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Quality level assessment of sorption chillers installed in solar cooling plants

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Abstract

The use of reliable, representative and reproducible data for the assessment of the quality level of HVAC systems and components on seasonal basis is crucial especially in view of the obligation of energy labelling, which is due by September 2015, and of the market surveillance.

An analysis on the current normative framework dedicated to sorption chiller has revealed that no exhaustive references for sorption technologies and applications exist. Therefore, two test procedures aimed at the mapping of performances of sorption chillers at full and part load have been developed. The procedures developed take into account also different machines operating modes (i.e. continuous and discontinuous). A first attempt of validation of the test procedures has been carried out and here presented.

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1. Introduction

In the last years, the European commission has pushed the selling of high-energy efficient products by issuing directives (*Eco-design and Eco-label Directives* [1], [2]) prescribing the minimum energy efficiency requirements for class of products as well as the indications for their labelling [3]. This has induced stakeholders (sector industry) and private organizations to develop, in parallel, voluntary third-party certification schemes with the aim of demonstrating that a specific product not only conforms to the relevant dedicate European standard, but fulfills further and more restrictive quality requirements. This has occurred especially in those sectors, like the HVAC

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sector, where the necessity to accelerate the standardization process and to make a sort of market surveillance through the affixing of certified energy labels was more pressing [4].

Also the solar thermal industry has developed its own certification scheme, the Solar Keymark [5], with the intent of reducing the trade barriers by promoting the use of high quality solar thermal products and to overcome normative lacks becoming an authoritative mark proving the energy consumption levels.

Within this context, the use of reliable, representative and reproducible performance data for the assessment, on seasonal basis, of the quality level of solar systems and components as well as the definition of the procedures to obtain them, play a crucial role.

An analysis on the current normative framework dedicated to solar cooling systems and, in particular, to sorption chillers, has revealed that, even if this technology has reached in the last years an increased level of development both in terms of components and of control strategies - new chillers, specifically intended for small-sized and medium-sized systems, have been commercialised as well as solar "kits" [6] -, no exhaustive and coherent references for their assessment exist. Therefore, the definition of a reference standard for sorption chillers is needed.

With this regard, in the subtask A1 of the project Task 48 [7], "*Quality Assurance & Support Measures for Solar Cooling*", promoted by IEA-SHC, two test procedures aimed at the "mapping" of the chiller performances at full load and at partial load and able to provide specific provisions on the basis of their operation (i.e. continuous and discontinuous) have been developed. The main expected result is to provide reliable data to be used as input for calculation methods for the seasonal performance evaluation of the chillers, like the BIN METHOD, or as input for the development of numerical models able to simulate their behaviour on annual basis within specific boundaries.

The present paper intends to illustrate the most relevant parts of the developed procedures and to present the results obtained from the first attempts of their validation.

Nomenclature

Continuous operation	Chiller's operation in which the four phases (i.e. desorption, condensation, evaporation, absorption) are processed continuously
Discontinuous operation	Chiller's operation in which the four phases (i.e. desorption, condensation, evaporation, absorption) are periodically shift among the internal components generating a cyclic functioning
Calculation cycle	Period between four consecutive swaps, i.e. shifts of the four (or couple of) phase among the internal components
EER_{th}	Thermal Energy Efficiency Ratio [kW/kW]
EER_{el}	Electrical Energy Efficiency Ratio [kW/kW]
T_in_GEN/ T_ GEN	Inlet temperature at the generator [°C]
T_out_GEN	Outlet temperature at the generator [°C]
T_in_COND/ Tcond/abs	Inlet temperature at the condenser/absorber [°C]
T_in_EVA	Inlet temperature at the evaporator [°C]
T_out_EVA	Outlet temperature at the evaporator [°C]
Flow_GEN	Flow rate at the generator [m^3/h]
AVG_Flow_GEN	Average of the generator's flow rate over the test period [m^3/h]
Criteria_STDEV_ Flow_GEN	Criteria for establishing the machine's stationary expressed in terms of permissible standard deviation of the generator's flow rate over the test period [m^3/h]
STDEV_ Flow_GEN	Standard deviation of the generator's flow rate over the test period [m^3/h]

