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A continuous commissioning analysis and its application to a new installed solar driven DEC system coupled with heat pump

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Abstract

The aim of this paper is to define and implement a continuous commissioning methodology that can be effectively applied to a solar driven desiccant and evaporative cooling (DEC) system. The objective is to assess the energy performance of the system's components and identify possible operation faults. The methodology consists in the breakdown and analysis of the DEC into sub-systems; for each of them a simplified dynamic mathematical model based on experimental data has been developed. A possible fault is detected when the difference between the theoretical and measured performances is higher than the accuracy of the methodology. The proposed methodology has been successfully implemented for a hybrid solar DEC system comprising a non-conventional DEC air-handling unit, a solar thermal system and an electrical heat pump.

The results of the methodology's application to the first experimental data of summer 2014 lead to the following conclusions: the solar sub-system operated as expected whereas the heat pump and the desiccant rotor did not. In particular, the electrical heat pump has a higher cooling capacity than the one predicted at partial load but with a similar COP value, this deviation is mainly due to the assumed partial load performance coefficient. The desiccant rotor presents a much lower performance than the one expected. However, the rotor inefficiency is difficult to highlight due to the high measurement uncertainties on the air side.

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Keywords: Desiccant evaporative cooling; Solar cooling; Contiuous commissioning analysis.

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1. Introduction

In the last decade, several experiences have been gained with desiccant and evaporative cooling (DEC) systems, including solar driven plants and hybrid configurations – i.e., where electrical driven heat pumps provide active heat recovery between return and supply air [1-2]. Among them, an hybrid solar DEC system has been designed and installed in 2013 [3]. In this novel concepts, the theoretical energy performances is often hardly achieved without the continuous monitoring and analysis of the correct system's components operation. The latter mainly due to the

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complexity of the control strategies linked with a larger number of components than in standard in AHU. Thus, the aim of this paper is to define and implement a “continuous commissioning methodology” that can be effectively applied to a solar driven DEC system in order to assess the energy performance of the system components and identify possible faults throughout the system operating life.

Nomenclature

DEC	Desiccant Evaporative Cooling	
DW	Desiccant wheel	
HP	Heat pump	
HU	Humidifier	
AHU	Air Handling Unit	
EHP	Electric heat pump	
RA	Return air	
SA	Supply air	
OA	Outside air	
EA	Exhaust air	
VE	Fan	
P	Pump	
COP	Coefficient of performance	(-)
T_a	External temperature	(°C)
G	total irradiance	(W)
T	Liquid temperature sensor	(°C)
M_w	Liquid flow rate sensor	(kg/s)
M_a	Air flow rate sensor	(kg/s)
T_{CL}	Collector loop mean temperature	(°C)
T_{TSL}	Typical solar load temperature, in this case is the low temperature of the solar tank (Tw5)	(°C)
E_{gain}	Produced solar energy	(kWh)
E_{B1}	Cooling energy at cooling coil (B1)	(kWh)
E_{elec}	Heat pump electrical consumption	(kWh)
E_{Lat}	Latent energy over the DW	(kWh)
E_{Sens}	Sensible energy over the DW	(kWh)
$\underline{\omega}$	Moist air water content	(kgw/kgDA)
ε_w	weighted error	(-)

Subscripts

a	Moist air
w	Water
DA	Dry Air
sim	Output value from simulation
real	Output value from monitoring data
nom	Nominal
max	Maximum
min	Minimum

2. Continuous commissioning methodology

In general, the complete breakdown or the serious malfunctioning of a plant component is relatively easy to detect during the commissioning, as the system will hardly be able to respect the target set points (e.g. temperature and humidity of the supply air) in nominal conditions. On the contrary, an overall performance reduction of the plant could not be easily identified, as the system components can deviate from their expected performance without compromising the plant ability to cover the thermal load. The continuous commissioning methodology presented below should help to detect the performance deviation of specific components.

2.1. Methodology

The proposed methodology consists in the comparison of the actual plant performance with the calculated one assuming the components' nominal performance. A modelling process is needed to assess the plant behavior in nominal conditions. Proper sub-systems shall be isolated and their input-output response modelled. This could be done by physical and empirical approaches.

