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Research Paper

Field testing of a novel hybrid solar assisted desiccant evaporative cooling system coupled with a vapour compression heat pump

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HIGHLIGHTS

- The experimental operation of a solar driven hybrid DEC system is presented.
- *In situ* monitoring data are analysed and compared to the system's expected performance.
- Drawbacks affecting the system's performance are explained.
- Fine-tuning of the control and maintenance strategy of the main system components is suggested.

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ABSTRACT

The aim of this paper is to report on a two-year operational experience with a solar driven desiccant and evaporative cooling (SDEC) system coupled with a vapour compression heat pump. The main objectives are to analyse the benefits and drawbacks of this innovative hybrid SDEC system, to compare the monitoring results against the expected theoretical ones, and to assess the system's performance with respect to a reference air handling unit. The comparison focuses on the summer key operation modes using Primary Energy Ratio (PER) as indicator of the entire system performance. The results of the detailed analysis lead to the following conclusions: the specific design of the hybrid SDEC leads to high air quality, simpler control process and low electricity consumption for partial load conditions. The monitoring results show a summer mode PER 20% lower than expected due to underperformance of the desiccant wheel. Nevertheless, this innovative system is still very efficient as its PER is twice as high as the one of the considered reference system. Lastly, suggestions for optimization of the existing system through the fine-tuning of the control strategy of its main components are presented.

1. Introduction

Reducing energy consumption and eliminating wastage are among the main goals of most of non-developing countries. Energy efficiency is decisive for competitiveness, security of supply and for meeting the commitments on climate change made under the Kyoto protocol. Buildings are responsible for roughly 40% of energy consumption and 36% of CO2 emissions in the EU, thus the EU has introduced legislation to ensure that they consume less energy. With the adoption of the recast EPBD in 2010 (Directive 2010/31/EU), EU Member States faced new tough challenges. Among them, moving towards new and retrofitted nearly-zero energy buildings by 2020 (2018 in the case of Public buildings), and the application of a cost-optimal methodology for setting minimum requirements for both the envelope and the technical systems. The so-called DEC (Desiccant Evaporative Cooling) is an air-conditioning system based on the use of a desiccant process combined with an evaporative cooling process [1]. A desiccant process consists in the absorption or adsorption of water vapour by a substance, which can be natural or synthetic. The driving force is the water vapour pressure difference between the surroundings moist air and the desiccant surface. Desiccant materials are primarily classified according to their states, liquid or solid, at operating condition. Generally, liquid desiccants are characterized by flexibility and lower regeneration temperature and pressure drop on air side. On the other hand, solid desiccants are compact and do not involve corrosion issues. The most used desiccant materials are: lithium chloride, triethylene glycol, silica gels, aluminium silicates (zeolites or molecular sieves), aluminium oxides, lithium bromide solution and lithium chloride solution with water. Moreover, tailored desiccant substance can be engineered like ionic liquid. Desiccant

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Nomenclature

G	solar irradiation, W/m^2
h	enthalpy, kJ kg^{-1}
$\dot{m}$	mass flow rate, kg s^{-1}
$\dot{P}$	electrical power, kW
$\dot{Q}$	heat transfer rate, kW
RH	relative humidity, –
T	temperature, °C
t	time, min
x	humidity by mass in the moist air, g_w kg_{DA}^{-1}

Greek symbols

Δ	difference
η_T	temperature efficiency

Subscripts

DA	dry air
e	electrical
lat	latent
ref	reference system
reg	DW regeneration
s	sensible
a	air
w	water
th	thermal
ufl	useful

Abbreviations

AC	active cooling mode
AH	active heating mode
AHU	air handling unit
AS-HP	electrical air source heat pump
B	coils
BLR	condensing gas boiler
BP	bypass
BUH	back-up heater
BUHE	back up heat exchanger
c.n.	case number
COP	coefficient of performance (cooling mode)
CV	control valve
d	day
DEC	desiccant evaporative cooling
DH	dehumidification mode
DW	desiccant wheel
DV	diverter valve
EA	External air (supply stream)
FC	free cooling mode
HP	heat pump
HR	heat recovery mode
hr	yearly hour
HX	static air heat exchanger
HU	humidifier
IEC	indirect evaporative cooling mode
m	month
OA	Outside air (regeneration stream)
P	pump
PEF	primary energy factor
PER	primary energy ratio
PI	proportional-integral control
RA	Return air
RPH	rotation per hour
SA	Supply air
SDEC	solar desiccant evaporative cooling
SF	solar fraction
ST	solar thermal field
VE	fan
WW-HP	electrical water-water heat pump
y	year

materials can be used in several technological arrangements. In the air-conditioning sector the most common use of desiccant materials is as coatings of rotating wheels, usually called desiccant wheels (or rotors). The desiccant wheel rotates slowly (order of magnitude 10 RPH) in a special containment structure and it is divided into two areas. The first area is used to adsorb the water vapour of process air, and the other is used to ensure a continuously operating cycle regenerating the rotor by removing the water uptake through an auxiliary hotter air flow (regeneration air). An issue of this arrangement is the carryover, which means that a transfer of air containing moisture or other contaminants from the regeneration to the process side of the wheel could occur, either by seal leakage or wheel rotation. In order to limit this effect, a purge section can be implemented, which acts as an extension of the exhaust air duct into the supply air duct. In the scientific literature, many studies deal with the mathematical modelling of the complex physical phenomena that occur in a desiccant wheel [2,3,4,5,6]. In the last few years many research works have dealt with solid DEC cycle for air-conditioning [1,7,8,9]. The reason is that a DEC cycle could be activated by low temperature heat like waste heat and solar heat. Under this condition a DEC cycle could become competitive and cost effective. An example is reported by Henning [10], which has described a DEC system installed at the building of the chamber of trade and commerce in Freiburg/Germany, using solar air collector for the desiccant wheel regeneration. Starting from standard solid DEC cycle, several configurations have been investigated in the scientific literature. The most common upgrades of the standard solid DEC cycle are: (a) increase the sensible cooling capacity of the system adding a post-cooling coil at the end of the supply air duct; (b) increase the dehumidification capacity adding a cooling coil before the desiccant wheel on the supply air duct; (c) increase the dehumidification capacity adding a second desiccant wheel heating coil pair in series to the first one. As previously mentioned, a DEC cycle cannot be compared with a reference system without the specification of the heating and cooling coils energy sources. For example, Henning et al. [11] has proposed a tri-generation system based on a solid DEC cycle, a co-generation system and an electric chiller. Specifically, the co-generation system drives both the DEC cycle regeneration and an electric chiller that feeds two additional cooling coils in the DEC cycle (one for pre-dehumidification and one for post-cooling). Another interesting configuration has been presented by Mazzei et al. [12] and further investigated by Beccali et al. [13,14] and Aprile et al. [15]. The basic concept is to use a solid DEC cycle with a post-cooling coil and a water-water chiller. As this configuration needs at the same time cooling power and heating power, the chiller heat source is the supply air and the heat sink is the regeneration air. Due to the maximum temperature levels limitation of the electric heat pump, both Beccali and Aprile have used the chiller rejected heat only for a pre-heating phase of the regeneration air, adding a second heating system in series. Frein et al. [16] have defined and applied a continuous monitoring methodology on the system presented by Aprile et al. [15], including transition and partial load behaviour, in order to assess the