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Research paper

Absorption solar cooling systems using optimal driving temperatures

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HIGHLIGHTS

- Instantaneous optimum driving temperature $t_{g,op}$ for solar cooling in Madrid.
- 3 absorption cycles tested: H_2O/LiBr and $NH_3/LiNO_3$ single effect and hybrid.
- The $t_{g,op}$ of the hybrid cycle is 16 °C lower than both single effect cycles.
- The best fixed driving temperature can reach almost the same behaviour than $t_{g,op}$.

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ABSTRACT

The optimum instantaneous driving temperature of a solar cooling facility is determined along a day. The chillers compared use single effect cycles working with $NH_3/LiNO_3$, either conventional or hybridised by incorporating a low pressure booster compressor. Their performances are compared with a H_2O/LiBr single effect absorption chiller as part of the same solar system. The results of a detailed thermodynamic cycle for the absorption chillers allow synthesizing them in a modified characteristic temperature difference model. The day accumulated solar cold production is determined using this optimum temperature during two sunny days in mid-July and mid-September, located in Madrid, Spain. The work shows the influences of operational variables and a striking result: selection of a time-constant temperature during all the day does not necessarily imply a substantial loss, being the temperature chosen a key parameter. The results indicate that the $NH_3/LiNO_3$ option with no boosting offers a smaller production above-zero Celsius degrees temperatures, but does not require higher hot water driving temperatures than H_2O/LiBr. The boosted cycle offers superior performance. Some operational details are discussed.

1. Introduction

The use of absorption chillers to produce cold by means of solar thermal energy has generated a high interest in the last decades; e. g. Zhai et al. [1] and Boophathi Raja and Shanmugam [2] among others, where the importance of the three temperatures of interchange of the absorption chiller is highlighted. The solar collectors produce hot water that drives the chiller. The synchronicity between heat production and cold demand makes this technology very attractive. The solar irradiance has a non-steady behaviour during the day what makes necessary to actively control the system. The solar thermal collectors exhibit a continuously decaying efficiency for collecting heat with an increase of the temperature of the flowing water inside them. On the other hand the conversion efficiency of the collected heat into cold by the absorption machine (*COP*) typically exhibits a continuously increasing value when the hot water temperature increases within the reasonable operating range, e. g. Fernández-Seara and Vázquez [3]. A further increase eventually leads to a slight decrease in *COP* that obviously is not of interest in this case; moreover some authors do not report this decrease, e. g. Sun [4]. Thus, a water temperature exists that results in maximum conversion of solar energy into cooling energy, quantified by *SCOP*, Eq. (14). Such optimum value depends on operating and environmental variables, and varies throughout the day. A suitable optimum driving temperature has been explored in the past with different aims and different methodologies. Albers [5] performs a theoretical and experimental study where both the driving and recooling (absorber and condenser) temperatures are controlled with the aim of minimizing the total cost of solar cooling. This cost is the addition of fixed plus variable cost, including backup heat from a district heating network and recooling fan electric consumption. Minimization was performed with a specified

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Nomenclature

a	absorber; constant
A_s	collector area, m^2
b	constant
COP	coefficient of performance
COP_e	electrical coefficient of performance
COP_M	asymptotic value for COP when $\Delta\Delta t \to \infty$.
c	condenser
e	evaporator
g	generator
G_T	solar intensity, tilted, W/m^2
h	specific enthalpy, external fluid, J kg^{-1}
H	specific enthalpy, internal fluid, J kg^{-1}
$\dot{m}$	mass flow rate, external fluid, kg/s
$\dot{M}$	mass flow rate, internal fluid, kg/s
P	pressure, Pa
pr	pressure ratio of booster compressor
Q	daily solar cold production, J/m^2
$\dot{Q}$	heat power, W
$SCOP$	solar coefficient of performance
SE	single-effect
she	solution heat exchanger
t	averaged external fluid temperature between inlet and outlet, °C
t'_e	equivalent external fluid temperature averaged between inlet and outlet, °C
$t_{g,op}$	optimum external generator temperature averaged between inlet and outlet, °C
$t_{g,0}$	activation external generator temperature averaged between inlet and outlet, °C
T	averaged internal fluid temperature between inlet and outlet, °C
T'_e	equivalent internal fluid temperature averaged between inlet and outlet, °C
UA	heat exchanger thermal conductivity, W/°C
$\dot{W}_c$	mechanical power to the booster compressor W