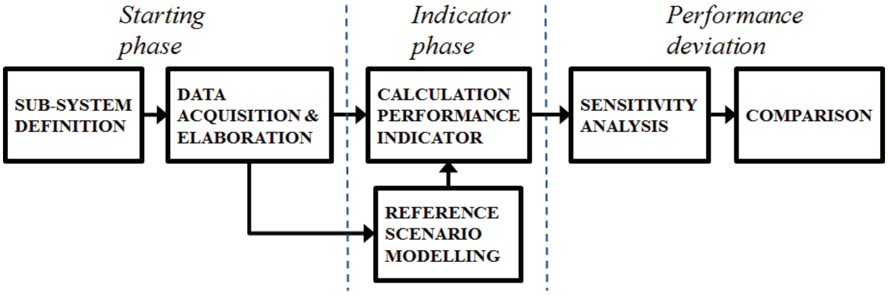

Fig. 1. Continuous methodology process

The logical flow, see Fig.1, starts by the definition of the sub-systems in terms of components to model, performance indicators to analyze, and monitoring sensors to install. Subsequently, the data acquisition and elaboration is performed for a period, sufficiently long to get consistent results. At given intervals (e.g. day, week, month), the calculation of the performance indicators for the real plant and the reference one can be done. The performance indicators for the real plant can be directly calculated from the measurements data, whereas those of the ideal one are based on suitable numerical models built on components characteristics. Finally, performance deviations can be assessed. It is of primary importance to evaluate the accuracy of the performance indicators for both the real and reference scenario. This will be presented in more details further.

2.2. Uncertainty cone

To detect a possible fault, the deviation between the real plant and its model should not come from measurement errors and thus the uncertainty of the measurements should be considered (see Table 1).

Table 1. – Measurement accuracies for the investigated DEC plant.

Measurement	Unit	Accuracy	Source
Air flow rate	m^3/h	±2%	Data Sheet
Water flow rate	m^3/h	±5%	Empirical Measurement
Air temperature	°C	$\pm(0.3+0.005\cdot T)$°C	Class B EN 60751
Water temperature	°C	$\pm(0.15+0.002\cdot T)$°C	Class A EN 60751
Relative humidity	UR%	±2%	Data Sheet
Irradiation	W/m^2	±5%	Class 1 ISO 9060
Electrical Counter	kW	±5%	Data Sheet

The propagation analysis could be carried out using the minimum-maximum value approach. The variation of each measured input within the accuracy range leads to an increase or decrease of the derived performance indicators. Thus, the suitable combination of these input uncertainties will provide maximum and minimum values of each indicator. Once this methodology is applied over a large number of evaluation time steps (e.g. day, week), it is possible to identify the min and the max functions for both, the real and ideal cases. The latter using a polynomial fitting of the points previously calculated (see Fig.2.a).

It shall be noticed that the minimum-maximum value approach is a conservative method that provides large deviations. It would be more accurate to do a statistical evaluation of the errors, e.g. by the Monte Carlo approach. Nevertheless, computational time can be an issue for the simulated plant. Due to this, the minimum-maximum approach was preferred.

By combining minimum and maximum deviations for the plant model and the real plant, the uncertainty cone related to a given performance indicator (e.g. daily energy gain of the solar plant) can be derived (see Fig. 2.b). An error is detected when a performance point (whose x-y coordinates are related to the real plant and the model, respectively) falls outside the cone.

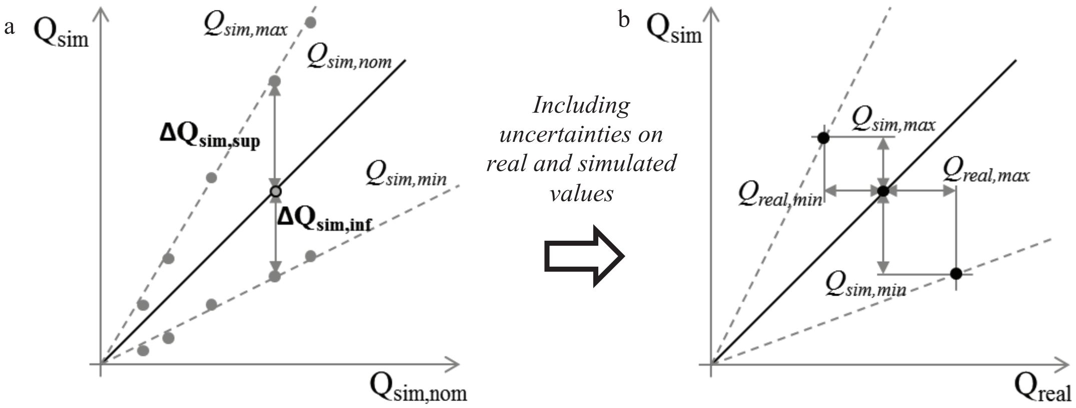

Fig. 2. (a) Min Max deviation functions according to central value and (b) uncertainty cone.

