Final deliverable

Chiller Characterization

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IEA Solar Heating and Cooling Program

The Solar Heating and Cooling Programme was founded in 1977 as one of the first multilateral technology initiatives ("Implementing Agreements") of the International Energy Agency. Its mission is *"to enhance collective knowledge and application of solar heating and cooling through international collaboration to reach the goal set in the vision of solar thermal energy meeting 50% of low temperature heating and cooling demand by 2050.*

The member countries of the Programme collaborate on projects (referred to as "Tasks") in the field of research, development, demonstration (RD&D), and test methods for solar thermal energy and solar buildings.

A total of 53 such projects have been initiated to-date, 39 of which have been completed. Research topics include:

- Solar Space Heating and Water Heating (Tasks 14, 19, 26, 44)
- Solar Cooling (Tasks 25, 38, 48, 53)
- Solar Heat for Industrial or Agricultural Processes (Tasks 29, 33, 49)
- Solar District Heating (Tasks 7, 45)
- Solar Buildings/Architecture/Urban Planning (Tasks 8, 11, 12, 13, 20, 22, 23, 28, 37, 40, 41, 47, 51, 52)
- Solar Thermal & PV (Tasks 16, 35)
- Daylighting/Lighting (Tasks 21, 31, 50)
- Materials/Components for Solar Heating and Cooling (Tasks 2, 3, 6, 10, 18, 27, 39)
- Standards, Certification, and Test Methods (Tasks 14, 24, 34, 43)
- Resource Assessment (Tasks 1, 4, 5, 9, 17, 36, 46)
- Storage of Solar Heat (Tasks 7, 32, 42)

In addition to the project work, there are special activities:

- SHC International Conference on Solar Heating and Cooling for Buildings and Industry
- Solar Heat Worldwide – annual statistics publication
- Memorandum of Understanding with solar thermal trade organizations
- Workshops and conferences

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Contents

1. Executive summary

The objective of Subtask A1 is to supply the tools necessary for assessing the quality level of the sorption chillers installed in solar cooling plants. Particular attention has been given therefore to all those methods able to characterize the chillers at off-design conditions and during the transitory phases typical for these kind of applications.

With this regard, two test procedures aimed at the "mapping" of the chillers 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 expected result is to achieve reliable data, coming from laboratory tests, that can 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 behavior on annual basis within specific boundaries.

For their drafting, the testing protocols available on the dedicated normative scenario and according to the current criteria of the Eco-design and the Eco-labeling directives have been used as reference.

The present final report deals with these two test procedures and includes the approach used for their drafting, the description of the test protocols in terms of rating conditions, testing methodology and the testing apparatus, and the results obtained from the first attempt of validation of the developed test procedures.

2. Approach

A preliminary study has been carried out with the aim to verify which testing protocols were at disposal to characterize the sorption chillers especially those installed in applications similar to solar cooling ones.
For the purpose, besides the laboratory internal protocols, the existing standards and regulations having in the "scope" the procedures for the performances evaluation of appliances used for space cooling have been selected on the basis of the:

- **Scope** - all appliances used for the space cooling (*and heating*) which are not properly indirect-fired sorption chillers (e.g., electrically driven chillers or heat pump; gas fired chillers or heat pump; etc…)

- **Application** - cooling and cooling & heating (*heating as secondary function);*

- **System boundaries –** control volume around the machine and its parasitic elements (EER or COP); control volume including the machine combined with climate, user and driven energy curves (SEER or SCOP).

The selection has covered a number of standards (ISO, CEN, ANSI/ASHRAE, AHRI, JRAIA/JSA, JRA, VDI and DIN) and regulations. An analysis carried out on them has revealed several critical issues regarding both the applicability of the test procedures prescribed in the analysed standards on the prototypes currently present on the market and the technologies covered by the analysed standards (i.e. the scope). All these aspects can be summarized as follow:

- The standard dedicated exclusively to the indirect-fired sorption chillers don't cover all sorption technologies, applications and they are not exhaustive (*general remark*);

- No specific provisions for discontinuous chillers (even if they are included in the scope of standard EN12309). The protocols analysed don't prescribe test procedures distinguished on the basis of chiller's operation;
- No standardized test procedures that include tests, stationary or dynamic, suitable for applications like solar cooling. They are available only at research level;
- The definition of performance figures as well as their nomenclature are not consistent trough the reviewed documents;
- No separate figures for thermally and electrically efficiencies of sorption chillers. Usually the electricity consumption is not considered and in some cases it is added to the thermally energy consumption;
- In the procedures dedicated to the sorption chillers, the electrical consumption due to peripheral devices, like pumps/fans, is not included;
- Test conditions prescribed in the review standards don't cover all application (especially those related to solar cooling applications);
- Not accurate information about testing under part load conditions;
- Most of the European standards are dedicated to electrically driven machines. Only the standard EN12309 is focused on direct-fired machines. The standards dedicated to thermally driven chillers (or chillers/heaters) are mainly Asiatic and American;
- No consistency among European 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 the test procedures described in the present report.
Specifically, the protocols prescribed in the analyzed standards and, in particular, in the standard EN12309, focused on the gas-fired sorption appliances, and in the standards EN14511 and EN14825, focused on electrically driven appliances, have been adapted for being applied on sorption chillers. The "missing parts" have been integrated through specific provisions strictly correlated to this type of machines and to this particular application: e.g. provisions related to machine operation, electric consumption, rating conditions representative for solar cooling applications, etc…

Before doing this, several considerations have been done with regard to the "applicability" boundaries of the drafted procedures, i.e. about the individuation of the reference control volume. At the beginning, it was thought to assess the seasonal performance of sorption chiller already at this level (i.e. at component level). Nevertheless, this evaluation foresees, once the climate and application are fixed, the definition of the plant configuration (i.e. Collector field, Storages, Backups, Heat rejection), component sizes and control strategies which are issues treated in the Subtask B1, focused on the system configuration. For this reason, it was decided that the subtask A1 supplied the means for the chiller characterization useful both for the evaluation of its seasonal performances based on calculation methods and for the development of simulation tools at base of dynamic tests.

On the basis of what just said, two test procedures specific for the two sorption chiller's operation, continuous and discontinuous, has been developed. They include protocols to perform stationary tests at full and partial load. Concerning the tests at part loads, two distinct type of tests are foreseen: continuous tests or ON-OFF tests.

For convenience reasons and in order to avoid unnecessary repetitions, the two test procedures are here described together and differentiated only where it is necessary, i.e. only in the sections which are closely related to the machine operation.

