Analysis and testing of a novel cascaded adsorption-compression chiller for industrial applications

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Abstract

Adsorption technology has experienced high R&D efforts in the last decades, becoming a mature technology with several systems on the market. Many features make the adsorption systems attractive: electricity consumption extremely low, limited maintenance needed, low noise operation and the possibility to be driven even by low-grade waste heat (< 90°C).
Also electric chillers present some unique features: high precision in temperature regulation and fast response to temperature fluctuations. Nonetheless, strict international regulations in terms of seasonal efficiency requirements and environmental issues related to the refrigerants used, determine new challenges for this field, especially for commercial and industrial installations.
In such a background, aim of this paper is to report an experimental analysis on a double-stage chiller realized by coupling in cascade an adsorption chiller and a vapour compression unit. Main feature in the operation of such system is the possibility to use waste heat from process, which is usually available in industrial applications, for the operation of a silica gel/water adsorption chiller (first stage). Chilled water obtained at high electrical efficiency in the first stage is then employed for cooling of the condenser in a traditional vapour compression chiller (second stage), thus working in a more favourable condition. To this goal, the experimental results from a testing campaign performed at CENTROPROVE of CNR-ITAE are presented. Results clearly show that it is possible to double the seasonal efficiency if compared with a standard electric chiller performance.

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Keywords: Hybrid chillers; cascade chillers; adsorption chiller; silica gel.

NOMENCLATURE

$\dot{m}$: flow rate, kg/s
c_p: specific heat, kJ/kg °C
T: temperature, °C
E: energy, kJ

Acronyms
COP: Coefficient of Perfomance

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HT: high temperature
LT: low temperature
MT: medium temperature

Greek symbols
τ: time, s

Subscripts
c: compression
e: electric
in: inlet
int.: internal loop
out: outlet
s: overall system

1. Introduction

Energy efficiency is a key issues in today's world, in all fields: from domestic to industrial, from mobile to stationary. Moreover, there is a growing need for the exploitation of renewable energy or waste heat. Space heating and cooling account for a significant amount to the energy consumption in the industrial field. In such a background, the use of hybrid chillers, realized through a parallel or series connection of a thermally-driven unit and a traditional vapor compression unit is indeed promising, because it allows to exploit the benefits and main peculiarities of both components. Indeed, sorption systems have electricity consumption extremely low and need limited maintenance while electric chillers offer high precision in temperature regulation and fast response to temperature fluctuations.

In literature, some cases have been analysed, mainly considering cascade chillers where the evaporator of an absorption unit is used as the condenser of a vapor compression one [1, 2], indicating a promising potential from the theoretical point of view. More recently, Garimella et al. [3] developed a model based on a waste-heat powered absorption unit, cascade with a CO_2 vapor compression cycle for space cooling applications in the naval field. The results showed that a significant increase in the performance of the system, in both terms of COP and Cooling Capacity with high heat rejection temperatures can be achieved (up to 40% with respect to the basic cycle). In [4], Jain et al. perform a complete energy, exergy, economic and environmental analysis on different configurations of cascade absorption/compression hybrid cycles. The findings demonstrate the feasibility and the promising potential of the technology in terms of reduction of operation costs, increase of thermodynamic performance of the system and reduction of CO_2 emissions.

In the adsorption field, instead, no actual studies exist on the combination with a compression unit. Adsorption chiller, if compared to absorption system, present some advantages, such as lower noise, no moving parts and the use of natural refrigerants such as water. In [5], van Der Pal et al. report the studies on a combined adsorption/vapour compression system for heating applications and in [6] a theoretical study is reported on a system where the same refrigerant (R134a) for both cycles is applied, resulting however in a very low performance of the adsorption unit.

In such a background, in the present paper, an experimental investigation of a cascade adsorption + compression hybrid cycle is reported. The cascade unit analysed is composed of an adsorption chiller, whose cold output is used for the cooling of the condenser of a R410A vapor compression unit. Target of the experimental campaign has been the verification of the benefits achievable with the cascade configuration for air conditioning applications. To this aim, the performance achieved has been compared with the theoretical one supplied by the manufacturer.

