Energy xxx (2014) 1–8

Contents lists available at ScienceDirect

Energy

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

Advanced exergy analysis of an air conditioning system incorporating thermal energy storage

A.H. Mosaffa [a,*], L. Garousi Farshi [b], C.A. Infante Ferreira [c], M.A. Rosen [d]

[a] Department of Mechanical Engineering, Azarbaijan Shahid Madani University, Tabriz, Iran
[b] Faculty of Mechanical Engineering, University of Tabriz, Iran
[c] Delft University of Technology, Department Process & Energy, Delft, 2628 CB, Netherlands
[d] Faculty of Engineering and Applied Science, University of Ontario Institute of Technology, Oshawa, ON, L1H 7K4, Canada

ARTICLE INFO

Article history:
Received 26 May 2014
Received in revised form
30 August 2014
Accepted 1 October 2014
Available online xxx

Keywords:
Latent heat thermal energy storage
Advanced exergy analysis
Cooling
Exergy
Exergy destruction

ABSTRACT

Air conditioning incorporating thermal storage, in which the cooling capacity needed for air conditioning is produced during the nighttime when the demand for air conditioning is small and then utilized to satisfy peak loads during the daytime, has received much attention recently. In this work, an air conditioning system consisting of a combination of LHTS (latent heat thermal storage) and VCR (vapor compression refrigeration) is analyzed with advanced exergy analysis. The analysis is performed based on splitting the exergy destruction into endogenous/exogenous and unavoidable/avoidable parts. The results show that all of the exergy destruction of the LHTS unit is endogenous, which indicates that the total exergy destruction of the LHTS unit is due only to its irreversibilities.

1. Introduction

The demand for AC (air conditioning) normally peaks during the daytime, and air conditioners are used much less during the nighttime. If equipment is designed to match such demands, its availability factor is low. For this reason air conditioning incorporating thermal storage, which produces and stores the cooling capacity needed for air conditioning during nighttime when the demand for air conditioning is small and utilizes the stored cooling capacity during daytime hours, is now receiving much attention. By using thermal storage in this manner, large air conditioning systems that are sized proportional to peak loads during daytime hours become unnecessary, and electricity costs are significantly reduced. Moreover, as the system produces and stores cooling capacity by using inexpensive nighttime electricity (provided the electricity cost differs between peak and off-peak load periods), the overall operating cost is lowered (for those with time-of-use electricity pricing). Thermal energy storages in general and PCMs (phase change materials) in particular have been the subject of much research over the last 20 years [1–6].

Analyses of energy quality and quantity are important for improving the efficiency of a thermodynamic system, and the conventional method for performance analysis of LHTS (latent heat thermal storage) systems is based on energy. Many energy analyses of LHTS have been reported. For instance, Mosaffa et al. [7] investigated the energy efficiency for free cooling LHTS systems using multiple PCMs inside flat slabs. Also, they performed a numerical investigation of performance enhancement measures for the same storage to improve energy storage effectiveness and COP (coefficient of performance) [8]. Anisur et al. [9] used a theoretical model to analyze a LHTS system with a cylindrical shell geometry for an air cooling–heating application. They concluded that the PCM container volume also needs to be considered in conjunction with COP for reducing the amount of PCM.

However, energy analysis is insufficient for complete thermodynamic evaluation of LHTS systems because it does not take into account all relevant performance aspects. This inadequacy of energy analysis leads to the use of exergy analysis, a technique based on the second law of thermodynamics, in LHTS system assessments. Exergy analysis determines efficiencies which provide a true measure of how nearly actual efficiency approaches the ideal, and identifies more clearly than energy analysis the sources, causes and locations of thermodynamic losses. The thermodynamic performance of cold thermal storage systems was assessed using exergy and energy analyses by Rosen et al.

