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Improvements of an unconventional desiccant air conditioning system based on experimental investigations

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ABSTRACT

Desiccant-based HVAC systems are nowadays a convenient alternative to conventional systems based on dehumidification by cooling, because they allow the reduction of equivalent CO_2 emissions, electric peak loads and black-outs, as well as energy savings, interesting payback periods in several cases, better indoor humidity control and air quality, separate control of thermal sensible and latent loads.

Their coupling with small scale natural gas-fired cogenerators is also suitable as thermal energy required for desiccant regeneration can be conveniently recovered from the microcogenerator.

In this paper, the main improvements of an innovative desiccant-based HVAC system, located in Southern Italy (Mediterranean climate), are presented. To this aim, three different desiccant system configurations are experimentally analysed, while a conventional HVAC system based on dehumidification by cooling is evaluated by means of numerical approach. Firstly, the primary energy savings (up to 20–25%) and the reductions of equivalent CO_2 emissions (up to 40–50%) of the desiccant systems compared to the conventional one are calculated when considering chillers with different energy efficiency ratio values. Successively, the above mentioned indices are evaluated as a function of the effectiveness of the heat exchanger and the cooling air humidifier installed in the proposed desiccant system configuration: primary energy savings up to 25–28% and reductions of equivalent CO_2 emissions up to 35–40% are obtained.

1. Introduction

Desiccant-based air conditioning systems are presently a valid alternative to traditional systems based on “dehumidification by cooling” (air dehumidification by means of cooling below the dew point) [1,2], as they can allow relevant advantages in terms of:

- reduction of reliance on grid electricity [3], electric peak loads and black-outs [4,5], as electricity requirement is reduced;
- energy savings and $CO_{2\text{-eq}}$ emission reductions [6–8], due to a more efficient process;
- interesting payback periods in several cases [9,10], thanks to the reduction of energy costs;
- better humidity control [11–13], thanks to separate control of sensible and latent loads;
- better indoor air quality (the use of desiccant material avoids the formation of condensed water on the cooling coils, so the presence of microorganisms is significantly reduced);
- a higher Energy Efficiency Ratio (EER) for the chiller in desiccant-based systems, because it has to handle only sensible loads, therefore it works at smaller temperature lifts;
- reduction in pollutant refrigerants' use [14], thanks to the lower size of the chiller in desiccant-based systems, and consequently to the lower refrigerant charge.

Presently, the main disadvantages of desiccant HVAC systems, compared to the conventional air conditioning systems, are the higher plant costs and the scarce knowledge of this technology.

The use of desiccant-based HVAC systems is typically referred to summer conditions, as air dehumidification is commonly needed in summer for climates with high or moderate humidity.

The air dehumidification is usually obtained through a rotary desiccant dehumidifier, also called desiccant wheel (DW), that meets the latent loads of the building. The desiccant material requires a suitable regeneration (or reactivation) by means of thermal energy. The building sensible thermal load is instead handled by means of a water cooling coil served by a vapour compression refrigerator, and/or by means of direct (DEC) or indirect (IEC) evaporative cooling, or by direct expansion evaporators of conventional or transcritical refrigeration cycles [15].

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Nomenclature

C	capacity rate (kW/K)
COP	coefficient of performance (–)
EER	Energy Efficiency Ratio (–)
FESR	Fuel Energy Saving Ratio (%)
P	power (kW)
RH	air relative humidity (%)
T	temperature (°C)
$\dot{V}$	volumetric air flow rate (m^3/s)

Greek symbols

$\Delta CO_{2\text{-eq}}$	avoided equivalent CO_2 emissions (%)
ε	effectiveness (–)
η	efficiency (–)
ω	air humidity ratio (g/kg)

Acronyms

AHU	Air Handling Unit
CS	conventional system
DCS	desiccant cooling system
DEC	direct evaporative cooling
DW	desiccant wheel
HC	heating coil
HEX	air-to-air heat exchanger
HVAC	heating ventilation and air conditioning
IEC	indirect evaporative cooling
LCA	Life Cycle Assessment
MCHP	Micro Combined Heat and Power

Subscripts

aux	auxiliaries
B	boiler
chil	chiller
cool	cooling
CS	conventional system
el	electric
grid	electric grid
HEX	heat exchanger
HUM	humidifier
MCHP	Micro Combined Heat and Power
min	minimum
p	primary
proc	process air
reg	regeneration air
th	thermal
us	user

Superscripts

g	related to gross electric efficiency or power

The required thermal energy for desiccant regeneration can be conveniently recovered from a small scale cogenerator (MCHP, Micro Combined Heat and Power), so a suitable coupling between microcogenerator and desiccant system can be considered [6–8].