3. Case study description

The previous methodology has been applied to the case of a solar driven DEC system coupled with an electrical heat pump. A summary of the plant characteristics is presented in the following section, as well as the identified sub-systems according to the aforementioned continuous commissioning methodology.

3.1. Plant description and control strategy

The installation being studied is a solar driven air conditioning plant, which combines a solar system with a desiccant and evaporative cooling air-handling unit and an electrical heat pump. The system description and the theoretical energy savings of this system have been assessed in [3]. The plant is intended to supply primary air to a dormitory in Milan (Italy). Focusing on the summer mode, the controller's goal is to dehumidify the supply fresh air (below 9.5 g/kg) and maintain the temperature within a neutral range (20÷24 °C). In summer, the heat pump cools supply air and pre-heats regeneration air when dehumidification is needed, whereas the rest of the regeneration process is done through solar energy (see Fig. 3). The state machine controller, developed through extensive simulations in [3], has been completed with safety controls and implemented into the real plant.

3.2. Sub-systems

This specific chapter describes the three sub-systems selected in the investigated plant. For each of them, the monitored inputs, the model parameters, the specific indicators and a brief description of the model are given.

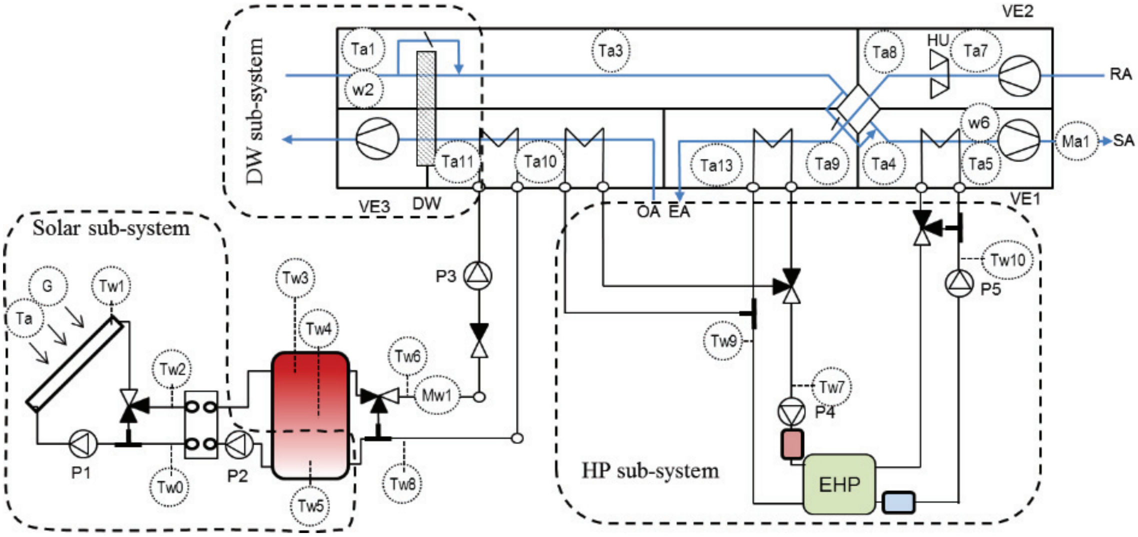

Fig. 3. Identified sub-systems.

- Solar sub-system

The solar sub-system is composed of all the primary loop components including the heat exchanger. The performance indicator of the solar sub-system is the solar gain provided to the tank, E_{gain}, see Fig.4. A single node differential equation has been implemented, based on the mathematical model developed in [4].

