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A systematic parametric study and feasibility assessment of solar-assisted single-effect, double-effect, and triple-effect absorption chillers for heating and cooling applications

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ABSTRACT

The present work investigates the feasibility of solar heating and cooling (SHC) absorption systems based on combining three types of LiBr–H_2O absorption chillers (single-, double-, and triple-effect) with common solar thermal collectors available on the market. A single-effect chiller is coupled with evacuated tube collectors (ETCs) – SHC1. A double-effect chiller is integrated with parabolic trough collectors (PTCs), linear Fresnel micro-concentrating collectors (MCTs) and evacuated flat plate collectors (EFPCs) respectively – SHC2, SHC3, and SHC4. PTCs are employed to provide high-temperature heat to a triple-effect absorption chiller (SHC5). Although triple-effect chillers have been around for a while, this paper represents the first system-level analysis of these chillers coupled with high-temperature solar concentrating collectors for air-conditioning applications. A simulation model for each configuration is developed in a transient system simulation environment (TRNSYS 17). Furthermore, a unique, comprehensive perspective is given by investigating the impact of characteristic solar beam radiation to global radiation ratios on the techno-economic performance of the proposed SHC plants for a wide variety of climatic regions worldwide. The results of parametric study suggest that a storage volume of around 70 L/m^2 is a good choice for SHC1, while 40–50 L/m^2 storage capacity is sufficient for the other configurations (SHC2 to SHC5). The simulation results reveal that when the fraction of direct normal irradiance (DNI) is less than 50%, SHC2, SHC3, and SHC5 require larger collector area compared to SHC1, showing there is no advantage in using concentrating collector powered multi-effect chillers over solar single-effect chillers in climates with low DNI level. However, in climates with DNI fractions above 60%, the smallest solar field is achieved by SHC5, followed by SHC2. SHC4, which benefits from both relatively high COP of double-effect chiller and the diffuse component in the solar field, results in the most reasonable trade-off between energetic and economic performance of the system in a wide range of climatic conditions.

1. Introduction

Air-conditioning demand in many countries accounts for about 50% of the energy consumption in buildings – which is mainly supplied by conventional fossil fuels [1,2]. The use of renewable energy technologies in buildings can reduce fossil fuel consumption, and as a result mitigate their environmental impacts [3,4]. Solar cooling is a promising, clean alternative which has the advantage of being *in phase* with the buildings' cooling demand [5–7]. The available technologies on the market for thermally driven cooling systems are absorption and adsorption chillers, solid and liquid desiccant cooling systems, and ejector refrigeration cycles [8]. Of these, absorption chillers are considered as the most desirable method for harnessing solar thermal energy due to their reliability and higher efficiency. In addition, absorption chillers can be available for large-scale applications and their cost is lower than the rest of thermally-driven air-conditioning systems for such uses [9,10]. There are three types of absorption chillers commercially available on the market – single-, double-, and triple-effect chillers. The advantage of moving toward a higher effect cycle is to enhance the COP of the chiller, if a high temperature heat source is available. The most common working fluid pair used in absorption chillers for air-conditioning applications is lithium bromide–water (LiBr–H_2O), where LiBr is the absorbent and water is the refrigerant [9]. The driving heat source temperature for

