Energy Conversion and Management 99 (2015) 81–91

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Thermo-economic and thermodynamic analysis and optimization of a two-stage irreversible heat pump

Hamed Sahraie [a], Mohammad Reza Mirani [b], Mohammad Hossein Ahmadi [c,*], Milad Ashouri [d]

[a] Faculty of Mechanical Engineering–Energy Division, K.N. Toosi University of Technology, No. 15–19, Pardis St., Mollasadra Ave., Vanak Sq., Tehran 1999 143344, Iran
[b] Department of Chemical Engineering, Razi University, Kermanshah, Iran
[c] Department of Mechanical Engineering, Pardis Branch, Islamic Azad University, Pardis New City, Tehran, Iran
[d] Faculty of Mechanical Engineering, K.N. Toosi University of Technology, No. 15–19, Pardis St., Mollasadra Ave., Vanak Sq., Tehran 1999 143344, Iran

ARTICLE INFO

Article history:
Received 19 February 2015
Accepted 22 March 2015
Available online 25 April 2015

Keywords:
Heat pump system
Specific heating load
Thermo-economic benchmark
Coefficient of performance
Decision making

ABSTRACT

This research study mainly deals with a comprehensive thermodynamic modeling and thermo-economic optimization of an irreversible absorption heat pump. For the optimization goal, various objective functions are considered comprising the specific heating load, coefficient of performance (COP) and the thermo-economic benchmark (F). In order to specify the optimum design variables, non-dominant sorting genetic algorithm (NSGA) is applied satisfying some restrictions. In this optimization study, all three objective functions (e.g. COP, F and specific heating load) are maximized. In addition, decision making is carried out using three well-suited approaches namely LINAMP and TOPSIS and FUZZY. Finally, sensitivity analysis and error analysis are conducted in order to improve understanding of the system performance.

1. Introduction

Increasing demands for energy and limitation of sources have led to a high rate of energy consumption and this will affect the future of energy sources seriously. Therefore, using energy efficient and environmentally-friendly energy conversion devices with optimized working conditions play a crucial role in future of our world. Heat pumps are widely used for transporting heat from low temperature sources to higher ones and are usually single-stage heat pumps. However, there are some limitations in conventional single-stage compression heat pumps, for example, the inefficient performance, high discharge temperature and low performance of compressor especially in winter which made them less popular. With the purpose of gaining a higher range of temperature difference between the environment and heated space, two stage heat pump plants are developed and are widely used in industrial scale. Many authors have investigated the performance of single stage vapor compression and absorption heat pumps and refrigeration cycles employing finite time thermodynamics [1–11]. Chen [1] optimized the characteristics of a solar driven heat pump for maximum COP using finite time thermodynamics. He assumed a linear heat transfer behavior between working fluid and heat reservoir. The results show an improvement in operating temperature of collectors and working fluids in heat exchangers. Chen [2] also optimized an endoreversible heat pump for minimizing heat transfer area at a specified COP and heat rate. The same author [3] optimized a general irreversible cycle based on COP for cooling and heating purposes. The irreversibilities include finite rate heat transfer between the working fluid and the external heat reservoirs, internal dissipation of working fluids and heat leakage between reservoirs. Davis and Wu [4] investigated a geothermal heat pump system and optimized the cycle using finite time thermodynamics. The system consists of a Rankine cycle to produce power needed for heat pump system. Results show an equation for maximum power and cycle efficiency. Wu et al. [8] considered a solar assisted heat pump system and optimized the collector operating temperature. Two heat transfer models were used between working fluid and the reservoirs of the heat pump. The optimization was performed based on COP of the reversible heat pump and maximum heat load of an endoreversible heat pump. Salah El-Din [9] optimized an internally and externally irreversible heat pump and refrigeration cycles. Irreversibilities include thermal resistance between engine and hot and cold reservoirs, also the internal irreversibilities. The optimal size of heat exchangers for optimal heat load of the two systems was obtained. Optimization was based on total thermal conductance constraint and total heat transfer area. Blanchard [10] presented a formula for the coefficient of performance of a heat pump for the minimum power input required for a given heat load. Wu et al. [11]

* Corresponding author.
E-mail address: mohammadhosein.ahmadi@gmail.com (M.H. Ahmadi).

http://dx.doi.org/10.1016/j.enconman.2015.03.081
0196-8904/

Nomenclature

A	total heat-transfer area (m^2)
a	investment cost parameter for the heat exchangers
b_1	investment cost parameter for the compressor and its driver
b_2	energy consumption cost parameter
b	$b_1 + b_2$
COP	coefficient of performance
C	cost
F	thermo-economic benchmark
I	internal irreversibility parameter
k	$\frac{a}{b}$
$\dot{Q}$	rate of heat transfer (kW)
q	specific heating load ($kW\,m^{-2}$)
R	heat-leakage parameter
T	temperature (K)
S	Entropy ($kJ\,K^{-1}$)
U	overall heat-transfer coefficient ($kW\,m^{-2}\,K^{-1}$)