Another important issue is related to the increasing requirement of summer cooling, usually only based on electric refrigerators. This demand is more frequent in climate zones with elevate sensible and latent loads [16,17] and often leads to electric peak loads and black-outs [4,5]. In order to reduce these problems, one way concerns the appropriate use of renewable energy [18–20]. Another way consists in the appropriate use of cogeneration systems. In fact, heating, cooling and electric end-user demand can be opportunely satisfied by small scale natural gas-fired cogeneration systems coupled to electric generators, heat pumps, desiccant wheels, etc.

The achievable energy savings and emission reductions by means of desiccant HVAC systems can significantly contribute to the implementation of nearly and Net Zero Energy Buildings [21].

Some works in literature investigated unconventional arrangements of desiccant cooling systems (DCS). In [15], a desiccant dehumidification system driven by low grade (<80 °C) waste heat was investigated on the basis of experimental data. The air flow at the outlet of the gas cooler of a transcritical cycle is forced through a desiccant wheel for regeneration purposes. The hybrid transcritical refrigerator-desiccant system improved COP by about 77% compared to a classical transcritical cycle. The environmental analysis was performed in terms of TEWI (Total Equivalent Warming Impact): the classical transcritical cycle has higher (60%) greenhouse gas emissions.

Hürdoğan et al. [22] described a new DCS, arranged with three air channels and with several rotary heat exchangers. Part of the sensible cooling of the process air was carried out by means of a cooling coil fed by an electric chiller. The initially recorded experimental data indicated that only 15% of cooling energy was provided by the electric chiller, and a reduction of the regeneration heating requirement of about 35% was achieved through rotary heat exchangers.

In [23], the same novel DCS was investigated, to evaluate the major inefficiencies of the components by an exergetic analysis. Obviously apart from the electric heater, the major irreversibility results from the dehumidifier, fresh air fan and evaporative cooler. Furthermore, the exergy efficiency of the entire experimental unit was 40.7% at a reference temperature of 15 °C.

In [24], three novel desiccant evaporative cooling system configurations were simulated and compared with a conventional system under a wide range of ambient air temperature (30–40 °C) and humidity ratio (10–20 g/kg). Energetic analysis revealed that configuration I has the highest cooling capacity, while configuration III has the highest energy performance, as it allows an increase of thermal COP of about 50% compared to the conventional system. Exergetic efficiency of configuration III is 54% higher on average than the conventional system.

To the authors' knowledge, there are no papers in literature that highlight the technical merits of hybrid DCS with three air channels compared to commonly used layouts. Furthermore, no studies are available that investigate the effect of chiller energy efficiency and use of a third air flow on the overall performance of the DCS. This knowledge gap is filled by this paper, where an unconventional desiccant-based air conditioning system (Fig. 1) is analysed and improved by means of an experimental investigation. The system is characterised by the following main devices: an Air Handling Unit (AHU) equipped with a desiccant wheel; a small scale cogenerator (MCHP) and an electric chiller. The microcogenerator provides electricity for the refrigerator and the auxiliaries, as well as thermal energy for the desiccant regeneration. A traditional natural gas boiler can also be activated, when the thermal energy from the MCHP is not sufficient for the complete desiccant regeneration.

First of all, the advantage related to the choice of an electric refrigerator, instead of DEC, to balance the sensible thermal load is clarified in Section 2.2.

Moreover, in this paper a configuration of the desiccant-based AHU different from that typically investigated in literature, is considered. In fact, a third air flow (the cooling air) has been added to