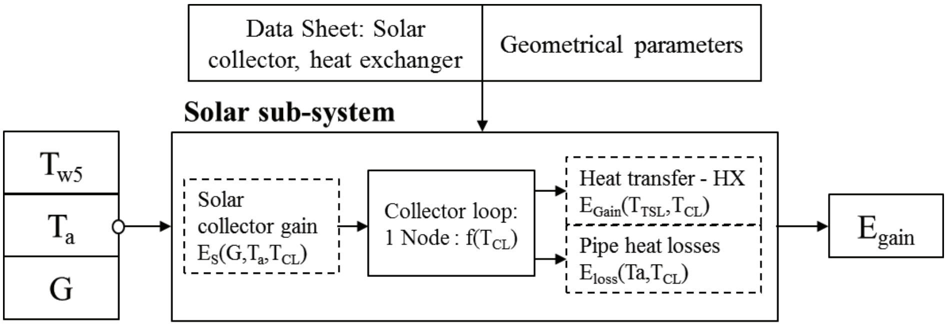

Fig. 4. Solar sub-system

- Heat pump sub-system

The heat pump sub-system (Fig. 3 and 5) performance indicator is the cooling energy provided to the air-handling unit and the electrical energy consumption. The heat pump is water cooled, reversible, and can modulate on two capacity steps. The mathematical model consists in a couple of algebraic equations, one for cooling power and the other for electricity consumption, identified in a previous work [3]. It is a grey box model that uses the nominal behavior of the two parallel compressors according to the feed water temperatures at evaporator and condenser combined with the energy balances on the evaporator and condenser loops. The behavior at partial load (i.e., only one compressor on), is declared by the manufacturer as 50% of the full load performance.

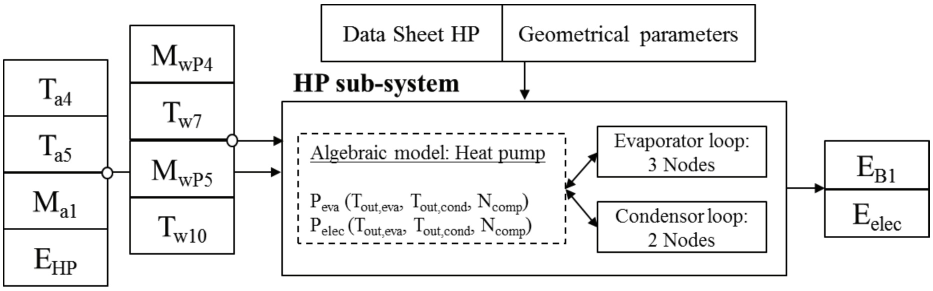

Fig. 5. Heat pump sub-system

- Desiccant Wheel sub-system

The rotor sub-system (Fig. 3 and 6) analyses the sensible and latent heat transfer of the desiccant wheel. For this specific sub-system, the choice of the reference model is a strong issue, as information on manufacturer's data sheets are not sufficient to get reliable models. A mathematical model has been developed [5], along with a fast computational method [6], and calibrated on a desiccant wheel similar to the one used in our plant. Regression coefficients are derived from this model to get simple algebraic equations, presented in [3], in the range of temperature and humidity of interest for the application.

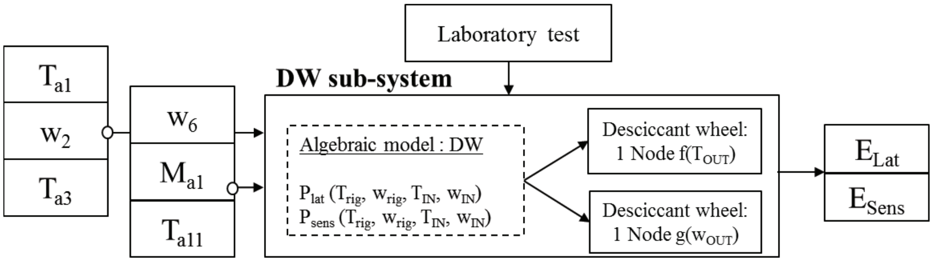

Fig. 6. Desiccant Wheel sub-system

4. Results and Discussions

The continuous commissioning analysis proposed in this paper has been applied to the aforementioned case study for the time period from the 1st of June to the 31st of august 2014. The main results presented on two time scales follow: whole period and daily period (19th of July with a data resolution of 10 minutes). In the daily charts, the red points represent the points outside of the uncertainty cones, the green point represents the 19th of July. For each of them the weighted error function is calculated as:

$$\bar{\varepsilon}_{\mathrm{w}} = \frac{\sum_i \varepsilon_i \times Q_{sim,i}}{\sum_i Q_{sim,i}} \text{with } \forall i, \qquad \varepsilon_{\mathrm{i}} = \frac{\left|Q_{sim,i} - Q_{real,i}\right|}{Q_{real,i}} \tag{1}$$

4.1. Solar sub-system

The comparison between the expected and measured daily solar gain is presented in Fig. 7b. The result shows a high matching level (weighted error equals 3.6%) as almost all points are near the optimum line within the uncertainty range. For the higher detail level presented in Fig. 1a, the sub-system operations are still in accordance with the model prediction. The outputs analysis shows a good accuracy of the selected modelling method [4], for whom the heat demand is a function only of the bottom temperature of the solar tank.