Symbol

γ	thermal conductance

Subscripts

X	warm working fluid of the first cycle
W	warm working fluid of the second cycle
Y	cold working fluid of the first cycle
Z	cold working fluid of the second cycle

compared the various heat transfer laws in finite time exergoeconomic performance of Carnot heat pumps. The exergoeconomic performance emphasized a compromise between profit and COP of the heat pump. The three common heat transfer laws were investigated including Newton's law, linear phenomenological law and radiative heat law. A few number of performance analysis on two stage heat pumps are conducted by authors [12–15]. Chen et al. [13] optimized the heat rate of a combined heat pump system with two Carnot heat pump cycles in series. The relation between COP and heat load was obtained. The objective function for the optimization purpose in these systems are generally coefficient of performance (COP), heating duty, heating load per unit total heat-transfer area (specific heating load) and total heat transfer area. In most of these studies, a single objective function is considered for optimization while the other parameters are kept constant. For example, some objective functions for optimization are related to investment costs and other objective functions are associated with the costs of energy consumption, but for a real situation it is desirable to comprise both the energy consumption and investment costs. A number of thermo-economic optimizations on heat engines, heat pumps, refrigeration systems and power cycles are carried out by authors. De Vos [16] applied an optimization on an endoreversible power plant regarding economic exploitation and thermodynamic performance. The findings show that optimum point lies between the Novikov working point and Carnot or reversible working point. He also [17] developed a model to process economics of heat engines through endoreversible modeling. The findings show an analogy between tax revenue in economics and produced work in thermodynamics. Dingec and Ileri [18] optimized a vapor compression refrigeration cycle with respect to a thermo-economic benchmark. Costs assigned with exergy losses are joined with recovery and capital costs. Finally the thermoeconomic optimization equation was derived. Chen et al. [19] optimized a three-heat-source reservoir heat pump based on the relation between COP and profit which was based on exergy output of the system. The equations give the relationship between reversible COP bound, the COP bound at maximum profit and the COP bound at maximum heating load. Wu and colleagues [20] studied the exergoeconomic performance of heat engines by defining a correlation between efficiency and profit of an endoreversible Carnot engine. The relation for the maximum profit at the analogous efficiency span was derived based on three heat-transfer laws. Chen et al. [21] applied an economic optimization of the endoreversible refrigerator. The coefficient of performance (COP) accounts for cooling rate and exergy output is constrained by economic considerations. Finally the profit objective function was optimized. Ahmadi et al. [22] conducted a modeling and thermodynamic and thermo-economic analysis of an irreversible regenerative closed Brayton cycle. Also they optimized the system using three objective functions comprising total cost rate, exergy efficiency and Co_2 emissions of the plant based on evolutionary algorithm. Sahin and Kodal [23,24] applied a detailed thermo-economic optimization for an endoreversible and irreversible single stage heat pump in order to determine the optimal design parameters. Heating load per unit total cost was chosen as the objective function for optimization of heat pump system for both the endoreversible and irreversible processes. Bhardway et al. [25,26] performed an optimization of a simple single effect vapor absorption refrigeration system with both internal and external irreversibilities using finite-time thermodynamics. Huang et al. [27] applied an optimization of the irreversible absorption heat pump with four-temperature-levels based on COP, surface area and ecological principles. Ngouateu Wouagfack et al. [28] applied a thermo-ecological optimization of an absorption heat pump working between three-temperature-levels. An ecological coefficient of performance (ECOP) was chosen as objective function to minimize the entropy generation and maximize the heating load.

Unraveling multi-objective optimization issues are a problematic task because the objective functions might conflict with each other and maximization of one objective leads to minimize the other one, therefore, a number of techniques are deployed and developed in which them evolutionary algorithm (EV) has attracted substantial interest in engineering which delivers a solution stochastically [29]. With this method, a group of optimal solutions is delivered and reach the desired optimization goals to a certain satisfactory degree known as non-dominated solutions [30,31]. A great number of categories for optimal solutions called Pareto frontier is delivered and among them the finest probable trade-offs could be found. Today, new multi objective algorithms are rapidly being generated and are widely used in thermodynamics engineering and energy related issues [32–47]. In the present research, a comprehensive thermodynamic simulation of a heat pump is conducted accompanied by an evolutionary based multi-objective optimization. The objective functions considered for this investigation comprising specific heating load (q_H), thermo-economic benchmark (F) and COP of the system.

2. Thermodynamic model

Fig. 1 illustrates the T–S diagram of the proposed model. This is a two stage irreversible heat-pump system. Because of a number of causes such as heat resistance, friction, internal losses and heat