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Nomenclature

A	heat transfer surface area (m^2)
a	characteristic coefficient (–)
A_a	aperture area (m^2)
A_r	receiver area (m^2)
c_1	first-order heat loss coefficient (W/m^2 K)
c_2	second-order heat loss coefficient ($W/m^2 K^2$)
c_3	wind speed dependence of heat losses (J/m^3 K)
c_4	long-wave irradiance dependence of heat losses (–)
c_5	the collector effective thermal capacitance (J/m^2 K)
c_6	wind dependence of the zero loss efficiency (s/m)
c_{CO_2}	CO_2 emission penalty cost (USD/tonne CO_{2-e})
CDE	carbon dioxide emission (tonne)
CDEC	carbon dioxide emission cost (USD)
c_E	unit cost of electricity (USD/kW h)
CI	capital investment cost (USD)
c_{NG}	unit cost of natural gas (USD/GJ)
COP	coefficient of performance (–)
C_{op}	operating cost (USD)
c_p	specific heat at constant pressure (kJ/kg K)
CR	concentration ratio (–)
DNI	direct normal irradiance (kW h/m^2)
E	energy (kW h)
e	characteristic coefficient (–)
EF	emission factor (kg CO_2/kW h)
EFPC	evacuated flat plate collector
E_L	long-wave irradiance (W/m^2)
ETC	evacuated tube collector
F'	collector efficiency factor (–)
$F'(\tau\alpha)_n$	collector zero loss efficiency at normal incidence (–)
GHI	global horizontal irradiance (kW h/m^2)
G_t	global irradiance on the tilted collector (W/m^2)
k	thermal conductivity (W/m K)
$K(\theta)$	incidence angle modifier (–)
M	mass (kg)
$\dot{m}$	mass flow rate (kg/s)
MCT	micro-concentrating collector
NTU	number of transfer units
PEC	primary energy consumption (kW h, GW h)
PEF	primary energy factor (–)
PTC	parabolic trough collector
$\dot{Q}$	heat transfer rate (kW)
r	characteristic coefficient (kW)
R^2	coefficient of determination
s	characteristic coefficient (kW °C^{-1})
SF	solar fraction
SPBP	simple payback period (year)
T	temperature (°C)
t	time (s)
U	overall heat loss coefficient (W/m^2 K)
u	wind velocity (m/s)
U_L	collector overall heat loss coefficient (W/m^2 K)
USD	US dollar
V	specific volume (L/m^2)
$\Delta\Delta T'$	characteristic temperature difference (°C)

Greek symbols

β	collector slope (°)
γ	collector azimuth angle (°)
γ_s	solar azimuth angle (°)
δ	thickness (m)
η	thermal efficiency (–)
θ	solar incidence angle on the collector (°)
θ_z	solar zenith angle (°)
σ	Stefan–Boltzmann constant (W/$m^2 K^4$)

Subscripts

a	air, ambient
AC	absorber–condenser
ACH	absorption chiller
AH	auxiliary heater
aux	auxiliary
avg	average
b	beam
C	cooling
CHW	chilled water
Config.	configuration
CT	cooling tower
CTRL	controller
CW	cooling water
d	diffuse
DV	diverting valve
E	electricity, evaporator
G	generator
H	heating
HW	hot water
L	load
l	linear, longitudinal
MV	mixing valve
NG	natural gas
P	pump
PRV	pressure relief valve
q	quadratic
SC	solar collector
SCW	solar collector water
ST	storage tank
t	transversal
u	useful
w	water

single-effect chillers is about 80–100 °C, while their COP is limited to around 0.7 [11]. Double- and triple-effect chillers, on the other hand, require driving temperatures of around 180–240 °C, and can reach COPs of up to 1.4 and 1.8, respectively [11].

The majority of solar absorption chillers installed around the world are based on single-effect chillers and low-temperature solar thermal flat plate or evacuated tube collectors (FPCs and ETCs) [12,13]. This configuration is usually considered as the most promising design in European climates [14]. The main drawback of solar single-effect chillers is the low COP of the chiller, requiring a large collector area to provide the thermal energy demand. In addition to the cost of large collector areas, this may be a significant limiting factor for the use of such systems in buildings with limited available rooftop area.

The combination of high-temperature solar thermal collectors and multi-effect absorption chillers is becoming more attractive due to their higher COP compared to single-effect chillers [15,16]. This means that the multi-effect chillers require less solar thermal energy (and potentially less collector area) to supply a given amount of cooling. However, they require very high driving temperatures which can only be achieved by more expensive collectors and pipework. If concentrating collectors are used, they have a lower solar gain per unit area because they can only utilize the direct normal irradiance (DNI) as opposed to FPCs and ETCs which can also harness solar diffuse radiation [17]. This disadvantage may be partially compensated by employing tracking systems, but these require regular maintenance, especially in dusty environments. Therefore, it is not clear if solar-powered multi-effect