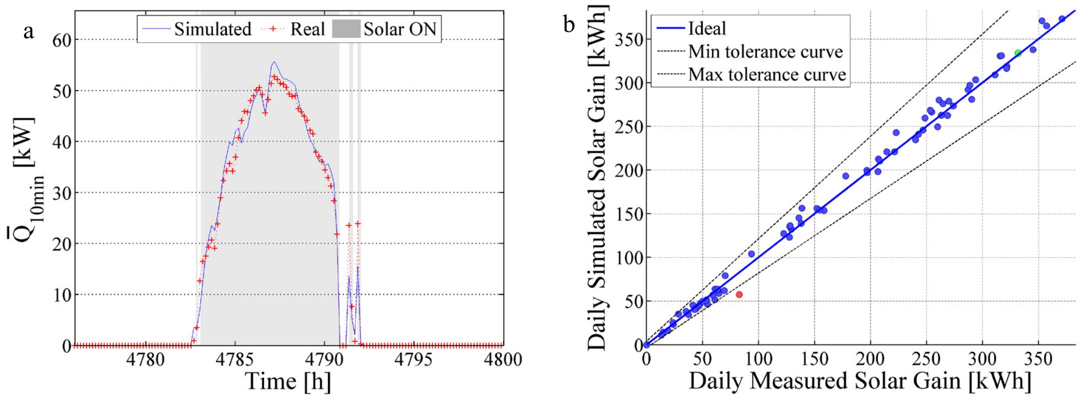

Fig. 7. Net Solar energy: (a) daily result, 19th July 2014; (b) summer 2014 result for solar sub-system.

4.2. Heat pump sub-system

The daily analysis result (Fig. 8b) shows that the measured cooling energy delivered to supply air by the heat pump is always comprised in the uncertainty boundaries. However, the measured cooling generated is always higher than the expected one (weighted error of 12%). The detailed analysis (Fig.8a) allows to detect the higher cooling load provided by the real sub-system during the steady operation with one compressor on. In contrast, it is possible to see the very good match between real and expected load at full capacity (two compressors on).

