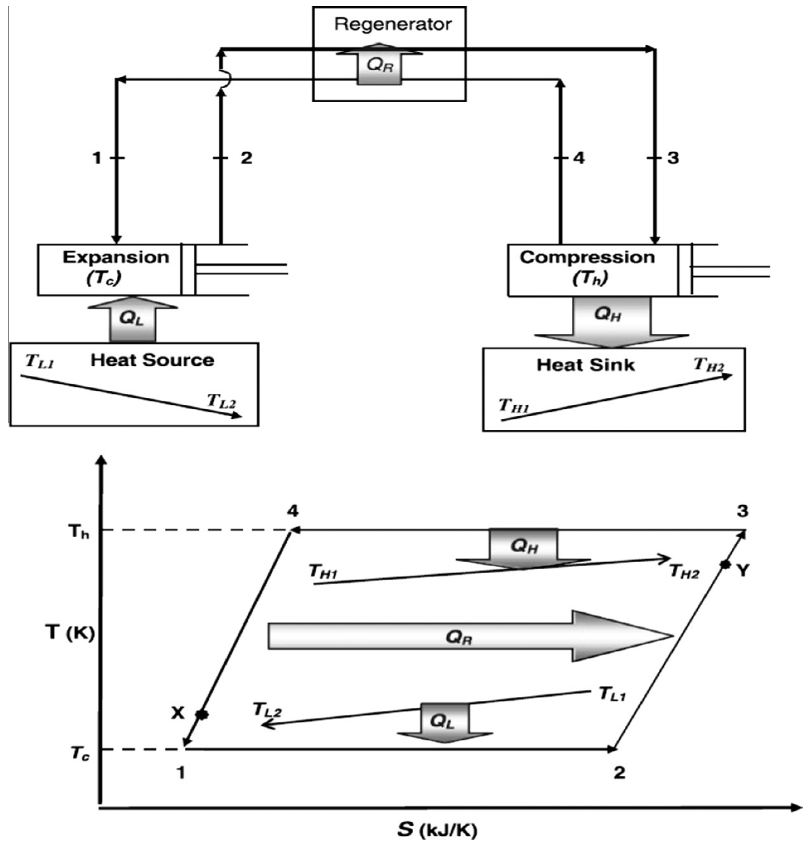

Fig. 1. Carton and *T–S* diagrams of an Ericsson refrigeration cycle [15].

cycles for various operating circumstances was also performed by Cheng and Chen [18,19], Yan and Lin [20], Chen and colleagues [21], Tyagi and colleagues [15] and Tyagi and colleagues [22].

Solving multi-objective optimization problems is too difficult because the resulting different objective functions should be satisfied simultaneously while they may even conflict. Evolutionary algorithms (EAs) were the first techniques developed and utilized during the mid-eighties which enabled solving problems of such generic class stochastically [23]. When such a method is to be used, a multi-objective issue gives rise to an assortment of optimum results, each of the objective functions is satisfied at an acceptable level where the other solutions are not being dominated [24]. In general, multi-objective optimization show a countless assortment of possible results called Pareto frontier, whose examined vectors throughout the objective function region illustrate the finest probable trade-offs. Nowadays, multi-objective optimization of various systems in energy and thermodynamics engineering is generating interest in many researchers throughout the world [25–45].

In the current work, a Ericsson cryogenic refrigerator cycle is optimized employing an EA, whereas input power, coefficient of performance and ecological objective functions are proposed as the optimization objectives, and thermal operating variables of the refrigerator, comprising the heat sink's capacitance rate, heat source's capacitance rate, temperature ratio $\left(\frac{T_h}{T_c}\right)$, effectiveness of the hot-side heat exchanger, effectiveness of the cold-side heat exchanger and temperature of cold side, are assumed as the decision parameters. Four different setups are evaluated for optimization of the Ericsson cryogenic refrigerator cycle. Throughout the three setups, a conventional single-objective optimization is utilized distinctly employing input power, coefficient of performance and ecological objective function. Throughout the last setup, the three objectives, containing input power, coefficient of performance and ecological objective function, are optimized concurrently employing the nondominated sorting genetic algorithm (GA) named NSGA-II. An ultimate optimum outcome is chosen from the potential outcomes of the Pareto frontier employing different well-known decision-makers comprising technique for order of preference by similarity to ideal solution (TOPSIS), linear programming techniques for multi dimensional analysis of preference (LINMAP) and Bellman and Zadeh (1970) fuzzy decision-making approaches. Lastly, optimum results gained via the four setups are discussed and compared employing an index of deviation presented throughout this research.

2. System description

As demonstrated previously, a magnetic material or a gas can serve as working fluid for an Ericsson cycle which shows different performance characteristics for the cycle. For an ideal gas as the working fluid, as illustrated on *T–S* diagram and picture in Fig. 1, the Ericsson cycle includes two isobaric and two isothermal processes. The isothermal process 1–2 is the approximation of the expansion stroke in the real cycle where the irreversible heat addition is performed at temperature T_c from a heat source with finite heat capacity where temperature changes from T_{L1} to T_{L2}. The heat is absorbed by the working fluid from the regenerator in an isobaric progression modeled in the process 2–3. The isothermal process 3–4 is a model for the compression stroke where the heat is rejected at temperature T_h throughout an irreversible process to the heat sink with finite heat capacity where temperature changes from T_{H1} to T_{H2}. To complete the cycle, the heat is removed from the working fluid to the regenerator through an isobaric progression modeled as process 4–1.

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