2. Approach

For the drafting of the two test procedures, a preliminary study on the existing testing protocols having in the "scope" the procedures for the performance assessment of sorption chillers or appliances belonging to the same class of products (e.g. gas fired and electrically driven chillers and heat pumps) has been carried out. Such study has covered a number of standards (ISO, CEN, ANSI/ASHRAE, AHRI, JRAIA/JSA, JRA, VDI and DIN) and EU regulations as well as protocols applied by laboratory test in Europe. An analysis on them has revealed that:

- The current standard dedicated exclusively to the indirect-fired sorption chillers do not cover all sorption technologies and applications and they are not exhaustive (general remark);
- No European standards for indirect-fired sorption chillers;
- No specific prescriptions on the basis of the sorption chillers working operation are foreseen;
- No separate figures for thermally and electrically efficiencies of sorption chillers are considered;
- In the procedures dedicated to sorption chillers, the electrical consumption due to peripheral devices, like pumps/fans, is not included;
- No consistency exists among European, American and Asiatic Standards concerning test conditions and test procedures (e.g. sampling time, tolerances).

All these remarks have been used as starting point for drawing up two procedures differentiated on the basis of the sorption chiller's operation, i.e. continuous and discontinuous, and including prescriptions for performing stationary tests at full and partial load. Specifically, the protocols included in the standards EN 12309, EN14511, EN14825 [8], [9], [10], focused respectively on the gas-fired sorption heat pumps and chillers and on electrically driven heat pumps and chillers, have been taken as reference and the identified missing parts included in order to adapt them for the intended purpose. Therefore, specific provisions focused to meet the peculiarities of the different working operation of the sorption chillers have been added. Furthermore, integrations related to the solar cooling application, such as dedicated rating conditions or part load conditions, as well as modification in the performance calculation method have been also inserted in order to make the procedures suitable for the specific application.

3. Test procedure

In order to make the procedure "familiar" to the test laboratories and "ready" to be included in a standard, it has been structured like the sector standards (HVAC standards). This includes:

- Definitions;
- Test Conditions (only for "Full load");
- Performance figures;
- Test Protocol;
- Data to be recorded;
- Test apparatus;
- Uncertainty calculation: basic rules.

For the sake of brevity, only the test conditions, performance figures with the basic principles and the test protocols are explained more in details. For the whole procedure instead, refer to [11].

3.1. Test conditions

Since in solar cooling applications sorption chillers often operate at conditions different from the design (or nominal) ones, the present protocol prescribes two series of tests at:

- **Standard rating conditions**, i.e. those conditions, which are mandatory and used for the product marking and for the comparison or certification purposes;
- **Off-design conditions**, i.e. those conditions outside the design or nominal ones.

Concerning the standard rating conditions, they have been selected starting from those prescribed in the above-mentioned standards. They refer only to the evaporator and condenser/ad-absorber, since the conditions at generator depend on the choices of the manufacturers, and only for full load tests. Specifically the test conditions refer to three different applications here classified as high, medium and low applications corresponding, respectively, to the radiant floor, radiant ceiling and fan coil; and for different transfer medium at the heat rejection circuit, i.e. air, water and brine.

The off-design conditions instead are obtained by varying one (inlet) temperature per time while the other two are kept fixed (the same could be done with the flow rate at the three circuits). These temperatures have to be varied around the chiller nominal conditions indicated by the manufacturer. The temperature at the inlet generator shall be set at least at the:

- minimum "firing" temperature;
- maximum "firing" temperature;
- Nominal temperature fixed by the manufacturer and meaningful for the specific application.

While at the condenser and evaporator, a minimum of other two temperatures shall be fixed according to the manufacturer's requirements and the specific application in order to have in total at least:

- 2-points as heat rejection temperature;
- 2-points at chilled water temperature.

3.2. Performance figures

The developed test protocols provides separated thermally and electrically performance figures. For their calculation, the control volume around the machine, including also the "virtual" internal pumps used to win the losses through the main heat exchangers, is considered (see Fig. 1). According to this, the measured quantities, such as the cooling capacity, heat input and electric power input, are corrected considering the contributions, in terms of heat and electricity consumption, due to these parasitic elements. Therefore, for each rated quantity there will be the "*measured"* quantity that, in case of thermal powers, is determined by applying the direct enthalpy method, and the "*effective"* one [11].