3. Test Procedures

The two test procedures have been structured like the sector standards. They include:

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

As said, the two procedures are illustrated together. Specific provisions correlated to the machine operations will be introduced only where it is necessary.

3.1 Definitions

In this section, the terms and the definitions used in the two procedures are specified. They are subdivided in terms related to the:

- Machine operation
- Loads and rating conditions
- Test protocol and calculations

Machine Operation

These terms are strictly related to the machine operation and their definition explains the basic difference between the two types of chillers.

- **Continuous chillers**

Chillers in which the four phases (i.e. desorption, condensation, evaporation, absorption) are processed continuously

or

Chillers in which the energy and mass exchanges are stationary, i.e., if the boundary conditions are stationary, the exchanges are uniform in time but not in space

- **Discontinuous chillers**

Chillers in which the four phases (i.e. desorption, condensation, evaporation, ad/absorption) are periodically shifted among the internal components.

Usually the shift occurs between the couples of phase executed at the same pressure level, i.e. between desorption and condensation and between sorption and evaporation

or

Chillers in which the energy and mass exchanges are not stationary, i.e., if the boundary conditions are stationary, the exchanges are not uniform neither in time nor in space.

- **Swap** *(For discontinuous chiller)*

Shift of the four (or couples of) phases among the internal components.

- **Swap Cycle** *(For discontinuous chiller)*

Period between two consecutive swaps. It could be characterized by two consecutive rough fluctuations (around 15%) of the generator flow rate.

- **Generator Cycle** *(For both chillers)*

Period between two consecutive switching OFF of the pump generator. It is used for ON-OFF tests.

- **Calculation Cycle**

In case of:

a. Full load test on discontinuous sorption chiller it consists of two “swap” cycle
b. Part load test, in ON-OFF mode, it consists of two “generator” cycle

Loads and Rating Conditions

These terms refer to the interactions between the building load and the machine and to the operative conditions at which the chiller’s capacity is rated.

- **Cooling Load**

Cooling load of the building at the reference design conditions for cooling and expressed in kW. According to the standards EN 14825 and EN 12309 as well as to the Eco-design directives, the reference design conditions for the cooling season are:

- Outdoor dry bulb temperature: 35 °C;
- Indoor design temperatures: dry bulb 27 °C, wet bulb 19 °C.

- **“Full Load” conditions**

Conditions at which

- the chiller is operated to provide the maximum useful (cooling) capacity
- the declared capacity of the appliance is assumed equal to the building load (capacity ratio=100%).

- **“Part Load” conditions**

Conditions at which

- the chiller is operated to provide a percentage of the maximum useful (cooling) capacity
- the declared capacity of the appliance is higher than the building load (the capacity ratio<100%)

- **Standard Rating Conditions**

Mandatory conditions that are used for marking and for comparison or certification purposes.

- **Application rating Conditions**

Rating condition which provides additional information on the performance of the appliance within its operating range when applicable (OFF-DESIGN CONDITIONS).

- **Nominal Test Condition**

Refers to the unique “Standard” rating condition used for the CE marking of appliance and selected by the manufacturer within the standard rating conditions. Only one nominal condition has to be defined for each appliance.

Test protocol and calculations

These terms refer to the operative conditions at which the test shall be performed, i.e. at stationary and equilibrium state of the chiller, and to the calculations coming from the measurements done.

- **Steady State Condition**

Condition obtained and maintained when all the measured quantities, included periodic fluctuations due to the operation of regulation and control devices, remain constant without having to alter the set values with respect to the tolerances given in Table 3 for continuous chillers and in Table 4 for discontinuous chillers.

- **Equilibrium period**

Period during which the chiller is operated while meeting the test tolerances specified in Table 3 for continuous chillers and in Table 4 for discontinuous chillers (i.e. Steady State Conditions). It comes before the Data Collection period.
The equilibrium period consists of :

  - 30 minutes for continuous chillers;
  - 4 swap cycles for discontinuous chillers.

- **Data Collection period (Test)**

Period whose data recorded are used for the calculation of performance figures. The data collection period immediately follows the equilibrium period.
The data collection period consists of:

- 40 minutes for continuous chillers;
- 4 swap cycles for discontinuous chillers.

- **Cooling Capacity ($Q_{cooling}$)**

It's the useful effect at the evaporator, i.e. it's the heat given off from the heat transfer medium (water) to the soprtion chiller per unit of time, expressed in kW.

- **Effective Cooling Capacity($Q_{E,cooling}$)**

It's the cooling capacity corrected of the capacity due to the pumps at the evaporator circuit and expressed in kW.

- **Heat Input (Q_{input})**

It's the heat given to the soprtion chiller through its generator per unit of time, expressed in kW.

- **Effective Heat Input ($Q_{E,input}$)**

It's the heat input corrected of the capacity due to the pumps at the generator circuit and expressed in kW.

- **Electrical Power Input (P_T)**

Electrical consumption of all control and safety devices of the appliance within the defined interval of time expressed in kW.

- **Effective Electrical Power Input ($P_{E,}$)**

It is the Electrical power input including the share of electrical consumption due to the 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).

- **Thermal Energy Efficiency Ratio (EER_{th})**

It's the ratio of the effective cooling capacity to the effective heat input of the unit, expressed in kW/kW.

- **Electric Energy Efficiency Ratio (EER_{el})**

It's the ratio of the effective cooling capacity to the effective electrical power input of the unit, expressed in kW/kW.

3.2 Test Conditions

This section specifies the test conditions for rating the energy parameters of sorption chillers installed in solar cooling plants.

They have been selected starting from those prescribed in the standards for the performance evaluation of appliances used for space heating and cooling, independently if they were thermally driven or electrically driven. They refer only to the evaporator and condenser/ad-absorber, since the conditions at generator depend on the choices of the manufacturers, and only to the full loads, for the reasons explained before. 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.

Table 1 summarizes the standard and application conditions suitable for the solar cooling applications.