2. The analysed system

The schematic layout of the analysed system is shown in Figure 1. The system is made up by a commercial silica gel adsorption unit with 2 adsorbers working in counter-phase, with nominal power of 10 kW and nominal COP of 0.6. The system has a modularity feature, as to be used also when higher power are needed. For performance assessment, however, a single module has been tested.

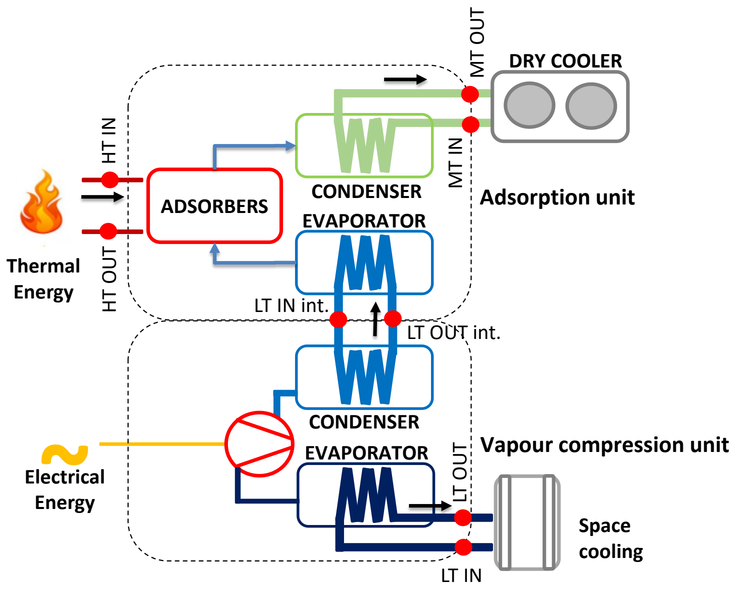

Figure 1: schematics of the analysed cascade system. Red dots indicate the position of the main temperature sensors.

The chilled water circuit of the adsorption unit is connected to the condenser of an OEM vapor compression chiller, employing R410a as refrigerant. The nominal power of the electric chiller is 10 kW as well. Both units are managed by a single controller, that includes the set-points, operating modes and allows a basic monitoring of the temperatures inside the system as well.

3. The testing bench

The testing bench used for the characterization of the hybrid system is located at "CENTROPROVE" of C.N.R. I.T.A.E. in Messina. A detailed description of the testing bench is given in [7]. It is mainly composed of a gas heater that is used to simulate the heat source, and an electric chiller, used to simulate the heat sink and the cooling load. The heater is connected to a 1500 litres storage, in order to guarantee constant inlet temperature to the hot water circuit of the chiller under testing. Medium temperature and low temperature sinks are simulated by a 1000 litres storage, inlet temperatures of the circuit are regulated by means of PID temperature controllers acting on motorised 3-way valves that allow mixing the inlet and outlet flow in order to maintain a constant inlet temperature. All of the circuits of the test bench are thermally insulated and equipped with the following sensors:

- Type "T" thermocouples with Class 1 tolerances for the measure of all the temperatures in the inlet/outlet pipes of every circuits and in the storages;
- Magnetic flow meters with 1% of reading accuracy for the measure of all the flow rates;
- Electric energy meter with Class 1 tolerances for the measure of electric input delivered to the chillers.

Variable speed pumps allow to control the Flow rates in all the circuits. A data acquisition and control system was realized by a specific software implemented in LabVIEW software; it allows the fully-automatic operation of the system and records all the measured parameters. A picture of the system connected to the testing bench is shown in Figure 2.

Figure 2: the system connected to the testing bench at CNR-ITAE.

4. Testing procedure and conditions

The procedure for a standard test is summarised in Figure 3 and mainly consists of two phases: after the aggregate is turned on, a "conditioning" of the overall system is realised, for a duration corresponding to 3 cycles of the adsorption chiller. Subsequently, the data logging is started, and an evaluation is realised for a duration corresponding to 5 cycles of the adsorption chiller. During this period, all the relevant parameters are recorded, i.e. the inlet and outlet temperatures of all the external and internal circuits, the pressure drops on the external circuits, the flow rates in all the external and internal circuits.