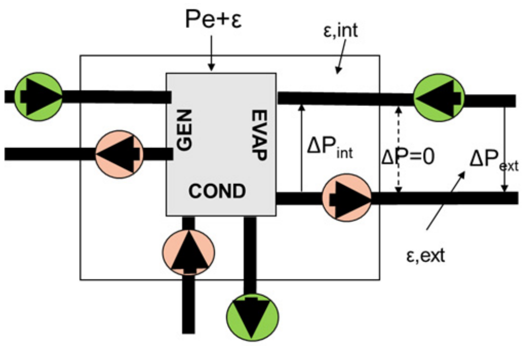

Fig. 1 System boundary including the virtual circulation pumps with the respective internal (ΔPint due to the machine) and external (ΔPext due to the external circuit) pressure drops. This control volume is used for the performance figures calculation

The main capacities and ratio calculated in the developed procedures are:
The **Thermal Energy Efficiency Ratio**, EERth, i.e. the ratio of the effective cooling capacity to the effective heat input to the unit, expressed in kW/kW determined through the following formula:

$$EER_{th} = \frac{Q_{Ecooling}}{Q_{Einput}} \quad (1)$$

Where:

- $Q_{Ecooling}$ is the Effective Cooling Capacity ($Q_{E,cooling}$), the cooling capacity corrected of the capacity due to the pumps at the evaporator circuit and expressed in kW;
- Q_{Einput} is the Effective Heat Input ($Q_{E,input}$), the heat input corrected of the capacity due to the pumps at the generator circuit and expressed in kW.

The **Electrical Energy Efficiency Ratio**, EER_{el}, i.e. the ratio of the effective cooling capacity to the effective electrical power input which is determined using the following formula:

$$EER_{el} = \frac{Q_{Ecooling}}{P_E} \qquad (2)$$

Where:

- $Q_{Ecooling}$ is the Effective Cooling Capacity($Q_{E,cooling}$), the cooling capacity corrected of the capacity due to the pumps at the evaporator circuit and expressed in kW
- PE is the effective Electric Power Input, in kW, i.e. the Electrical power input including the share of electrical consumption due to all conveying devices (e.g. fans, pumps) that ensure the transport of the heat transfer media inside the appliance (i.e. at the generator, evaporator and condenser).

For discontinuous chillers, the energy efficiency ratios, both thermal and electrical, are calculated separately for each operational cycle and eventually averaged.

3.3. Test protocol

The procedure consists of two test protocols: one for tests at full load and one for tests at partial loads. This last, in turn, comprises other two sub-procedures: one for continuous tests and one for cyclic tests (ON-OFF tests).

Both protocols include, where necessary, specific provisions related to the specific chiller operation (continuous and discontinuous) and consist of four main phases:

- "Set-up of the machine": phase during which the chiller is installed and connected to the test bench according to the manufacturer's instruction in order to obtain a quasi-real installation. Moreover, it should take care to properly install the machine in order to avoid external direct/indirect positive or negative influences on its operation;
- "Test Set-up": during this phase the desired test conditions, i.e. the flow rates and the inlet temperatures of the three heat exchangers, are set through the test bench; while the minimum cooling temperature is set on the machine in order to provide the maximum useful cooling capacity either if the test is at full load or at partial load; "Equilibrium phase": phase during which it is verified that all quantities under control lie within specific intervals without having to alter the test set values for a certain period, which differs depending on the chiller operation (continuous or discontinuous). Specifically, it is verified that the averages and the standard deviations, calculated with regard to the set values, of all quantities at the inlet and outlet of the machine do not differ from the set values by a certain amount (test tolerances). An example of these tolerances is given in Table 1, where the test tolerances for continuous chillers are listed. The procedure prescribes four different series of tolerances, each listed in a table, which differ as a function of the chiller operation mode, i.e. continuous or discontinuous tests, and of the type of the test (continuous or cyclical test – ON-OFF tests). Such tolerances are more stringent for continuous chillers. When these conditions are fulfilled, chiller can be considered in steady-state;
- "Data collection period": period during which, once the equilibrium is reached, all meaningful data are collected. Such period lasts 30 minutes for continuous machines and 2 cycles for the discontinuous machines.