Table 1 Full load Test Conditions

			Generator		Condenser/Absorber		*Evaporator*	
	Type of appliance	Temperature Application	Inlet temperature °C	Outlet temperature °C	Inlet temperature °C	Outlet temperature °C	Inlet temperature °C	Outlet temperature °C
Standard Rating Conditions	Water-to-water d)	Low	a)	a)	30	35	12	7
	Water-to-water d)	Medium	a)	a)	30	35	15	10
	Water-to-water d)	High	a)	a)	30	35	23	18
	Air-to-water	Low	a)	a)	35 b)	/	12	7
	Air-to-water	Medium	a)	a)	35 b)	/	15	10
	Air-to-water	High	a)	a)	35 b)	/	23	18
Application Rating Conditions	Water-to-water d)	High	a)	a)	32	38	12	7
	Air-to-water	Low	a)	a)	27 b)	c)	12	7
	Air-to-water	Medium	a)	a)	27 b)	c)	15	10
	Air-to-water	High	a)	a)	27 b)	c)	23	18
	Air-to-water	Low	a)	a)	46 b)	c)	12	7
	Air-to-water	Medium	a)	a)	46 b)	c)	15	10
Note	a) Manufacturer specified conditions.							
	b) Dry bulb temperature							
	c) The tests shall be carried out with the flow rate obtained during the test at the corresponding standard rating conditions							
	(d) Standard rating conditions for water to water or water to brine appliances can be extended to brine to water and brine to brine appliances respectively							

The manufacture shall indicate which one, among them, is used as Nominal test condition for its product. Nevertheless, since in the solar cooling applications the sorption chillers operate often at conditions different from the design (*or nominal*) ones, the manufacturer declares a map of performances at different working conditions. So besides the tests carried out at standard rating conditions, it's necessary to test the appliance at further conditions which are meaningful for the specific application.

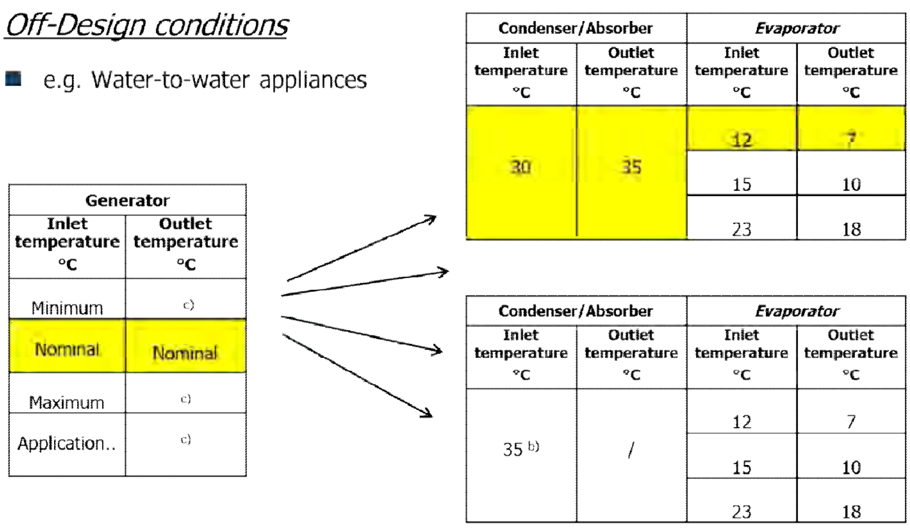
For this reason, the present protocol prescribes to test the machine at off-design conditions, i.e. the conditions obtained by varying one (inlet) temperature per time while the other two are kept fixed (the same could be done with the flow rate at the three circuits). These temperatures have to be varied around the chiller nominal conditions indicated by the manufacturer according to the approach showed in Figure 1, where the inlet generator temperature shall be set 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 other two temperatures shall be fixed according to the manufacturer and the specific application in order to have in total:

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

Figure 1 Off- Design Conditions



b) Dry bulb temperature

c) The tests shall be carried out with the flow rate obtained during the test at the corresponding standard rating conditions

3.3 Performance figures: *basic principles*

For the calculation of the capacities and the main ratios, the control volume around the machine, including also the "virtual" internal pumps used to win the losses through the main heat exchangers, is considered. According to this, the measured quantities, such as the cooling capacity, heat input and electric power input, shall be corrected of 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, will be determined by applying the direct enthalpy method at the three water heat exchangers (i.e. generator, evaporator and condenser), and the effective ones. Figure 2 shows the control volume used and the virtual circulation pumps with the respective internal (ΔPint due to the machine) and external (ΔPext due to the external circuit) pressure drops.

The thermal capacities are determined by applying the direct enthalpy method at the three water heat exchangers (i.e. generator, evaporator and condenser). They are calculated as the product of mass flow rate or the volume flow rate multiplied by density of the heat transfer medium with the difference between the inlet and outlet temperatures and the specific heat capacity or as the product between the mass flow rate (or the volume flow rate multiplied by density) of the heat transfer medium and the enthalpy change.

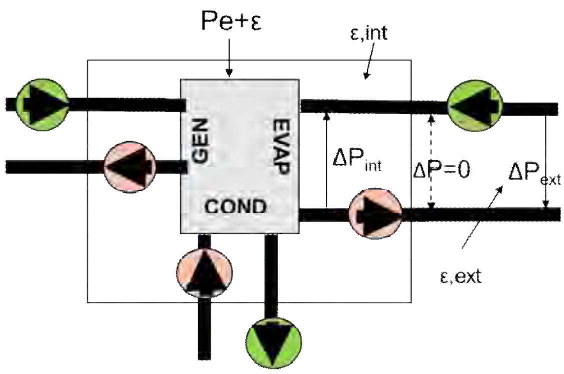


Figure 2 System boundary used for the definition of Test Methods and performance evaluation procedures

3.4 Performance Figures

As explained above, the thermal capacities are determined by the direct enthalpy method, i.e. as the product of mass flow rate or the volume flow rate multiplied by density of the heat transfer medium with the difference between the inlet and outlet temperatures and the specific heat capacity or as the product between the mass flow rate (or the volume flow rate multiplied by density) of the heat transfer medium and the enthalpy change.

According to this, the **Measured Cooling Capacity**, $Q_{cooling}$, is determined through the following formula:

$$Q_{cooling} = \frac{\sum_{j=1}^{n}(Vm_j \cdot \delta_j \cdot Cp_j \cdot \Delta t_j)}{n}$$ **Eq. 1**

where:

- j is the scan number;
- n is the number of scan of the data collection period;
- Q_j is the measured cooling capacity, in kilowatt;
- Vm_j is the volume flow rate of the heat transfer medium into the evaporator at the considered scan, in cubic meters per second;
- δ_j is the density of the heat transfer medium into the evaporator at flow meter temperature at the considered scan, in kilogram per cubic meter;
- Cp_j is the specific heat of the heat transfer medium into the evaporator at constant pressure at mean temperature of the heat transfer medium at the considered scan, in kilojoule per kilogram and kelvin;
- Δt_j is the difference between inlet and outlet temperatures of the heat transfer medium at the evaporator and at the considered scan, in kelvin.