Greek

$\Delta\Delta t$	characteristic temperature difference, °C
ΔT_{ml}	mean logarithmic temperature difference, °C
ε	efficiency of heat exchanger in the solar facility
η_c	isentropic efficiency of the compressor

Subscripts

a	absorber
ac	absorber–condenser
atm	atmospheric
c	condenser
e	evaporator
g	generator
i	inlet
o	outlet
r	solution or refrigerant, internal fluid of the absorption chiller
s	solution
she	solution heat exchanger, State at the outlet of the absorption pump
w	water, external fluid of the absorption chiller
x	components of the absorption chiller: a, c, e, g

cooling water temperature and cooling capacity (load). The optimization algorithm is based on a modified characteristic temperature difference method $\Delta\Delta t$ as the design variable, which will be explained in Section 2. It was enhanced by considering internal variable losses of the real absorption machine to better follow its performances, instead of constant values as in the original method. This modification requires additional internal data from the machine, what is an undesirable condition for commercial application. In Ref. [6] Li et al. perform a theoretical study of the dependence of *SCOP* on the hot water temperature, evaporator temperature and recooling temperature, for constant hot water flow rate and a simplified CPC collector efficiency equation. A numerically solved thermodynamic absorption cycle represents a generic double effect machine. From this study the optimum monthly average hot water temperature is deduced for a single specific subtropical location. More straightforward criteria for optimization seem desirable, especially for on-line control.

The optimum driving temperature has been already analytically made explicit and applied to commercial H_2O/LiBr absorption chillers, Lecuona et al. [7] using the concept of an empirical characteristic temperature difference $\Delta\Delta t$ [8], Kühn and Ziegler, defined in Eq. (1). The experimentally obtained $\Delta\Delta t$ serves to describe the cooling power of the absorption chiller [8], and it is able to describe different commercial absorption chillers, in both the configuration of single and double effect, as it has been demonstrated by Puig-Arnavat et al. in Ref. [9], with advantages over other approximate methods. This model has been extended to absorption chillers with adiabatic absorbers [10] by Gutiérrez-Urueta et al. underlining the usefulness of the concept.

The most common working pair used in absorption chillers for air-conditioning is H_2O/LiBr. This working pair yields a good performance for air-conditioning temperatures but it risks of crystallizing and it cannot produce cold under 0 °C temperatures. For temperatures under 0 °C the common working fluid is NH_3/H_2O. There is an alternative working fluid, $NH_3/LiNO_3$. This pair does not need a rectification tower, reaches a higher efficiency in single effect cycles, e. g. Sun [4], and does not suffer from crystallization risk, so that a dry cooling tower is possible. In addition, the absence of water with this working fluid offers a low risk of corrosion. NH_3 is a natural refrigerant and $LiNO_3$ is an inorganic salt; neither of them does represent an environmental hazard when recycled at the end of their long operating life. Some experimental works show the good performance of this working solution [11–14]. In Ref. [11] Antonopoulus and Rogdakis show that $LiNO_3$ is superior to other salts with NH_3. In Ref. [12] Llamas-Guillén et al. show the feasibility for high recooling temperatures. New absorbing technologies for this working pair have been explored in Refs. [13,14] by Zacarías et al. for coping with the high viscosity of this fluid at low temperatures. They take advantage of the high pressure differential.

In order to produce cold when the solar irradiance is not enough to satisfy the cold demand it is necessary to use additional chillers, generally consuming electricity. This independent backup system increases cost and complexity, difficulting the solar cooling implementation. Burning a fossil fuel for helping the absorption chiller drive means net direct and indirect CO_2 emissions that can be higher than using mechanical compression cooling, at least for single-effect absorption cycles, Fig 1a. For a more widespread implementation of solar cooling it seems that an integrated