Concerning the ON-OFF tests, further explanations are required. First of all the ON-OFF tests are those test that shall be performed when at specific part load conditions, i.e. at specific inlet temperature at the condenser and desired outlet temperature at the evaporator, the minimum capacity provided by the machine is higher than the required part load. In this case, the desired part load is achieved as the average of the cooling capacity rated over the "ON" and "OFF" periods of the machine (see Fig. 2). The duration of the ON and OFF periods depends on the resulting cooling capacity calculated as mean over the two periods: i.e. if the cooling capacity calculated is higher than the desired part load, the OFF period is extended otherwise it is reduced, while the ON period is kept constant (20 minutes). The whole procedure is explained below. The formula for the calculation of the OFF period is:

$$t_{OFF} = 20 \cdot \left(\frac{Q_{Ecooling}}{PL} - 1 \right) \quad \text{[minute]} \qquad (3)$$

Where:

- $Q_{Ecooling}$ is the effective cooling capacity obtained during the ON period [kW];
- PL is the required partial load [kW].

Table 1 Permissible deviations on the set values during stationary tests for Continuous machines. They refer to continuous "Full load" tests and continuous "Partial load" tests.

Measured quantity	Permissible deviations of the time average measured values from set values		Permissible standard deviation from the set values*	
GENERATOR (water or brine)				
Inlet temperature Outlet temperature Flow rate Static pressure difference	entire load	± 0,2 K ± 0,3 K ± 2 % /	entire load	0,5 K 0,6 K 5% 10%
EVAPORATOR (water or brine)				
Inlet temperature Outlet temperature Flow rate Static pressure difference	entire load	± 0,2 K ± 0,3 K ± 2 % /	entire load	0,5 K 0,6 K 5% 10%
CONDENSER				
Air :				
Inlet temperature: Dry-bulb (wet-bulb)a Air flow rate (volume) Air static pressure	entire load	± 0,3 K (± 0,4 K) / /	entire load	1,0 K (1,0 K) / /
Water or Brine:				
Inlet temperature Outlet temperature Flow rate Static pressure difference	entire load	± 0,2 K ± 0,3 K ± 2 % /	entire load	0,5 K 0,6 K 5% 10%
Electrical input				
- voltage	± 4 %		4%	
NOTE 1 Permissible deviation includes the regulating capability of the test apparatus.				
a For appliances with outdoor heat exchanger surfaces greater than 5 m², the deviation on the air inlet dry bulb is doubled.				

*Standard deviation calculated considering the set value instead of the mean

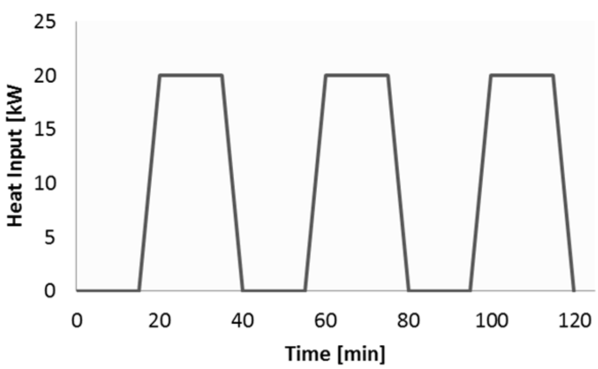

Fig. 2 ON-OFF tests

4. Validation

The validation of the test procedures has been first carried out on both commercial and prototypal chillers performing continuous and discontinuous cycles. Such activity has mainly involved the protocols for the assessment of continuous machines at full and partial load (ON-OFF tests have been skipped), the criteria to define the steady state condition of the chillers and the formulas used for the performance calculation according to the defined control volume. The aim was to demonstrate the applicability of the developed procedures to the intended purposes as well as to verify their representativeness, reproducibility and repeatability in the application range.
For this purpose, the partners of Task 48 involved in this project carried out the validation tests in their laboratories, both according to their internal protocols and applying the procedures described above,. Following, the results of tests performed ad-hoc by the Politecnico di Milano and by CNR-ITAE in Messina on a continuous and on a discontinuous chiller respectively, are presented.