The mass flow can be determined directly instead of measuring the volume flow and the density; in this case, in Eq. 1, the term $(Vm_j \cdot \delta_j)$ has to be replaced with mj.

Alike, the enthalpy variation ΔHj can be determined directly instead of the term $(Cp_j \cdot \Delta t_j)$.

While the **Effective Cooling Capacity,** $Q_{Ecooling}$ is obtained from the measured cooling capacity corrected of the heat from the pump(s) according to the following formula:

$$Q_{Ecooling} = Q_{cooling} + \varepsilon_{pump,eva}$$ **Eq. 2**

where:

- $Q_{Ecooling}$ is the effective cooling capacity, in kilowatt;
- $Q_{cooling}$ is the measured cooling capacity, in kilowatt;
- $\varepsilon_{pump,eva}$ is the capacity correction due to the pump(s) responsible for circulating the heat transfer medium through the evaporator, in kilowatt.

Now:

a) if the pump(s) is (are) an integral part of the appliance, the capacity correction due to the pump(s), $\varepsilon_{pump,eva}$, calculated according to Eq. 6, which is excluded from the total electric power input, shall be added to the cooling capacity (the correction is positive).

b) if the pump(s) is (are) not an integral part of the appliance, the capacity correction due to the pump(s), $\varepsilon_{pump,eva}$, calculated according to Eq. 7, which is added to the total electric power input, shall be subtracted from the cooling capacity (the correction is negative).

The **Measured Heat Input**, Q_{input} , is determined using the following formula:

$$Q_{input} = \frac{\sum_{j=1}^{n}(Vm_j \cdot \delta_j \cdot Cp_j \cdot \Delta t_j)}{n} \qquad \textbf{Eq. 3}$$

where:

- j is the scan number;
- n is the number of scan of the data collection period;
- Q_{input} is the measured Heat input, in kilowatt;
- Vm_j is the volume flow rate of the heat transfer medium into the generator at the considered scan, in cubic meters per second;
- δ_j is the density of the heat transfer medium into the generator at flow meter temperature at the considered scan, in kilogram per cubic meter;
- Cp_j is the specific heat of the heat transfer medium into the generator at constant pressure at mean temperature of the heat transfer medium at the considered scan, in kilojoule per kilogram and kelvin;
- Δt_j is the difference between inlet and outlet temperatures of the heat transfer medium at the generator and at the considered scan, in kelvin.

Also in this case the mass flow can be determined directly instead of measuring the volume flow and the density; in this case, in Eq. 3, the term $(Vm_j \cdot \delta_j)$ has to be replaced with mj.

The same for the enthalpy variation ΔHj that can be determined directly instead of the term $(Cp_j \cdot \Delta t_j)$.

Concerning the **Effective Heat Input**, Q_{Einpu}, it is calculated only if the pump(s) is (are) an integral part of the appliance. Indeed, in this case, the capacity correction due to the pump(s), $\varepsilon_{pump, gen}$, calculated according to Eq. 6, shall be added to the heat input (the correction is positive) to the measured heat input according to the following formula:

$$Q_{Einput} = Q_{input} + \varepsilon_{pump,gen} \qquad \textbf{Eq. 4}$$

where:

Q_{Einput} is the effective Heat input, in kilowatt;

Q_{input} is the measured Heat input, in kilowatt;

$\varepsilon_{pump,gen}$ is the capacity correction due to the pump(s) responsible for circulating the heat transfer medium through the generator, in kilowatt.

The same capacity correction is excluded from the total electric power input; while if the pump(s) is (are) not an integral part of the appliance, the capacity correction due to the pump(s), $\varepsilon_{pump,gen}$, calculated according to Eq. 6, shall be added to the total electric power input.

The **Effective Electric Power Input,** P_E, includes the electrical power input for all control and safety devices of the appliance and the shares of electrical power input of the conveying devices (e.g. fans, pumps) that ensure the transport of the heat transfer media inside the appliance. It is determined according to the following formula:

$$P_E = \frac{\sum_{j=1}^{n}(P_{Tj})}{n} + \varepsilon_{pump,eva} + \varepsilon_{pump,gen} + \varepsilon_{pump,cond} \qquad \textbf{Eq. 5}$$

where:

j is the scan number;

n is the number of scan of the data collection period;

P_E is the effective electrical power input, in kilowatt;

P_{Tj} is measured (total) electrical power input at the considered scan, in kilowatt;

$\varepsilon_{pump,eva}$ is the capacity correction due to the pump responsible for circulating the heat transfer medium through the evaporator, in kilowatt.

$\varepsilon_{pump,gen}$ is the capacity correction due to the pump responsible for circulating the heat transfer medium through the generator, in kilowatt.

$\varepsilon_{pump,cond}$ is the capacity correction due to the pump responsible for circulating the heat transfer medium through the condenser, in kilowatt.

The capacity correction are always positive if the pump(s) of the circuit in which they are installed is (are) not an integral part of the appliance; they are negative in the opposite case, i.e. in case of the pump(s) is (are) an integral part of the appliance.

If the heat transfer medium at the condenser is the air and the conveying device is an (integral) fan, the consumption of the fan is completely included in the electric consumption of the appliance.

The capacity correction, as already explained, is the share of the electrical power input to the pump motor(s) and of heat that shall be included or excluded in the effective electrical power absorbed by the appliance and added or subtracted to the cooling capacity and heat input capacity dependently if the pump(s) or fan(s) is (are) an integral part of the appliance or not. It shall be calculated for all pumps responsible for circulating the heat transfer medium through the evaporator ($\varepsilon_{pump,eva}$), the generator ($\varepsilon_{pump,gen}$) and the condenser ($\varepsilon_{pump,cond}$) where applicable and the formula used depend if the pump is internal or external the appliance.

If the pump(s) is (are) an integral part of the chiller, the Capacity Correction is calculated using the following formula:

$$\varepsilon_{pump} = \frac{q \cdot (-\Delta p_e)}{\eta \cdot 1000}$$ **Eq. 6**

where:

- ε_{pump} is the electrical correction due to the pump responsible for circulating the heat transfer medium through the heat exchanger, in kilowatt;
- η is the efficiency of the pump calculated according to **Erreur ! Source du renvoi introuvable.**
- Δp_e is the measured available external static pressure difference, in pascal;
- q is the measured water flow rate, in cubic meters per second.