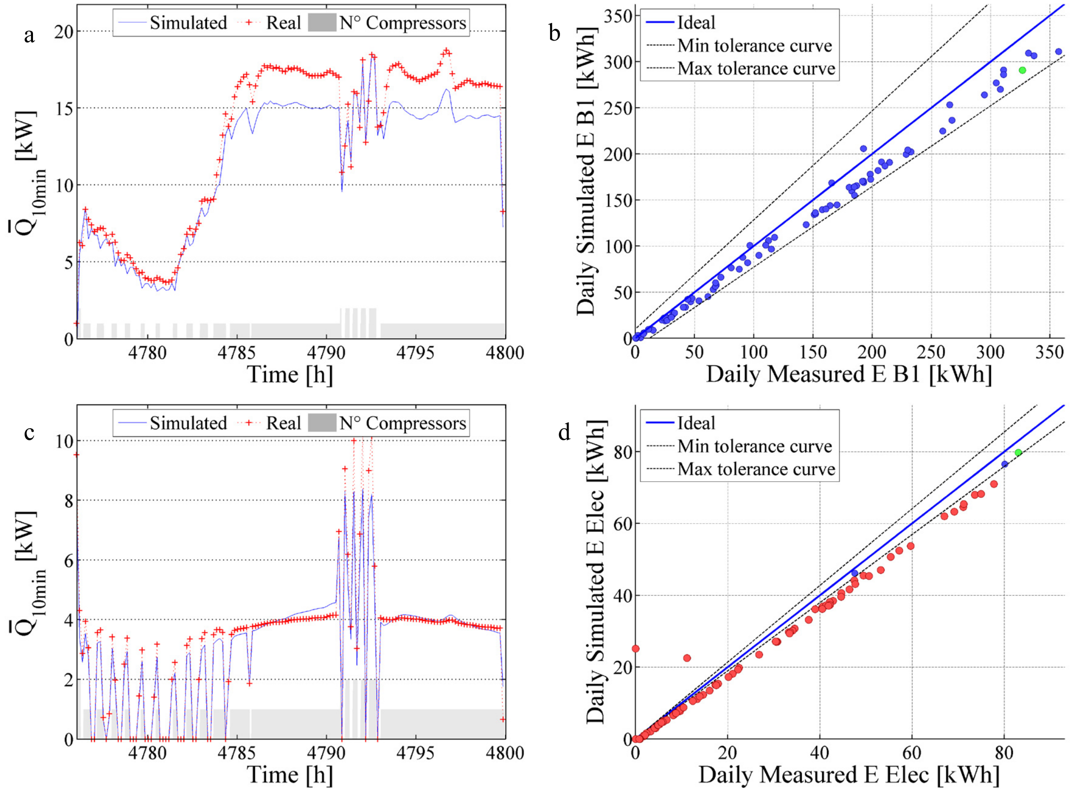

Fig. 8.Cooling energy: (a) daily result, 19th July 2014; (b) summer 2014 result for heat pump sub-system.
Electrical energy: (c) daily result, 19th July 2014; (d) summer 2014 result for heat pump sub-system.

The real electrical consumption (Fig.8d) appears to be always higher than expected, as the points are out of the uncertainty cone, with a weighted error equals to 12%. The single-day result (Fig.8c) shows the greater consumption in the cases of one and two compressors active during non-steady state operation, approximatively 6% higher, whereas this error becomes negligible during steady state operation.

During the partial load operation (i.e. one compressor active), the ideal cooling capacity is under-estimated but a similar daily trend (Fig.9.a), probably due to the performance improvement of the evaporator and condenser heat exchangers. In fact, by using 57% of nominal load instead of the 50% from the data sheet, the matching is improved significantly, as weighted error is reduced to 3.4%.

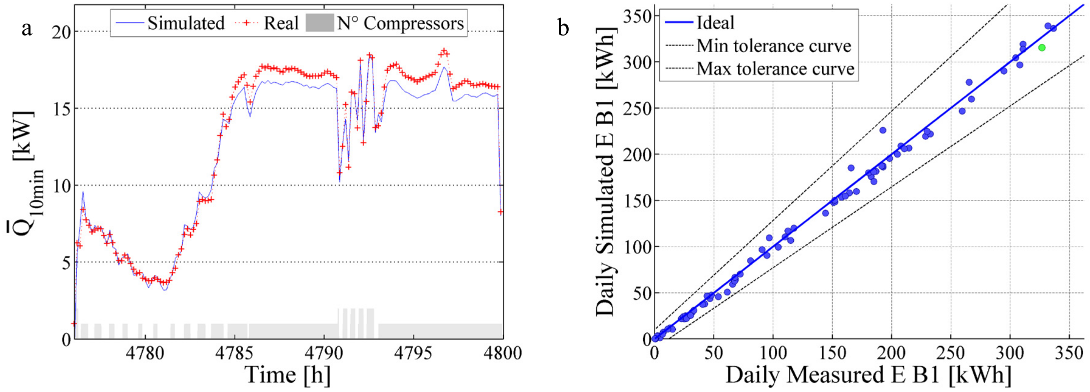

Fig. 9.Cooling energy with partial load coefficient 57%: (a) daily result, 19thJuly 2014; (b) summer 2014 result for heat pump sub-system.

4.3. Desiccant wheel sub-system

The real daily latent energy (Fig. 10b) is much lower than the expected one, with a weighted error equal to 29%. The comparison response is positive because of the large amplitude of the uncertainty range. This behavior is reflected in the detailed analysis (Fig. 10a), where the real dehumidification is always under the predicted one.

Both in the daily (Fig. 10d) and in the detailed analysis (Fig. 10c), the sensible behavior appears to be more accurate (weighted error 22%) but it is possible to notice the higher heating of the supply air caused by the real component.

The result presents an important under performance behavior of the installed wheel according to the laboratory one, caused by a lower dehumidification capacity and by a higher sensible heating of the supply air stream. This large deviation could be due to large inaccuracy of air measurement sensors or/and the use of mathematical model calibrated on a different desiccant wheel. The lack in technical information, due to deficiency in standard procedures for manufacturer’s performance data, does not allow applying an accurate continuous commissioning methodology but gives a good performance trend of the sub-system.