Concerning the validation on continuous chillers, the new laboratory RELAB of Politecnico di Milano, accredited ISO/IEC 17025 for testing electrically and thermally (including gas) driven chillers and heat pumps and HVAC components, has carried out a test campaign on a new prototype of air-to-water absorption chiller. Specifically, the machine has been tested by applying the investigated procedure for continuous chillers and by varying the inlet temperature at the generator and condenser while the temperature at the evaporator has been kept constant in the typical range for fan coil application (12 -7°C). Furthermore, in order to test the procedure also for the partial loads, different temperatures at the condenser have been set and the flow rate and temperature at the generator have been varied.

From an analysis on the test results, it emerged that:

- The drafted protocol for continuous chillers is easily applicable and repeatable;
- As it is possible to observe in Fig. 3 and in Fig. 4, the criteria proposed for the verification of the test stationarity, both in terms of boundary conditions and chiller operation, are appropriate and conform to the cycle thermodynamic. Furthermore such criteria, together with a measurement equipment having the accuracy required by the protocol, assure a repeatability below the 3% and an uncertainty of cooling capacity under 5% for a ΔT of 5°C at the evaporator;
- The equilibrium period needed for the machine to reach the steady state conditions and the data collection period are adequate and allow to obtain meaningful data;
- As shown in Fig. 5, the partial loads can be achieved for different condensation temperature, by varying the working point (temperature) and the power (flow rate) at the generator likewise it is usual for the electric chillers.

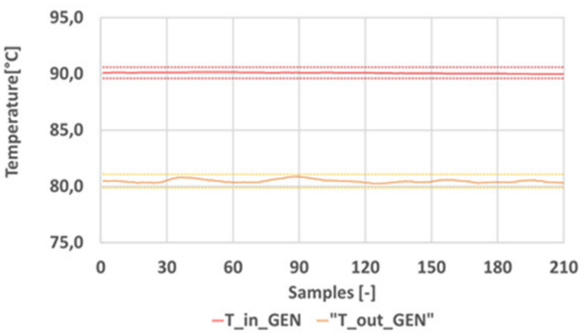

Fig. 3 Inlet and outlet temperatures at the generator and permissible fluctuation intervals (stationary criteria)

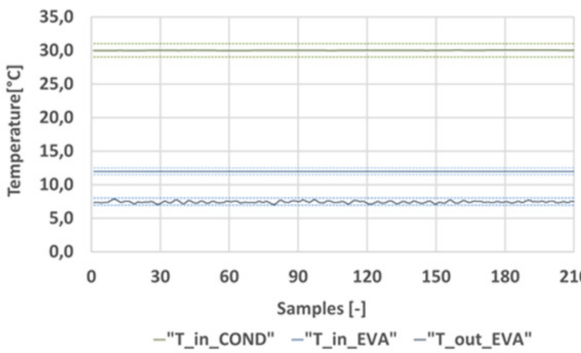

Fig. 4 Inlet and outlet temperatures at the evaporator and inlet air temperature at the condenser and permissible fluctuation intervals (stationary criteria)

In Fig. 5 for privacy reasons, dimensionless data, calculated with the respect of nominal capacity, are presented. Nominal point is marked

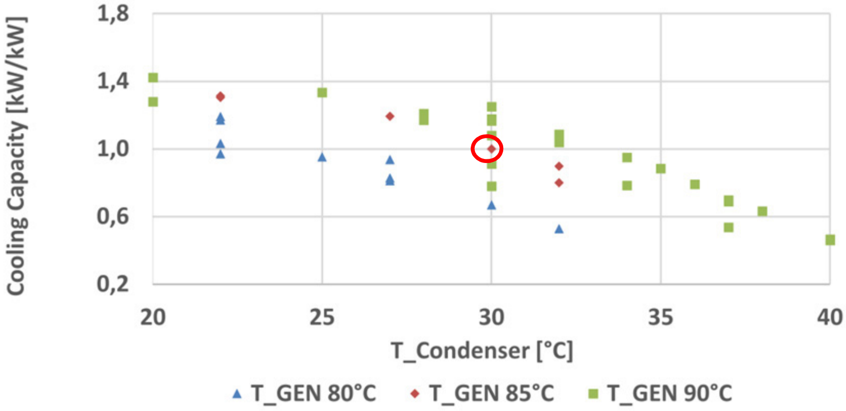

Fig. 5 Part load cooling capacities vs. condenser temperature and with different "firing" temperature (inlet temperature at the generator)

The validation of the test procedure for the discontinuous chillers has been carried out by the "CENTROPROVE" of CNR- ITAE in Messina . To achieve this, two different adsorption chillers have been tested: a three-bed adsorption chiller prototype, developed within the activity of a national founded project and a commercial water-to-water chiller. For advisability and brevity reasons, only the results obtained from this last one are presented here. Nevertheless, all the results showed below have been verified by means of all the data available (tests on the chiller prototype, data supplied by the other project partners, etc.).