If no pump is provided with the appliance, the part of the electrical power input which is to be included in the effective electrical power absorbed by the appliance, shall be calculated using the following formula (the correction is positive):

$$c_{pump} = \frac{q \cdot (-\Delta p_i)}{\eta \cdot 1000}$$ **Eq. 7**

Where:

c_{pump} is the electrical correction due to the pump responsible for circulating the heat transfer medium through the heat exchanger, in kilowatt;

η is the efficiency of the pump calculated according to **Erreur ! Source du renvoi introuvable.**

Δp_i is the measured available internal static pressure difference, in pascal;

q is the measured water flow rate, in cubic meters per second.

At this point it is possible to rate the performance coefficients both in thermal terms and in electrical terms. They are evaluated on the basis of the effective quantities - e.g. Effective Power Input, Effective cooling power, Effective heat Input - where applicable, otherwise through the measured quantities – i.e. Measured Power Input, Measured Cooling Capacity, Measured Heat Input.

Specifically, the **Thermal Energy Efficiency Ratio**, EER_{th}, is the ratio of the effective cooling capacity to effective Heat input determined trough the following formula:

$$EER_{th} = \frac{Q_{Ecooling}}{Q_{Einput}} \quad \textbf{Eq. 8}$$

where:

EER_{th} is the thermal EER, in kilowatt per kilowatt;

$Q_{Ecooling}$ is the effective cooling capacity, in kilowatt;

$Q_{E,\, input}$ is the effective Heat input, in kilowatt.

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

$$EER_{el} = \frac{Q_{E,cooling}}{P_E} \quad \textbf{Eq. 9}$$

where:

EER_{el} is the electrical energy efficiency ratio, in kilowatt per kilowatt;

$Q_{Ecooling}$ is the effective cooling capacity, in kilowatt;

PE is the effective electrical power input, in kilowatt.

For discontinuous chillers it is possible to evaluate the energy efficiency ratios, both thermal and electrical, for each operational cycle separately and then to average them. The formulas to use are respectively:

- For the **Thermal Energy Efficiency Ratio**, EER_{th}:

$$EER_{th} = \frac{\sum_{i=1}^{n} EER_{th,i}}{n} \quad \textbf{Eq. 10}$$

where:

i is the cycle number;

n is the number of entire cycles included in the data collection period;

EER_{th} is the thermal EER, in kilowatt per kilowatt;

$EER_{th,i}$ is the thermal EER at the considered cycle, in kilowatt per kilowatt;

- For the **Electrical Energy Efficiency Ratio**, EER_{el}:

$$EER_{el} = \frac{\sum_{i=1}^{n} EER_{el,i}}{n} \quad \textbf{Eq. 11}$$

where:

i is the cycle number;

n is the number of entire cycles included in the data collection period;

EER_{el} is the electrical EER, in kilowatt per kilowatt;

$EER_{el,i}$ is the electrical EER at the considered cycle, in kilowatt per kilowatt;

3.4.1 Pump Efficiency

The pump efficiency can be determined in two ways: from a certificate issued by an accredited laboratory; or as a function of the hydraulic power delivered by the pump as prescribed in the standards EN14511-3:2011. In this last case, depending if the hydraulic power of the pump is lower or higher than 500W, the pumps efficiency is determined as follows:

- for Hydraulic Power < 500W

$$\eta = 0{,}0721 \cdot P_{hydrau}^{0{,}3183} \quad \textbf{Eq. 12}$$

- for Hydraulic Power > 500W

$$\eta = 0{,}092 \cdot Ln(P_{hydrau}) - 0{,}0403 \quad \textbf{Eq. 13}$$

Where in both cases

η is the efficiency of the pump, watts per watt;

P_{hydra} is the hydraulic power of the pump, in watts.

Concerning the Hydraulic Power of the pump, P_{hydra}, when the pump is an integral part of the appliance it is defined as:

$$P_{hydrau} = q \cdot \Delta p_e \quad \textbf{Eq. 14}$$

Where

P_{hydra} is the hydraulic power of the pump, in watts.

q is the water volume flow rate, in cubic meters per second;

Δp_e is the measured available external static pressure difference, in pascals.

While, when the pump is not an integral part of the appliance, the hydraulic power of the pump is defined as:

$$P_{hydrau} = q \cdot (-\Delta p_i) \quad \textbf{Eq. 15}$$

Where

P_{hydrau} is the hydraulic power of the pump, in watts.

q is the water volume flow rate, in cubic meters per second;

Δp_i is the measured internal static pressure difference, in pascals.

Figure 3 shows the graph of the efficiency of the pump versus its hydraulic power for pumps having P_{hydrau}< 500W. While Figure 4 shows the same trend but for pumps having P_{hydrau}> 500W.

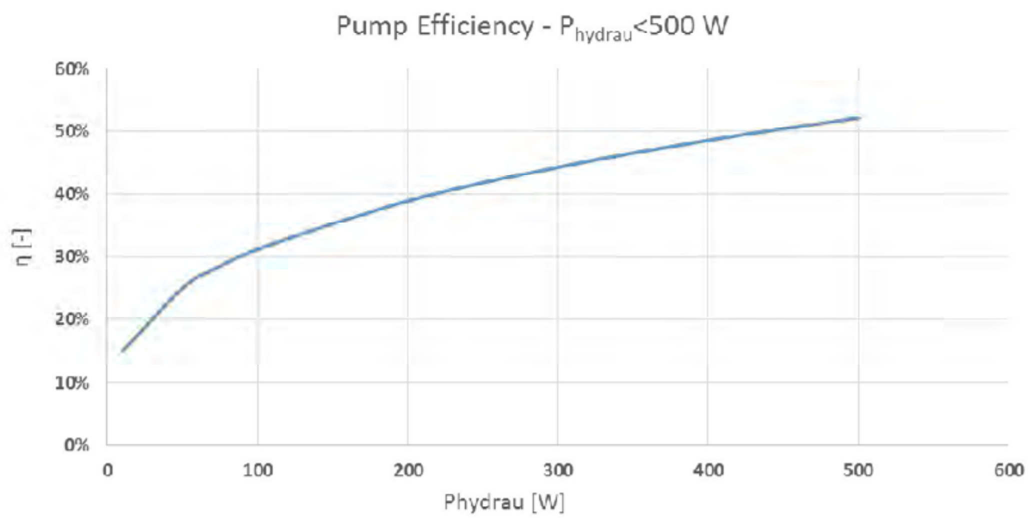


Figure 3 Pump efficiency vs. its hydraulic power (<500W)

