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Experimental study of a thermochemical compressor for an absorption/compression hybrid cycle

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ABSTRACT

An experimental study of a thermochemical compressor with ammonia–lithium nitrate solution as working fluid has been carried out. This compressor incorporates a single-pass adiabatic absorber and all the heat exchangers are of the plate type: absorber subcooler, generator and solution heat exchanger. The thermochemical compressor has been studied as part of a single-effect absorption chiller hybridized with an in-series low-pressure compression booster. The adiabatic absorber uses fog jet injectors. The generator hot water temperatures for the external driving flow are in the range of 57–110 °C and the absorber pressures range between 429 and 945 kPa. Experimental results are compared with a numerical model showing a high agreement. The performance of the thermochemical compressor, evaluated through the circulation ratio, improves for higher absorber pressures, indicating the potential of pressure boosting. For the same circulation ratio, the driving hot water inlet temperature decreases with the rise of the absorber pressure. The thermochemical compressor, based on an adiabatic absorber, can produce refrigerant with very low driving temperatures, between 57 and 70 °C, what is interesting for solar cooling applications and very low temperature residual heat recovery. Efficiencies and cooling power are offered when this hybrid thermochemical compressor is implemented in a chiller, showing the effect of different operating parameters.

1. Introduction

Absorption machines are a key technology for solar cooling, where hot water produced by solar collectors drives an absorption chiller to produce cold for industry or for air conditioning. Solar cooling is attractive due to the seasonal coincidence of high solar intensity and cooling demand. Single-effect absorption chillers can be activated with relative low driving temperatures [1], which are compatible with the efficient operation of flat plate and evacuated collectors. Using conventional technology the minimum for refrigerant production is not less than about 70 °C for air-conditioning applications. This minimum is higher on hot days and for low temperature cold water production [2]. This requirement makes that in the morning, evening and during cloudy periods solar energy is wasted because the minimum driving temperature (activation temperature) cannot be reached. Thus, operating efficiently with a low driving temperature is of much interest. Moreover, during higher solar intensity periods, a benefit of a lower hot water temperature would be a higher collector efficiency [3], less investment on the solar collectors and also smaller maintenance costs, as a result of less thermal degradation of the materials. If collecting solar energy with a photo-thermal combined collector (PVT) the lower fluid temperature leads also to higher efficiency in the electricity production.

The single-effect absorption cycle can be hybridized with an integrated in-series booster compressor, between evaporator and absorber, thus located at the low-pressure side of the cycle. This offers reducing the hot water temperature needed, taking advantage of a simple hardware. The cost to pay is an additional small electricity consumption, reaching a 10%, as a maximum, of the total power consumption of the machine [4]. For low driving temperatures the performance of the absorption cycle with a compressor booster was studied theoretically in [4] highlighting the efficiency gains and the high electrical *COP*. That paper presents the state of the art of oil-free, leak-free, semi-hermetic compressors as a technological support for the feasibility of the proposed cycle. There, a conventional diathermal absorber was considered. Other authors have studied hybrid cycles for cooling production integrating absorption and vapour compression, being these cycles conceived in several configurations, e.g. [5]. A similar configuration than on this work but for GAX cycles has been too studied showing the high potential of the integration of a mechanical compressor with an absorption chiller [6,7].

The NH_3–$LiNO_3$ pair is a promising alternative to NH_3–H_2O that has been already assessed as working fluid [8–11]. The single-effect (SE) absorption cycle using this solution offers higher *COP*, less size and less investment cost than NH_3–H_2O, as it does not

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Nomenclature

A	heat transfer area, m^2
cr	circulation ratio
COP	coefficient of performance
COP_e	electric coefficient of performance
F_{ad}	approach to adiabatic equilibrium factor
h	specific enthalpy, J kg^{-1}
$h_{eq,ad}$	adiabatic equilibrium specific enthalpy at the outlet of the absorber, J kg^{-1}
$\dot{m}_r$	refrigerant mass flow rate, kg s^{-1}
$\dot{m}_{r,eq}$	adiabatic equilibrium refrigerant mass flow rate, kg s^{-1}
$\dot{m}_5$	solution mass flow rate at absorber outlet, kg s^{-1}
$\dot{m}_8$	solution mass flow rate at generator outlet, kg s^{-1}
$\dot{m}$	external circuit mass flow rate, kg s^{-1}
P	pressure, kPa
$P_{eq,ad}$	adiabatic absorber equilibrium pressure, kPa
$\dot{Q}$	heat power, W
pr	pressure ratio
rr	recirculation ratio
SE	single-effect
T	temperature, °C
U	global heat transfer coefficient, W m^{-2} K^{-1}
$X_{eq,ad}$	adiabatic equilibrium ammonia mass fraction, outlet of absorber
X_5	ammonia mass fraction, outlet of absorber
X_8	ammonia mass fraction, outlet of generator
$\dot{W}_c$	compressor power, W
$\dot{W}_p$	pump power, W
η_c	isentropic efficiency of the compressor
η_{elec}	electricity production efficiency from thermal sources