The "CENTROPROVE" has employed one of its consolidated test rigs to carry out the tests for the procedure validation. This testing station consists of a system of storages capable to guarantee the temperatures stability during the tests, a gas heater and a cooling circuit to drive the chiller and dissipate the process heat respectively. Moreover, the test bench is able to simulate all desired operating conditions including those ones typical for solar cooling applications, by means of 3-way valves, all managed by advanced controls.

Also in this case, the validation has been carried out by testing the commercial unit according to the procedures for discontinuous chillers and by varying the inlet temperatures and the flow rates at the three heat exchangers, i.e. generator, condenser, evaporator, in order to validate the protocol also in partial load conditions

The analysis of the achieved results has revealed some critical issues partly due to the nature of the machine operation itself and partly due to the variety of appliances sold on the market or currently at developing stage.

These critical issues can be summarized as follow:

- Difficulty to satisfy all "stationary" criteria. As it is possible to observe from the Fig. 6, with the exception of the evaporator, the fluctuations of the flow rates and, consequently, of the pressure drops at the generator and condenser are so big that the criteria on the permissible standard deviations from the set point are not satisfied. However, this does not occur with other discontinuous chillers analysed. Nevertheless, since the proposed standard should have a general value, these criteria shall be changed or deleted. Further tests on different chillers, heat pump or adsorption prototypes are needed;
- As cooling capacity provided by the chiller is far from nominal one, it is hard to meet the requirements related to the outlet temperature at the evaporator .This is mainly due to the machine operation. Also in this case, further tests are needed;
- The number of calculation cycles (4) used for defining the equilibrium period (2), needed by the machine for reaching the stationarity, and the data collection period (2) are adequate and allow obtaining meaningful data. Nevertheless it is preferable to consider a higher number of these calculation cycles;
- As shown in Fig. 7, also in this case, for each condensation temperature, the partial loads can be obtain by varying the working point (temperature) and the power (flow rate) at the generator but not linearly way like for continuous chillers.

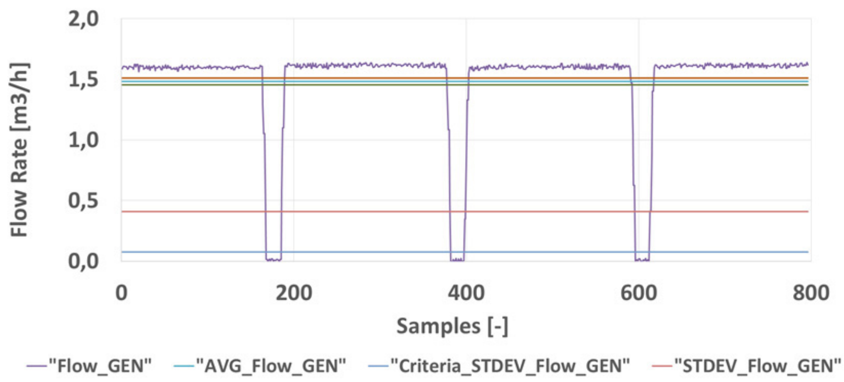

Fig. 6 Generator flow rate and stationary criteria defined with respect to the average and standard deviation from the set value of the flow rate