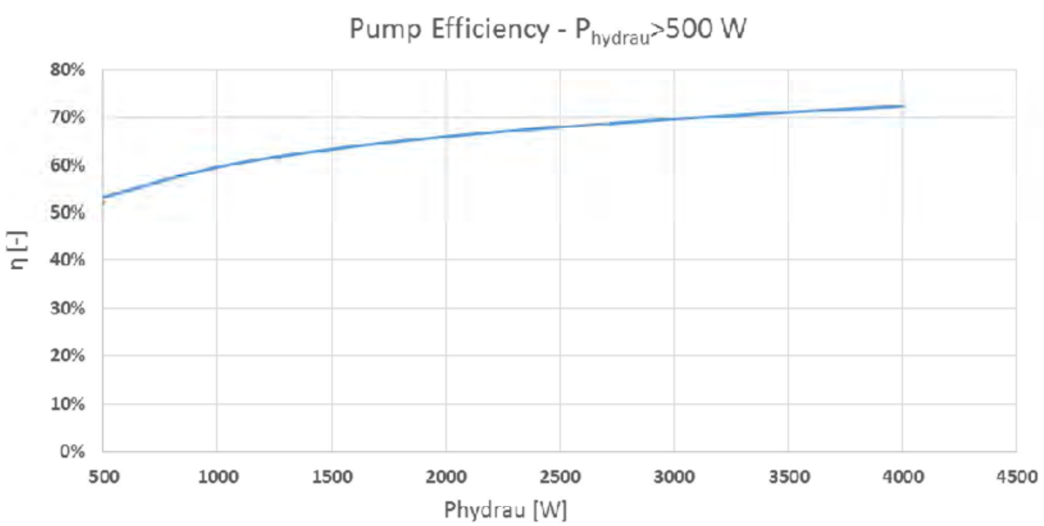


Figure 4 Pump efficiency vs. its hydraulic power (>500W)

3.5 Test Protocol

This section deals with the procedures developed for performing tests on sorption chillers, both continuous and discontinuous, at full and partial load. They concern only stationary tests and describe step by step how to run the tests on the appliance, i.e. from the its installation into the test apparatus until the data recording for the performance figures calculation.

Below the two test procedures at full load and partial load are described separately. Where necessary, specific provisions linked to the machine operation (continuous or discontinuous) are provided promptly.

3.5.1 "FULL LOAD" Test Procedure

The procedure for **full load tests** consists of the following steps:

1. Install and connect the sorption chiller to the compensation system (i.e. test apparatus) as recommended by the manufacturer in the installation and operation manual. The accessories provided by option shall not be included in the test.

   SPECIFIC RECOMENDATIONS

2. For appliances having air as heat transfer medium at the condenser:
   a. In case of ducted appliances, the connection to the test apparatus shall be sufficiently air tight to ensure that the measured results are not significantly influenced by exchange of air with the surroundings;
   b. In case of non-ducted appliances, set louvers and fan speed in order to obtain the maximum steady-state operation air flow. After that setting, the air flow rate is left under control of the appliance. If the sorption chiller is modulating, when it modulates, no disturbance of air flow should be perceived by the appliance as a consequence of the operation of test room apparatus.

3. For appliances with integral and adjustable water or brine pump(s), set the pump(s) (speed step or frequency) in order to obtain an external static pressure (ESP) as close as possible to 10 Pa. This setting shall be done at the same time as the temperatures are set.

4. Set the lowest room temperature on the unit control device (e.g. on the thermostat connected to the machine) or set the lowest water temperature directly on the machine's interface. In this way, the appliance is operated to provide the maximum useful cooling capacity.
5. Set the nominal (water or brine) flow rates at the three heat exchangers declared by the manufacturer for the corresponding standard (nominal) rating conditions. After this setting, the water flow rate is left under control of the appliance.
   a. *For Continuous chiller*

      Once all quantities under control are stable (e.g. the inlet/outlet temperatures at the heat exchangers, the flow rates, etc...), if the flow rate set previously does not guarantee the desired temperature difference (ΔT) at the inlet and outlet of three the heat exchanger, especially at the evaporator, change the flow rate until the desired value of ΔT is matched.
6. Measure the resulting pressure drops and in case of values higher than 10 Pa, decrease again the speed or frequency of the pump if possible.
7. Set the desired rating conditions in terms of the inlet temperatures at the three heat exchangers and air dry and wet bulb;

<u>SPECIFIC RECOMMENDATIONS</u>

8. In case of appliances using brine as heat transfer medium, state the nature and the concentration of the product to use for the tests. (The minimum brine concentration shall be chosen to provide proper operation at minimum outlet temperature stated).

9. Wait until the steady state operation is achieved (**equilibrium period**).
   - *c.* *<u>For Continuous chiller</u>*

     All the measured quantities shall remain constant without having to alter the set values for a minimum duration of 30 minutes, with respect to the tolerances given in Table 2.
   - *d.* *<u>For Discontinuous chiller</u>*

     All the measured quantities shall remain constant without having to alter the set values for a minimum duration of two calculation cycles, with respect to the tolerances given in Table 3.

10. After that equilibrium period ends, start collecting all meaningful data with the same frequency.
    - *e.* *<u>For Continuous chiller</u>*

      The data collection period shall last 40 minutes. The sample time shall be at least 10seconds.
    - *f.* *<u>For Discontinuous chiller</u>*
    - g. The data collection period shall last two calculation cycles. The sample time shall be at least 2 seconds.

11. Rate the thermal and electrical power and calculate the EER

Table 2 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	entire load	± 0,2 K	entire load	0,5 K
Outlet temperature		± 0,3 K		0,6 K
Flow rate		± 2 %		5%
Static pressure difference		/		10%
EVAPORATOR (water or brine)				
Inlet temperature	entire load	± 0,2 K	entire load	0,5 K
Outlet temperature		± 0,3 K		0,6 K
Flow rate		± 2 %		5%
Static pressure difference		/		10%
CONDENSER				
Air :				
Inlet temperature: Dry-bulb (wet-bulb)a	entire load	± 0,3 K (± 0,4 K)	entire load	1,0 K (1,0 K)
Air flow rate (volume)		/		/
Air static pressure		/		/
Water or Brine:				
Inlet temperature	entire load	± 0,2 K	entire load	0,5 K
Outlet temperature		± 0,3 K		0,6 K
Flow rate		± 2 %		5%
Static pressure difference		/		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

