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Adsorption-compression cascade cycles: An experimental study

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ABSTRACT

In this paper the experimental testing of a cascade chiller composed of an adsorption unit and a vapour compression unit is reported. The operation of the cascade under realistic operating conditions, differing for the temperature of the heat source available and the environmental temperature is analysed. A comparison was made between the application of the cascade and a vapour compression chiller only for air conditioning applications. According to the heat source temperatures, an increase in the electric COP of the system ranging from 25% to 50% was measured, with a maximum value of 8. An optimization of the system was subsequently proposed, by evaluating different adsorbent materials and refrigerants through the use of thermodynamic models. The theoretical study revealed that a performance up to 110% higher with respect to traditional chillers could be obtained if the cascade was used in refrigeration applications.

1. Introduction

CO_2 emissions have been long proven to be one of the major causes of climate change [21], with more than 20% of them due to the industry sector worldwide. Air conditioning and refrigeration cause both "direct" and "indirect" emissions, due to the leakage of refrigerant and the production of electric energy needed to drive the vapour compression chillers [27]. In order to reduce such causes for pollution and comply with the increasing standards in terms of energy efficiency, thermally-operated chillers have been proposed, especially for the re-utilization of low-temperature waste heat [1,7]. Indeed, in the last decade, great effort were made in order to improve the TRLs of adsorption technology, at different levels: new materials have been synthetized and characterised [3,16,23,24], innovative reactor designs have been evaluated [20,23,26,34,37,38,39], and the integration of the chiller into a complete system has been simulated and the operation analysed [17,28,29,35,36]. Research is also being done addressing issues related to the industrialisation, for example by evaluating new materials for the components of the chillers [19] and characterization through new techniques or apparatuses [4,14,30,32]. Nonetheless, some limitations still exist, especially due to the low volumetric cooling power and low efficiency when chilled water temperature under 10 °C is required. In such a background, the use of hybrid chillers, realised through a parallel or series connection of a thermally-driven unit and a traditional vapour compression unit is indeed promising and can help speed up the technological advancement of alternative systems. They allow exploiting the benefits and main peculiarities of both technologies: sorption systems have electricity consumption extremely low and need limited maintenance, but their efficiency with a high temperature lift between condenser and evaporator is limited and their response time to load fluctuation is low. On the contrary, electric chillers offer high precision in temperature regulation and fast response to temperature fluctuations, but require a significant amount of energy to work, especially at higher condensation temperatures.

The possibility of combining sorption and compression cycles has been deeply analysed in literature and an overview of existing studies is given in Table 1.

Most studies focus on a cascade operation, with the thermal chiller in the high temperature stage and the compression chiller in the low temperature stage; only some of them [18,31] consider a different layout, where the absorption and the compression chiller share the condenser, the evaporator and other components of the cycle. Moreover, all the studies deal with refrigeration applications, at temperature levels variable between −50 °C and 0 °C, where the "thermal" stage is covered by an absorption chiller, employing either H_2O–LiBr or NH_3–H_2O working pairs. In particular, the thermodynamic models developed in [12,25] deal with the application of the hybrid chiller as part of a cogeneration or trigeneration system, respectively. The results of [12], which are confirmed by [9], show that the choice of the refrigerant does not influence the performance of the system significantly, differently from the intermediate temperature, which is the condensation temperature of the thermal chiller, that holds a great influence on

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Nomenclature

c_p	specific heat, kJ/kg K
E	electric power, kW
h	specific enthalpy, kJ/kg
H	enthalpy, kJ
L	latent heat of evaporation, kJ/kg
m	mass, lg
$\dot{m}$	mass flow, kg/s
Q	energy, kJ
$\dot{Q}$	thermal Power, kW
T	temperature, °C
W	uptake, g/g
$\dot{W}$	compressor work, kW

Greek letters

Δ	delta
η	efficiency
τ	time, s

Subscripts

adsorbent	adsorbent
comp	compressor
cond	condensation
eV	evaporation
el	electric
el-a	electric without auxiliaries
in	inlet
int	internal
is	isentropic
isc	isosteric cooling
isc	isosteric heating
out	outlet
ref	refrigerant
sc	subcoooling
sh	superheating
th	thermal

Abbreviations

COP	Coefficient of Performance
EES	Engineering Equation Solver
HT	High Temperature
MT	Medium Temperature
LT	Low temperature
TRL	Technology Readiness Level
VCC	Vapour Compression Chiller

the COP and the energy utilization of the system.

