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Optimization of a residential solar combisystem for minimum life cycle cost, energy use and exergy destroyed

Jason Ng Cheng Hin, Radu Zmeureanu *

Department of Building, Civil and Environmental Engineering, Concordia University, Montreal, Quebec H3G 1M8, Canada

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Abstract

This paper presents the optimization of a model of a solar combisystem in an energy efficient house in Montreal (Qc), Canada. A hybrid particle swarm and Hook–Jeeves generalized pattern search algorithm is used to minimize the life cycle cost, energy use and exergy destroyed of the combisystem. The results presented include four different optimal configurations depending on the objective function used. The optimizations were able to reduce, compared with the base case combisystem, the life cycle cost of the combisystem by 19%, the life cycle energy use by 34%, the life cycle exergy destroyed by 33% and 24% using the technical boundary and physical boundary, respectively. Due to the high cost of the solar collector technologies and the low price of electricity in Quebec, none of the optimal configurations have acceptable financial payback periods. However, they all have energy payback times between 5.8 and 6.6 years. The use of technical boundary in the exergy analysis favors the use of electricity over solar energy due to the low exergy efficiency of the solar collectors. The use of the physical boundary, on the other hand, favors the use of solar energy over electricity, and all of the combisystem configurations have exergy payback times between 4.2 and 6.3 years.

Keywords: Solar combisystem; Optimization; Life cycle cost; Life cycle energy; Life cycle exergy destruction

1. Introduction

A solar combisystem is defined as a solar heating system that is configured to provide heat for space heating as well as for domestic hot water production for a residential household. Combisystems normally consist of five sub-systems: solar collector loop, heat storage, heat distribution, controls, and auxiliary power supply. Combisystems have been extensively studied in the last 15 years, with numerous international and collaborative research efforts taking place. The International Energy Agency Solar Heating and Cooling Programme devoted one of their working tasks, Task 26, to solar combisystems (IEA, 2002). The project, which lasted from 1998 to 2002, involved a thorough analysis of different combisystem designs which were generalized into 21 different configurations. From 2001 to 2003, the European Commission, under the Altener programme and in collaboration with Task 26, studied over 200 combisystems in seven European community countries, monitored 39 different systems and developed guidelines for installation and design (Ellehauge, 2003). Furthermore, from 2007 to 2010, Intelligent Energy Europe (IEE) commissioned a project known as Combisol (Papillon, 2010). The objectives of this project were to develop best practices, standards, and recommendations for manufacturers, installers, authorities and technical experts. A few examples of other combisystem related research efforts are given in (Jordan and Vajen, 2001; Lund, 2005; Anderson and Furbo, 2007; Streicher and Heimrath, 2007).

* Corresponding author. Tel.: +1 514 848 2424/3203; fax: +1 514 848 7965.

E-mail addresses: jason.ngchenghin@gmail.com (J.N. Cheng Hin), radu.zmeureanu@concordia.ca (R. Zmeureanu).

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Nomenclature

BCSCS	base case solar combisystem
Cp	specific heat
DHWHX	domestic hot water heat exchanger
DHWT	domestic hot water tank
EE	embodied energy
EPR	energy payback ratio
EPT	energy payback time
F	primary energy factor
HUSP	hours under set point
LCC	life cycle cost
LCE	life cycle energy
LCX	life cycle exergy
LCXp	life cycle exergy considering the physical boundary
LCXt	life cycle exergy considering the technical boundary
PSO	particle swarm optimization algorithm
PW	present worth
RFT	radiant floor tank
T	temperature
V	volume
X	exergy
XPR	exergy payback ratio
XPT	exergy payback time
η	efficiency

Subscripts

a	ambient
aux	auxiliary
col	collector
comp	component
CS	combisystem
d	destroyed
emb	embodied
f	collector fluid
HX	heat exchanger
II	second law or exergy efficiency
L	leaked
p	absorber plate
phys	physical
r	room
repl	replacement
S	stored
Sol	solar
St	storage
Tech	technical
W	water

Several recent studies have used optimization techniques to optimize solar thermal systems. The most popular optimization technique lately for solar water heating systems has been the Genetic Algorithm (GA). Loomans and Visser (2002) used a GA to minimize the payback time of a large scale solar domestic hot water heating system. Kraus et al. (2002) also used a GA to optimize large solar domestic hot water systems to minimize solar heat cost. Kalogirou (2004) combined artificial neural networks (ANN) with GA to optimize an industrial solar water heater for maximum life cycle savings. Bales (2002) and Calise et al. (2011) used a deterministic optimization algorithm, known as the Hooke–Jeeves (HJ) generalized pattern search algorithm, instead. Bales maximized the fractional energy savings of a solar combisystem using the HJ algorithm and the TRNSYS simulation software while Calise et al. used a modified HJ algorithm to minimize the payback period and annual costs of three different solar heating and cooling systems. Bornatico et al. (2012) used a particle swarm optimization (PSO) to optimize a solar combisystem to minimize a weighted combination of solar fraction energy use and cost.

Dincer and Rosen (2007) pointed out that an energy analysis of a thermodynamic system can be misleading since it does not necessarily explain how closely the system is performing to ideality. An exergy analysis can make up for this shortcoming by using the second law of thermodynamics. There are numerous studies that used exergy to characterize solar collector systems including (Altfeld, 1988a,b; Luminosu and Fara, 2005; Gunerhan and Hepbasli, 2007). In general, solar collectors tend to have low exergy efficiencies, mostly between 2% and 11%, due to the conversion of high quality solar heat at 6000 K for low quality heating purposes at low indoor air temperature around 293 K. Also, the solar collectors tend to be responsible for the majority of the overall thermal system's irreversibilities, where they often represent up to 95% of the exergy destroyed by the whole system.

Fraisse et al. (2009) compared various energy, exergy and economic optimization criteria for a solar domestic hot water system by computer simulation with TRNSYS and GenOpt programs. They concluded that it is better to oversize the collector area and reduce the storage tank volume.

This paper, an extension of a study by Leckner and Zmeureanu (2011), that presented the performance of a base case solar combisystem (BCSCS), focuses on the search for the optimal configurations of a residential solar combisystem for minimum life cycle cost, life cycle energy use, and life cycle exergy destroyed in Montreal. The comparison with the BCSCS configuration in terms of performance is also presented.