* Corresponding author. Tel.: +98 412 4327566.
E-mail address: mosaffa@azaruniv.ac.ir (A.H. Mosaffa).

http://dx.doi.org/10.1016/j.energy.2014.10.006
0360-5442/

Nomenclature

c_p	specific heat at constant pressure (J/kg K)
COP	coefficient of performance
$\dot{E}x$	exergy rate (W)
L	latent heat (J/kg)
$\dot{m}$	mass flow rate (kg/s)
m	mass (kg)
$\dot{Q}$	heat rate (W)
$\overline{\dot{Q}}$	time averaged heat transfer heat (W)
RI	relative irreversibility
s	specific entropy (J/kg K)
T	temperature (K)
$\overline{T}$	time averaged temperature (K)
$\overline{T}_0$	thermodynamic averaged environment temperature (K)
T_m	melting temperature (K)
t	time (s)
$\dot{W}$	power (W)

Greek symbols

T	operating time (s)
Ψ	exergy efficiency

Subscripts

CM	compressor
CD	condenser
D	destruction
e	end of the PCM slab in the direction of the air flow
el	electricity
EV	evaporator
EX	expander
F	fuel
i	initial
l	liquid
P	product
s	solid
TV	throttling valve

Superscripts

AV	avoidable
EN	endogenous
EX	exogenous
H	hybrid
R	real
T	theoretical
UN	unavoidable

Abbreviations

AC	air conditioning
LHTS	latent heat thermal storage
PCM	phase change material
VCR	vapor compression refrigeration

[10]. Mosaffa et al. [11] performed energy and exergy analyses for a free cooling system using a LHTS unit with multiple PCMs. They showed that the increase in exergy efficiency due to reducing inlet air temperature is more significant than the effect of increasing the air flow rate during the cooling (discharging of LHTS) process. Ezan et al. [12] investigated energetically and exergetically a shell-and-tube LHTS unit during solidification and melting processes. Tyagi et al. [13] reported energy and exergy analyses of LHTS systems for space heating and cooling applications for two LHTS types: rectangular and balls filled with PCM. Li et al. [14] experimentally determined the energy and exergy performance of an adsorption storage system for residential applications. They showed that, as ambient temperature increases, the total energy storage density and energy efficiency increase, while the overall exergy efficiency decreases. Li et al. [15] presented energy and exergy analyses for an adsorption cold thermal energy storage system, for a space cooling application. The results show that the cold energy storage density and recovered exergy increase as the inlet temperature of the heat transfer fluid used in the adsorption system decreases.

In the present work, advanced exergy analysis is applied to a cooling system using a LHTS unit which consists of several parallel layers of PCM slabs. A conventional exergy analysis identifies the components of the system with the highest exergy destructions and the processes that cause them. Then, the performance of a component of the system can be improved by reducing its exergy destruction. However, part of the exergy destruction may be unavoidable and part may be due to the exergy destruction occurring in other components (exogenous exergy destruction). This can be identified by performing an advanced exergy analysis. This type of analysis provides enhanced information and can show, for instance, if it is worthwhile to improve other components instead of only the component which has the highest exergy destruction.

The LHTS unit cools air during the day and the absorbed heat is extracted during the night by employing an AC system (see Fig. 1). An advanced exergy analysis for the transient processes in the proposed system provides engineers with useful information related to energy system improvement potential. Splitting the exergy destruction within each component into unavoidable/avoidable and endogenous/exogenous parts via advanced exergy analysis can provide meaningful results not obtained through conventional exergy analysis [16–19].

2. Description of processes

For the system considered, air cooling (PCM melting), releasing heat from LHTS unit (PCM solidification) and air-side heat transfer are taken to be unsteady two-dimensional problems. To develop a mathematical formulation of the melting and solidification processes, it is assumed that the PCM thermophysical properties are independent of temperature, but differ between solid and liquid phases. Further assumptions are that the air velocity profile is fully developed and, due to the negligible variation of container-wall temperature, temperature variations normal to the flow direction are neglected [20]. The effect of natural convection is negligible for this PCM storage geometry [21].

Fig. 2 illustrates the proposed air cooling system using a LHTS unit. Heat is extracted from the PCM by employing a VCR (vapor compression refrigeration) cycle during the night when condensation takes place at lower temperature and, in some regions, electricity is less expensive. The solidified PCM can be used to cool the air in the buildings during the hot hours of the day.

3. Conventional analyses

3.1. Energy analysis

An energy analysis of an air cooling system using a LHTS unit has been reported in detail previously by the authors [7,8]. According to

Please cite this article in press as: Mosaffa AH, et al., Advanced exergy analysis of an air conditioning system incorporating thermal energy storage, Energy (2014), http://dx.doi.org/10.1016/j.energy.2014.10.006