The studies reported in [10,22,25] all deal with the energy, exergy, economic and environmental analysis on different configurations of cascade absorption/compression hybrid cycles. The findings of all of them demonstrate the feasibility and the promising potential of the technology in terms of reduction of operation costs, increase of thermodynamic performance of the system with respect to the reference case (a single-stage absorption chiller) and reduction of CO_2 emissions.

The studies in [8,15] differ from the others because they take into account not only the thermodynamic evaluation, but also the heat transfer inside the various components, either by defining suitable heat transfer coefficients for each device [15] or through the usage of a complete simulation software such as Aspen, that already includes the model of the components [8]. The evaluation of the concept reported in [11] is twofold, since it is based on first and second law thermodynamic analysis: while, according to first law analysis the system employing CO_2 performs better, exergy analysis reveals that the irreversibilities of the system operating with R134a are lower than those of the system using CO_2.

All of the research reported deals with absorption-based systems. Instead, in the adsorption field, no actual studies exist on the combination with a compression unit. Adsorption chiller, if compared to absorption system, presents some advantages, such as lower noise, no moving parts and the use of natural refrigerants such as water. Moreover, adsorption units are present on the market in also in small-to-medium sizes, whereas absorption chillers on the market all have cooling capacity higher than 20 kW [2], thus leaving a gap for small sizes applications, which will instead be the focus of the present work. Regarding adsorption systems, in [33], Van der Pal et al. analyse the possible application of an adsorption/vapour compression system for heating applications, using ammonia and chloride salts in the thermal stage and ammonia as a refrigerant in the compression cycle. In [5], a theoretical study is reported on a system where the same refrigerant (R134a) for both the adsorption and compression stage of the cycle is applied, resulting however in a very low performance of the adsorption unit. In both the analysed cases, the hybrid systems are quite complex and do not lead to a significant improvement of the efficiency of the hybrid system over the adsorption or vapour compression one, thus indicating that cascade connection is the most promising among the investigated possibilities so far.

In such a background, the present paper presents the characterization of a cascade adsorption-compression chiller for air conditioning applications. The cascade unit analysed is composed of an adsorption chiller, whose cold output is used for cooling the condenser of a R-410A vapour compression unit. Target of the experimental campaign has been the verification of the benefits achievable with the cascade configuration for air conditioning applications. The main novelties proposed in the work are: (i) the application, for the first time, of a cascade cycle on a silica/gel water adsorption chiller, (ii) the experimental characterization of the system, instead of a theoretical analysis only, (iii) the analysis of the behaviour of the system under different operating conditions.

Moreover, a theoretical analysis was carried out, in order to evaluate the possible improvements on both sides of the cascade: a first thermodynamic evaluation, based on experimental measurements of adsorbent materials, was realised to estimate the benefits deriving from the replacement of the adsorbent material of the thermal chiller. State equations for the electric chillers were also implemented in EES, comparing different refrigerants and evaluating the possible application of the system not only for air conditioning but for refrigeration purposes as well.

2. Description of the system

The schematic layout of the analysed system is shown in Fig. 1. The system is made up of two sub-units:

- a "thermal" unit, which is a commercial silica gel/water adsorption unit, commercialized by Fahrenheit, with 2 adsorbers working in counter-phase. The thermal unit receives heat from a heat source and generates as output chilled water at a temperature up to 20 °C. It is connected to a heat rejection system for the release in the environment of condensation and adsorption heat (the dry cooler in the schematics).
- an "electric" unit, which is a vapour compression chiller (VCC), employing R-410A as refrigerant and equipped with a non-

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