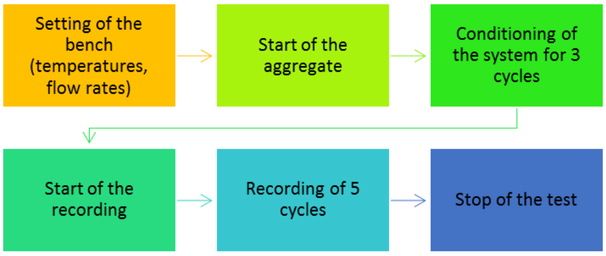

Figure 3: testing procedure.

Table 1: testing conditions

Parameter		Tested values
Driving temperature (HT)	[°C]	65, 75, 85, 95
Recooling temperature (MT)	[°C]	25, 27, 30, 33, 37, 40
Adsorption chiller cold water set-point	[°C]	17
Electric chiller cold water set-point	[°C]	7

For the examined case, the parameters varied for the analysis are summarised in Table 1. The nominal flow rates of the chillers in the cascade unit have been set for all tests. On the load side (chilled water circuit of electric chiller), simulation of a constant 10 kW thermal load has been considered, by defining an inlet temperature of the LT circuit of the electric chiller of 12°C.

Two main parameters have been used for the assessment of the performance of the system, namely the electric

COP of the system ($COP_{e,s}$) and the equivalent electric COP of the compression chiller ($COP_{e,c}$), calculated as follows.

- The electric COP of the system is the ratio between the overall cooling energy provided by the compression chiller during the test, and the overall electric consumption. This term takes into account the electric consumption of the compression chiller and all the pumps included in the cascade. It is calculated as:

$$COP_{e,s} = \frac{\int_0^{\tau_{test}} \dot{m}_{LT} \cdot c_p \cdot \left(T_{LT\_in} - T_{LT\_out}\right) \cdot d\tau}{\int_0^{\tau_{test}} \left(E_{chiller} + E_{pumps}\right) \cdot d\tau} \quad (1)$$

- The equivalent electric COP of the compression chiller is the ratio between the overall cooling effect produced by the compression chiller and its electric consumption:

$$COP_{e,c} = \frac{\int_0^{\tau_{test}} \dot{m}_{LT} \cdot c_p \cdot \left(T_{LT\_in} - T_{LT\_out}\right) \cdot d\tau}{\int_0^{\tau_{test}} \left(E_{chiller}\right) \cdot d\tau} \quad (2)$$

It is worth noticing that, in both cases, the heat input to the adsorption chiller has not been included in the calculation since the application of such a cascaded aggregate in presence of process waste heat (which is freely available) has been considered.

5. Results and discussion

In the following, the typical trends for a test are discussed, in order to give an overview of the operation of the system. In Figure 4, the temperatures recorded on the external and internal circuits of the cascade are shown. Regarding the high temperature circuit, looking at the outlet temperature, it is possible to clearly distinguish the different cycles of the adsorption chiller. Also the trend for the recooling (MT) temperature is that typical of the operation of an adsorption chiller, with the switch between the phases clearly marked by the peaks in the temperature.

Instead, the trends for the temperature of the chilled water from the adsorption system (LT IN int. and LT OUT int. in the picture) and the ones for the electric chiller (LT IN and LT OUT) are strictly connected. In fact, whenever the temperature in the LT external circuit arises, the electric chiller is started, thus determining an increase in the inlet LT temperature from the adsorption chiller, since the condensation heat of the electric chiller has to be compensated. The outlet from the electric chiller keeps to a stable value, with the 7/12°C temperatures maintained.