Subscripts

a	absorber
ad	adiabatic
ahx	absorber heat exchanger (subcooler)
bo	boiling
c	condenser
col	cooling
e	evaporator
g	generator
i	inlet
r	refrigerant
sub	subcooling
sup	superheating
tp	two-phase
shx	solution heat exchanger
SE	single-effect
w	water of external loops

require a rectification tower [9–11]. This working pair does present neither known relevant risks nor difficulties in comparison with the much experienced pair NH_3–H_2O, excepting a higher viscosity. For the preceding reasons it seems that NH_3–$LiNO_3$ is worth to further investigate, as a not so different alternative to the well documented NH_3–H_2O solution. Recent works have provided thermodynamic properties correlations [12,13] to support the advance with this working fluid.

The absorber tends to be the biggest size component of the absorption single-effect machines [1] due to the heat and mass transfer occurring at the same time, being the mass transfer the process that limits the overall rate [14]. An improvement is to divide these two processes as the adiabatic absorbers do [15]. The heat evacuation occurs in a conventional single-phase heat exchanger, this way optimizing the contact area [16]. It acts as a subcooler, removing the absorption heat upstream the adiabatic absorber, where only the mass transfer takes place. The solution is atomized as small drops inside the adiabatic absorber plenum, so that viscosity related problems and tube wetting difficulties are removed. When the drops start absorbing vapour, their temperatures rise due to the vapour turning into liquid. If the residence time is large enough, the adiabatic equilibrium is reached at the outlet of the absorber.

The adiabatic absorption process has been studied theoretically by different authors; some of them are [17–20]. They give mathematical models for different levels of simplification. Only a few theoretical studies about adiabatic absorbers using ammonia–lithium nitrate solution are available [19,20]. Experimental studies were carried out by few authors [14,21–24]. [24] offers experimental results for adiabatic absorbers with ammonia–lithium nitrate solution successfully sprayed with a flat fat nozzle.

Plate heat exchangers are a key technology to reduce the components size and cost of absorption machines [16] at the same time contributing to reduce the NH_3 inventory. Their use as generators has been studied in the recent years with the NH_3–$LiNO_3$ solution [25] and with the NH_3–H_2O solution [26], among others.

The main objective of this work is to show the performance of a thermochemical compressor that in absorption machines replaces the mechanical vapour compressor of conventional heat pumps. It is based on an adiabatic absorber. The results of the measurement campaign are compared with a numerical model of the experimental setup. The operating conditions are applicable to single-effect absorption chillers. They are also applicable to an absorption hybrid cooling cycle with an in-series low-pressure compression booster, because much different pressures and solution concentrations have been experimented. In this simulated cycle, the thermochemical compressor is boosted with an in-series mechanical compressor so that it can be viewed as a single unit.

2. Experimental setup

The experimental facility used in the present study is a test rig for absorption machine components. Fig. 1 shows the experimental facility used to carry out this work. Fig. 2 offers a layout of the experimental setup, which is based on a thermochemical compressor of a single-effect absorption cycle, implementing a generator, a single-pass absorber, an absorber subcooler and a solution heat exchanger for heat recuperation. In the facility, there is no condenser neither evaporator, as there would be in a normal absorption machine. The vapour, separated from the solution in the generator, flows through a valve, lowering its pressure. Downstream it is cooled by means of a heat exchanger. This simulates the inlet vapour temperature and pressure to the absorber from the evaporator in a real cooling machine. There are two auxiliary fluid loops: the driving hot water loop and the cooling loop, which sends waste heat to a cooling tower.

All the heat exchangers of the test rig are of the fusion plate type, made of stainless steel. Fig. 3 depicts a diagram of the adiabatic absorber, formed by a cylindrical vessel constructed on stainless steel with 400 mm of inlet diameter yielding a total internal volume of 0.0542 m^3. The absorber incorporates three ports: a top inlet port for the poor in refrigerant subcooled solution, a lat-