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ScienceDirect

Solar Energy 84 (2010) 432–449

SOLAR ENERGY

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Transient analysis and energy optimization of solar heating and cooling systems in various configurations

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Received 4 March 2009; received in revised form 15 December 2009; accepted 1 January 2010
Available online 27 January 2010

Communicated by: Associate Editor Dr. C. Estrada-Gasca

Abstract

In this paper, a transient simulation model of solar-assisted heating and cooling systems (SHC) is presented. A detailed case study is also discussed, in which three different configurations are considered. In all cases, the SHC system is based on the coupling of evacuated solar collectors with a single-stage LiBr–H_2O absorption chiller, and a gas-fired boiler is also included for auxiliary heating, only during the winter season. In the first configuration, the cooling capacity of the absorption chiller and the solar collector area are designed on the basis of the maximum cooling load, and an electric chiller is used as the auxiliary cooling system. The second layout is similar to the first one, but, in this case, the absorption chiller and the solar collector area are sized in order to balance only a fraction of the maximum cooling load. Finally, in the third configuration, there is no electric chiller, and the auxiliary gas-fired boiler is also used in summer to feed the absorption chiller, in case of scarce solar irradiation.

The simulation model was developed using the TRNSYS software, and included the analysis of the dynamic behaviour of the building in which the SHC systems were supposed to be installed. The building was simulated using a single-lumped capacitance model. An economic model was also developed, in order to assess the operating and capital costs of the systems under analysis. Furthermore, a mixed heuristic-deterministic optimization algorithm was implemented, in order to determine the set of the synthesis/design variables that maximize the energy efficiency of each configuration under analysis.

The results of the case study were analyzed on monthly and weekly basis, paying special attention to the energy and monetary flows of the standard and optimized configurations. The results are encouraging as for the potential of energy saving. On the contrary, the SHC systems appear still far from the economic profitability: however, this is notoriously true for the great majority of renewable energy systems.

Keywords: Solar energy; Evacuated collectors; Absorption chiller; Dynamic simulation; Renewable energy

1. Introduction

Solar-assisted air conditioning is a very promising concept. Usually, the maximum demand for cooling coincides with the maximum availability of solar radiation, whereas conventional electric-driven systems have the problem of providing their minimum capacity in the hottest day hours.

In addition, the use of solar energy in refrigeration can be very useful in order to limit the growth of the electric energy demand in summer and for sustaining the development of technologies based on renewable energy sources.

Many institutions are presently involved in R&D activities in this field, and a lot of demonstration projects have been developed: for example, the International Energy Agency (IEA) launched a program ("Solar Heating and Cooling Programme, SHC", Task 25 "Solar-Assisted Air Conditioning of Buildings", initiated in June 1999 and completed in November 2004) aimed at improving condi-

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doi:10.1016/j.solener.2010.01.001

Nomenclature

c_{NG}	unit cost of natural gas (€/Sm^3)
c_{EE}	unit cost of electric energy (€/kWh)
c_p	constant pressure specific heat (kJ/kg K)
c_v	constant volume specific heat (kJ/kg K)
f	dimensionless design factor
$\dot{m}$	mass flow rate (kg/h)
v	ratio between tank volume and SC area (m^3/m^2 or l/m^2)
t	temperature (°C)
A	area (m^2)
AF	annuity factor (years)
C	annual cost (€/year)
COP	coefficient of performance
E_{el}	electric energy (kJ)
F_R	heat removal factor
F_{sol}	solar fraction
$FFLP$	fraction of full-load power
HDD	heating degree day (Kd)
I_T	total radiation on SC surface (kJ/h m^2)
J_i	capital cost of a single component (€)
J_{tot}	capital cost of the overall plant (€)
LHV	natural gas lower heating value (kWh/Sm^3)
M_i	mass of the TK1 *i*-th segment (kg)
OF	objective function (€/year)
$\dot{P}$	mechanical power (kJ/h)
P	nominal capacity (kJ/h)
PE	primary energy (kJ)
PES	primary energy saving
PLR	part-load ratio
R_{COP}	ratio of actual to nominal COP (electric chiller)
R_Q	ratio of actual to nominal cooling capacity (electric chiller)
Q	thermal energy (kJ)
$\dot{Q}$	thermal energy flow rate (kJ/h)
$\dot{Q}_{B,lsm}$	building maximum cooling load (kJ/h)
$\dot{Q}_{fluid}$	thermal energy flow rate transferred to the fluid (kJ/h)
$\dot{Q}_{ambient}$	thermal energy flow rate transferred to the environment (kJ/h)
$\dot{Q}_{SC}$	useful solar collector energy gain (kJ/h)
SPB	simple Pay Back (years)
$T_{off,ACH}$	ACH shut-down temperature (K)
U	transmittance (kJ/h m^2 K or W/m^2 K)
U_L	SC transmittance (first term, kJ/h m^2 K)
$U_{L/T}$	SC transmittance (second term, kJ/h m^2 K^2)
UA	overall transmittance (kJ/h K)
V	volume (m^3)
η_{el}	conventional efficiency in thermoelectric conversion
η_{motor}	motor efficiency
$\eta_{pumping}$	pump efficiency
η_{SC}	solar collector efficiency
η_{AH}	AH efficiency
η_{comb}	combustion efficiency
$(\tau\alpha)_n$	transmittance-absorptance at normal incidence angle
α_{SC}	SC slope (deg)
ϑ	time (h)
β_i	power coefficient
ρ	density (kg/m^3)
γ	control function
φ_{P2}	mass flow rate per SC area (kg/h m^2)
Δt_n	nominal temperature difference (°C)
Δt_{TK1}	ACH re-activation set-temperature (°C)
ΔC	operating cost savings

Subscripts

DL	design load
H	TK1 top
L	TK1 bottom
amb	ambient
c	cooling
cap	capital
EE	electric energy
h	heating
in	inlet
n	nominal
NG	natural gas
out	outlet
op	operating
opt	optimal
rated	referred to nominal conditions
req	required
rej	rejected
s	summer
set	set by the controller
tot	total
w	winter

tions for the market introduction of solar-assisted cooling systems. This task, and the subsequent ones (IEA, Task 38), promoted a reduction of primary energy consumption and electricity peak loads due to air conditioning and thereby developed an environmentally friendly way for air conditioning (IEA).

In this framework, a lot of experimental and theoretical research work has been done in the last few years. In particular, in the field of the analysis and optimization of solar cooling systems, many simulation codes for the design analysis and optimization were developed, usually with transient simulation environments, such as TRNSYS, ENERGY PLUS, etc. For example, Florides et al. developed a very interesting simulation model in TRNSYS for a Cypriot building (Folrides et al.,2001, 2002). Such model was based on the use of several built-in components (ther-