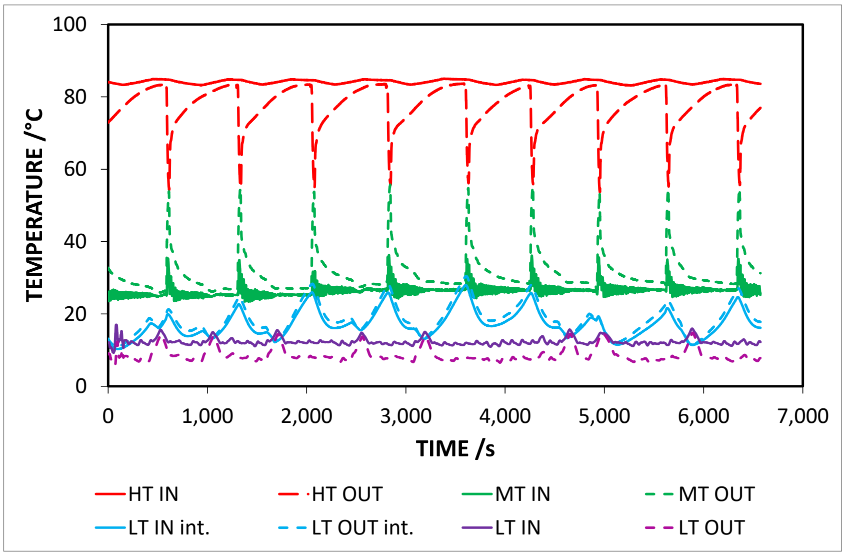

Figure 4: temperatures of the aggregate during a typical test.

In Figure 5, all the measured thermal powers and the electric power from the grid are plotted. The electric consumption of the system (in yellow in the picture) clearly indicates when the electric chiller is turned on or off. The thermal powers measured on the driving circuit and the recooling circuit of the adsorption chiller are consistent with its cyclic operation. However, the actual power measured on the chilled water circuit of the adsorption chiller (and indicated as LT int. in the picture) is not the actual cold produced by the adsorption chiller. As previously stated, what is actually measured in this internal loop is the difference between the actual power produced by the thermally-driven chiller and the condensation power of the electric chiller.

In Figure 6, the COP_e of the compression chiller is shown under different testing conditions, in terms of both driving temperature and recooling temperature. What is clearly shown is that the COP_e of the compression chiller can reach values up to 8 and that, even for higher recooling temperatures, it is possible to obtain a noticeable increase with respect of the values declared by the producer. More specifically, for driving temperatures of 95°C and 85°C, the COP_e of the system is almost doubled. Instead, when the driving temperature of the adsorption chiller is 65°C, the effect of the cascade chiller is marked only for recooling temperatures up to 32°C.

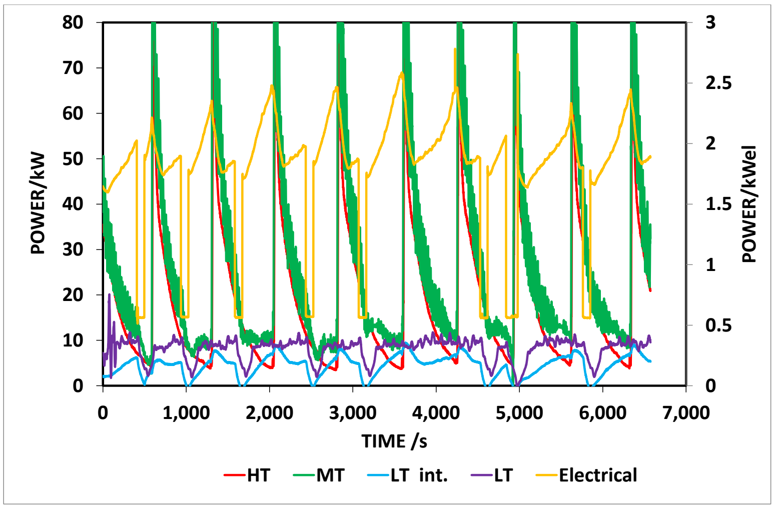

Figure 5: instant powers during a typical test.