** Standard deviation calculated as it is

Table 3 Permissible deviations on the set values during stationary tests for Discontinuous 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	entire load	± 0,2 K	entire load	1,5 K
Flow rate		± 2 %		5%
Static pressure difference		/		10%
EVAPORATOR (water or brine)				
Inlet temperature	entire load	± 0,2 K	entire load	1,5 K
Outlet temperature or Mean temperature		± 0,5 K		1,5 K
Flow rate		± 2 %		5%
Static pressure difference		/		10%
CONDENSER				
Air :				
Inlet temperature: Dry-bulb (wet-bulb)[a]	entire load	±1,5 K	entire load	2,5 K
Air flow rate (volume)		/		/
Air static pressure		/		/
Water or Brine:				
Inlet temperature	entire load	± 0,2 K	entire load	1,5 K
Flow rate		± 2 %		5%
Static pressure difference		/		10%
Electrical input				
- voltage	± 4 %		± 4 %	
Cycle Time				
- Cycle	/		5%**	
Efficiency				
- EER (of each Cycle)	5%		2,5%**	
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

** Standard deviation calculated as it is

3.5.2 "PART LOAD" Test Procedure

Concerning the tests at partial loads, they can be performed in two ways: as "Continuous" tests or as "ON-OFF" tests.

In the "Continuous" test, the part load is obtained by controlling continuously the quantities at the inlets of the machine. The "typical" way is to adjust the output of the sorption chiller, i.e. cooling capacity, by controlling:

- either the inlet temperature at generator, i.e. the heat input (see Figure 5);
- or inlet temperature at condenser, i.e. the heat rejected (see Figure 6);
- or both.

(*This kind of control shifts the thermodynamic working points*)

Another way is to vary the flow rates at the three heat exchangers. Nevertheless, this last practice is not so common since it foresees a more complex control of the actuators involved.

In the ON-OFF tests instead, the desired part load is achieved as the average of the cooling capacity rated over the "ON" and "OFF" periods of the machine (see Figure 7). 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; instead, if it is lower than the desired part load, the ON period is extended. The whole procedure is following explained.

Provided that the characterization of the chillers at partial loads can be done with both types of tests, the logic that should be used for this kind of tests is the following one:

- Perform continuous tests until the desired part load can be reached by this procedure (restrictions can be given by technological limitations of the appliance under test such as the maximum or minimum inlet temperature at the generator);
- Then, if the minimum part load reachable in continuous mode is higher than the desired part load, perform ON-OFF tests.

Below, the two procedures are described in detail. Where necessary, specific provisions linked to the machine operation (continuous or discontinuous) are provided promptly.

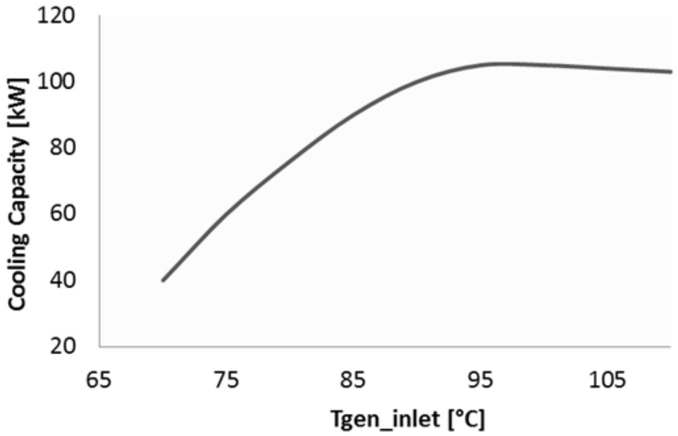


Figure 5 Part loads vs. the inlet temperature at the generator

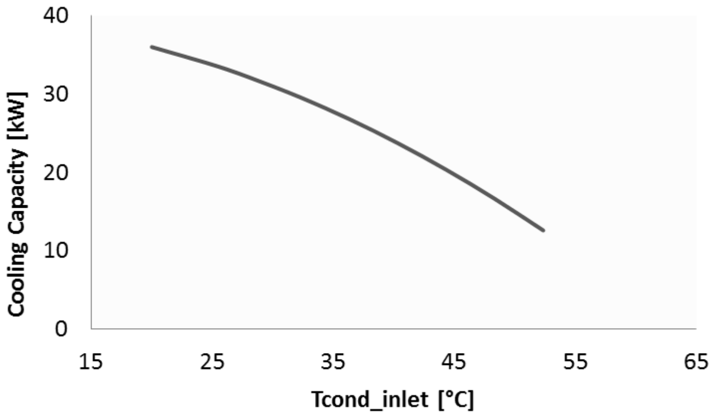


Figure 6 Part loads vs. the inlet temperature at the condenser

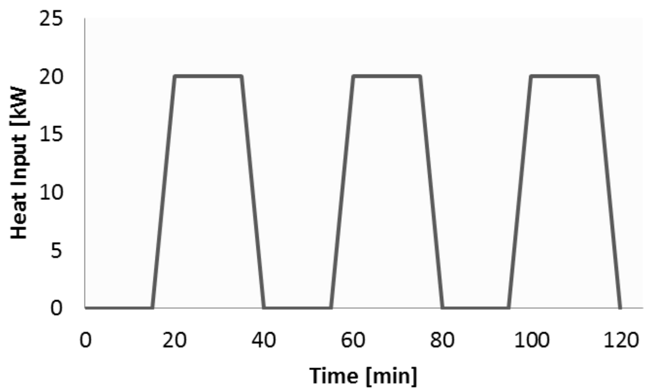


Figure 7 ON-OFF tests

3.5.3 Continuous Test: Procedure

The procedure to perform part load tests in continuous mode consists of the following steps:

1. On the basis of the desired part load, calculate the inlet temperatures at the evaporator using as inlet parameters:
    a. the water flow rate determined at standard rating test conditions that will be kept fixed during the test;
    b. the outlet temperature required at the desired part load (if the climatic curve[1] is used) and for the specific application (e.g. 7°C for fan coil; 18°C for radiant floor). The outlet temperature will be kept fixed during the test;
2. Set the calculated inlet temperature at the evaporator and the inlet temperature at the condenser corresponding to the desired part load;
3. Set the flow rates at the three heat exchanger as determined at standard “full load” rating conditions;
4. Put appliance controller in manual mode and let the appliance provide the maximum useful cooling capacity;
5. Adjust the output of the sorption chiller (i.e. Cooling capacity) by controlling the inlet temperature at generator (i.e. the heat input) keeping fixed the other quantities.

OTHER PROCEDURES

6. Adjust the output of the sorption chiller (i.e. Cooling capacity) by controlling, one per time,
    a. the inlet temperature at generator (i.e. the heat input)
    b. the inlet temperature at condenser (i.e. the heat rejection)
    c. the flow rate at generator (i.e. the heat input)
    d. the flow rate at condenser (i.e. the heat rejection)

    and keeping fixed the other quantities in the meantime.