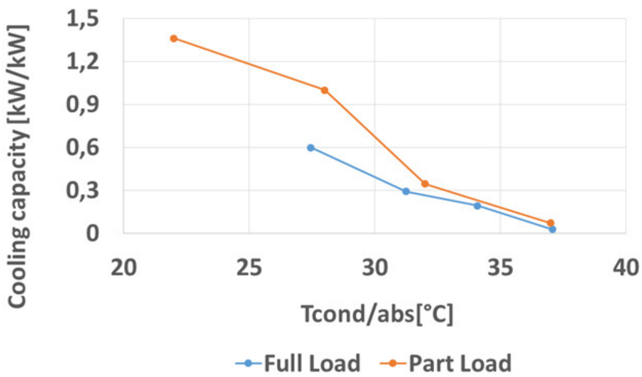

Fig. 7 Part load cooling capacity vs. Condenser Temperature

Since the machine under test is a commercial unit, the test conditions reported in the data sheet have been produced in laboratory and the performances obtained have been compared with those declared by the manufacturer. The comparison has shown that, with the exception of the nominal conditions where the performances declared and those obtained were almost similar, far from these conditions, the difference among them is more consistent, in the order of several percentage points, thus demonstrating the importance of having a reference standard for performance certification. In Fig. 8 the "declared" and the "real" performance curves are shown as ratio of actual and nominal values. The nominal points are marked.

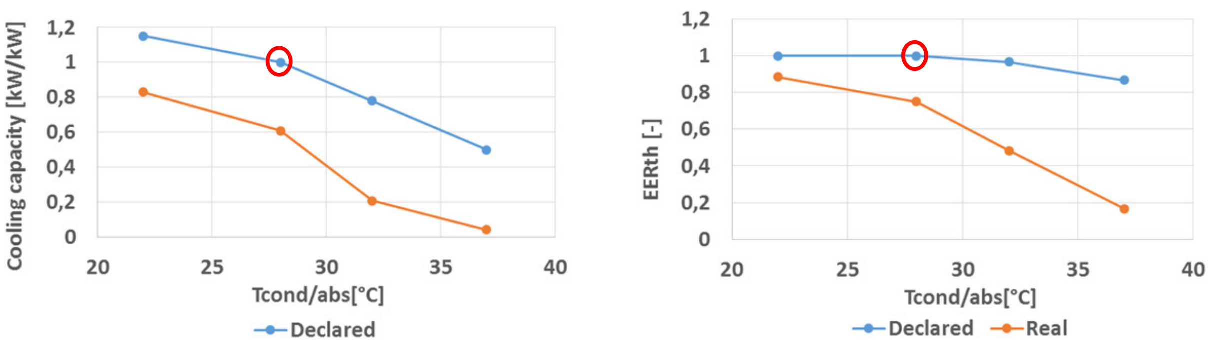

Fig. 8 Declared vs. Real Cooling capacity and Thermal Energy Ratio Efficiency at different condenser temperatures and with generator temperature and evaporator temperature at 72°C and 18°C respectively.

5. Conclusions

The European Community is pushing more and more for the use of high-energy efficiency products and for this purpose, it is adopting policy for rewarding products and systems able to contain the energy consumption. Encouraged by this, public and private organizations are creating labelling and certification schemes aimed at provide reliable proof of the energy quality level of class of product. Reference standards to measure and calculate performance figures in unified way are therefore required.

An analysis on the current normative scenario has revealed that, for the solar cooling technology and in particular, for one of its core components, i.e. sorption chillers, the few reference standards used to assess them are not adequate and coherent among them. For this reason, in order to overcome this lack, two test procedures aimed at the complete "mapping" of the sorption chillers and able to provide reliable data to be used as input for the calculation of their seasonal performances and for the development of simulation tools have been developed.

The protocols, here presented in their crucial parts, allow taking into account the peculiarities related to the specific chiller operation (i.e. continuous and discontinuous) and include prescriptions for performing stationary tests at full and partial load at the conditions more representative for solar cooling applications.

Finally, in order to demonstrate their applicability to the intended purposes and to verify their representativeness in the application range, a first attempt of validation has been carried out. The main results have been presented above. It clearly emerged that the procedures for continuous chillers are adequate for the purpose; while for discontinuous chillers, due to their operation and the variety of chillers on the market or under development, more efforts are required.

Nevertheless, since this process did not cover all parts of the procedures, further efforts shall be done in such direction. The next steps will regard the complete validation of the test procedures.

Although some parts of the developed procedures still need to be tested and validated, they represent a valid boost for the standardization work, step necessary for the consolidation and recognition of the entire solar cooling technology. The complete claim, through official references, of each single component installed in solar cooling plants will allow stakeholders and final users facing with the technology in a more familiar and confident way, bringing, consequently, to its promotion and affirmation on the market.

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