Finally, in Figure 7, the COP_e of the entire system, including the electric consumption of the auxiliaries needed for the operation of the adsorption chiller, is shown for the various testing conditions. Even considering the effect of the thermal chiller, there is still a significant improvement with respect to the usage of a traditional chiller only. In particular, with driving temperatures of 95°C, COPs of 5.50 to 4 have been measured. Moreover, for lower condensation temperatures (25°C-30°C), that are characterised by a higher efficiency of the chillers, the effect of the auxiliaries becomes important and, for different driving temperatures, the EER of the system is almost constant.

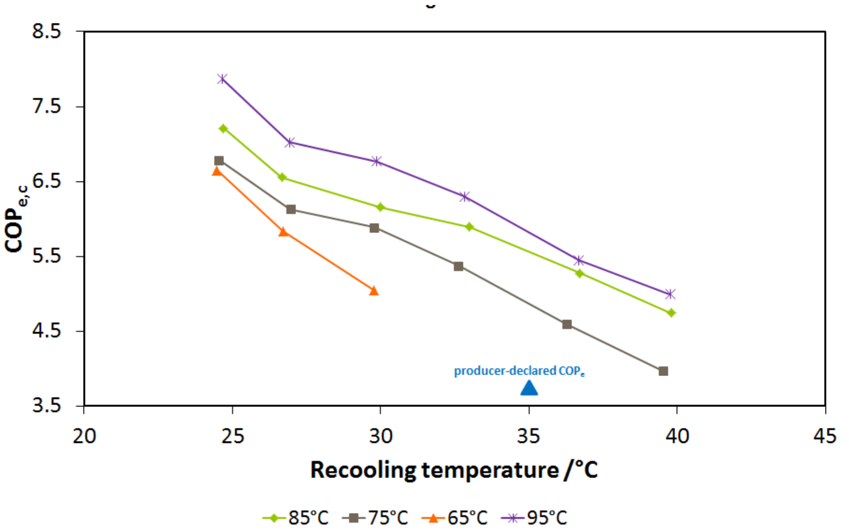

Figure 6: electric COP of the compression chiller.

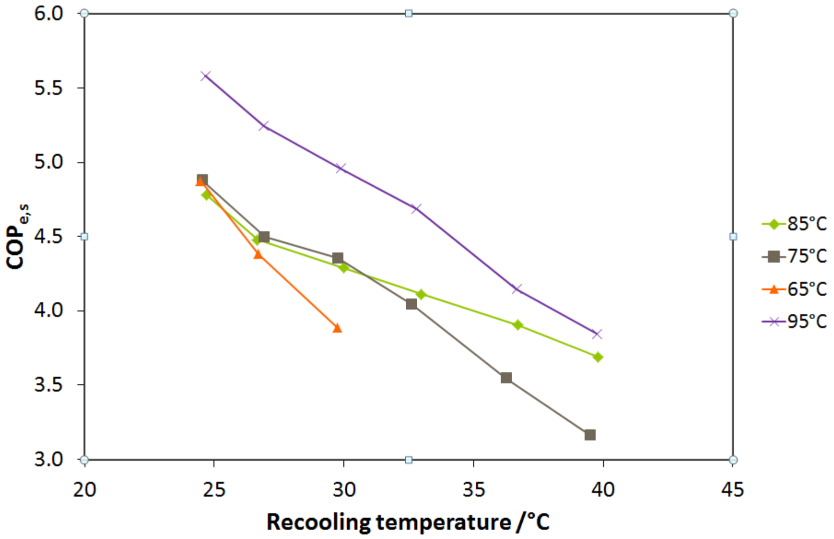

Figure 7: electric COP of the hybrid cascade system.

6. Conclusions

In the present paper, the results of an experimental campaign of a hybrid system made up of an adsorption chiller and an electric chiller are presented. The chillers are connected in series, as to form a cascade, with the evaporator of the adsorption chiller used to cool down the condenser of the electric chiller. The cascade system has been tested at "CENTROPROVE" of CNR-ITAE in Messina and the results have been reported. The hybrid chiller allows to reach electric COP for the compressor up to 8, while, when the energy consumption of the auxiliaries needed for the operation of the cascade are considered, overall values of electric COP up to 6.5 have been measured.

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