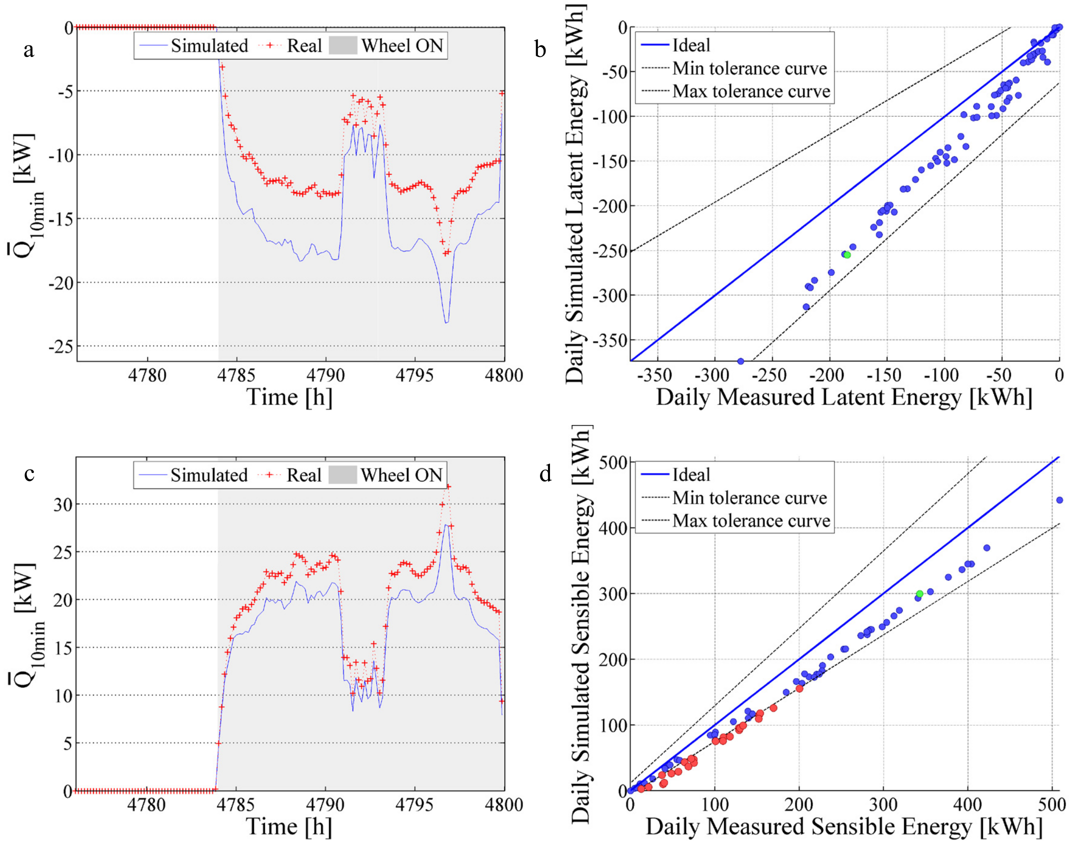

Fig. 10. Latent Energy: (a) daily result, 19th July 2014; (b) summer 2014 result for rotor sub-system.
Sensible energy: (c) daily result, 19th July 2014; (d) summer 2014 result for rotor sub-system.

5. Conclusion and future works

A continuous commissioning procedure has been defined and successfully implemented for a hybrid solar DEC system. The procedure, made by three main phases, allowed analyzing the operation of single sub-systems, through a comparison between real monitoring data and a defined ideal model considering measurement uncertainties. The results of the methodology's application to the first experimental data of summer 2014 allowed the following conclusions: the solar sub-system operated almost as the ideal one whereas the heat pump and the desiccant rotor have a larger deviation. In particular, the electrical heat pump has a higher cooling power capacity than the one predicted at partial load but with higher electrical consumption. Moreover, the desiccant rotor presents a much lower performance than the ideal condition due to: the measurement issues on the air flow; the lack of certifications and performance behaviors. However, the rotor inefficiency is included in the uncertainty range, and for the heat pump, a specific analysis of the partial load conditions has to be implemented, as a small change in its partial performance (57% of nominal load instead of the 50% from the data sheet) leads to correct results. This continuous commissioning methodology allows detecting some performance reductions that simple setpoint comparison would not.

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