7. Wait until the steady state operation is achieved (**equilibrium period**).
    h. *For Continuous chiller*

       All the measured quantities shall remain constant without having to alter the set values for a minimum duration of 30 minutes, with respect to the tolerances given in Table 3.
    i. *For Discontinuous chiller*

       All the measured quantities shall remain constant without having to alter the set values for a minimum duration of two calculation cycles, with respect to the tolerances given in Table 4.

VALIDATION CRITERIA

8. To validate the test, it is necessary that the deviations of the achieved cooling capacity are within the ± 10% compared to the target value. If the deviations are more than ± 10%, a second series of test shall be carried out to get a measurement above the target value and a measurement below the target value. In this case, the result is determined by linear interpolation. If the smallest cooling capacity of the unit obtained by a continuous test is higher than the required cooling load, an ON-OFF test shall be performed.

[1] Climatic curve is the trend of the outlet temperature at the evaporator as a function of external ambient conditions (T_{amb}).

3.5.4 ON-OFF Test: Procedure

The procedure for performing the part load tests in ON-OFF mode foresees the control of some actuators, such as the pump at the generator's circuit, necessary for imposing the ON and OFF periods. Specifically the procedure consists of the execution of the first four points of the previous procedure and of further steps here explained:

1. As in the previous procedure, on the basis of the desired part load, calculate the inlet temperatures at the evaporator using the water flow rate determined at standard rating test conditions and the outlet temperature required at the desired part and for the specific application;
2. Set the generator at the minimal heat input allowed in continuous operation mode (i.e. minimal inlet temperature)
3. Set the calculated inlet temperature at the evaporator and the inlet temperature at the condenser corresponding to the desired part load;
4. Set the flow rates at the three heat exchanger as determined at standard "full load" rating conditions;
5. Put appliance controller in manual mode and let the appliance provide the maximum useful cooling capacity;
6. wait until the equilibrium is reached in accordance with the tolerances specified in the Table 4, for continuous chillers, and Table 5, for discontinuous chillers, and stay in this condition for 60min;
7. Start the cycle with an OFF period of 20 min.
8. After that, start with ON period of 20 min.
9. Complete the cycle with OFF period of duration equals to:

$$20 \cdot \left(\frac{Q_{Ecooling}}{PL} - 1 \right) \cdot \min utes$$

Where:

$Q_{Ecooling}$ is the effective capacity during the ON period;

PL is the required partial load.

10. Repeat the steps from 7 to 9 for addition three times (total 4 ON-OFF cycles)

VALIDATION CRITERIA

11. If measured partial load exceeds the tolerance limit of ± 10%, repeat steps 1 to 6 using an OFF period whose duration allows the interpolation or the extrapolation of results at targeted partial load.

Table 4 Permissible deviations on the set values during ON-OFF tests for Continuous machines

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 / ± 2 % /	entire load	0,5 K / 5% 10%
EVAPORATOR (water or brine)				
Inlet temperature Outlet temperature Flow rate Static pressure difference	entire load	± 0,2 K ± 0,5 K ± 2 % /	entire load	0,5 K / 5% 10%
CONDENSER				
Air :				
Inlet temperature: Dry-bulb (wet-bulb)a Air flow rate (volume) Air static pressure	entire load	± 0,3 K (/) / /	entire load	1 K (/) / /
Water or Brine:				
Inlet temperature Outlet temperature Flow rate Static pressure difference	entire load	± 0,2 K / ± 2 %	entire load	0,5 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

** Standard deviation calculated as it is

Table 5 Permissible deviations on the set values during ON-OFF tests for Discontinuous machines

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 Flow rate Static pressure difference	entire load	± 0,2 K ± 2 % /	entire load	1,5 K 5% 10%
EVAPORATOR (water or brine)				
Inlet temperature Outlet temperature or Mean temperature Flow rate Static pressure difference	entire load	± 0,2 K ± 0,6 K ± 2 % /	entire load	1,5 K / 5% 10%
CONDENSER				
Air :				
Inlet temperature: Dry-bulb (wet-bulb)[a] Air flow rate (volume) Air static pressure	entire load	±1,5 K / /	entire load	2,5 K / /
Water or Brine:				
Inlet temperature Flow rate Static pressure difference	entire load	± 0,2 K ± 2 % /	entire load	1,5 K 5% 10%
Electrical input				
- voltage	± 4 %		± 4 %	
Cycle Time				
- Cycle	/		/	
Efficiency				
- EER (of each Cycle)	/		/	
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

** Standard deviation calculated as it is

3.6 Test data to be recorded

The data to be recorded for assessing cooling capacity, heat input, electrical power inputs and the thermal and electrical EER are listed in Table 6. The table identifies the general information required but is not intended to limit the data to be obtained.

These data shall be the mean values taken over the data collection period, with the exception of time measurement.

Table 6 – Data to be recorded

MEASURED QUANTITY OF RESULT	UNIT
Ambient conditions	
- air temperature, dry bulb	°C
- atmospheric pressure	mbar
Electrical quantities	
- voltage	V
- total current	A
- total power input, P_T	kW
- effective power input, P_E	kW
Thermodynamic quantities	
Condenser -Air	
- inlet temperature, dry bulb	°C
- inlet temperature, wet bulb	°C
For duct connection	
- outlet temperature, dry bulb	°C
- outlet temperature, wet bulb	°C
- external/internal static pressure difference	Pa
- volume flow rate	m3/s
Condenser – water/brine	
- inlet temperature	°C
- outlet temperature	°C
- flow rate	m^3/s or kg/s
- pressure drop	kPa
Evaporator (water/brine)	
- inlet temperature	°C
- outlet temperature	°C
- flow rate	m^3/s or kg/s
- pressure drop	kPa
Generator (water)	
- inlet temperature	°C
- outlet temperature	°C
- flow rate	m^3/s or kg/s
- pressure drop	kPa

Heat transfer medium (other than water) - concentration - density - specific heat	 % kg/m³ J/kg.K
Data collection period	s
Capacities - effective cooling capacity (Q_{Ec})	 kW
Ratios - EER_{th} - EER_{elec}	 kW/kW kW/kW

3.7 Test apparatus

The test apparatus shall be design in such a way that all requirements on adjustment of set values, stability criteria and uncertainties of measurement can be fulfilled. Examples of test rig distinguished for type of appliances under test are here provided.

3.7.1 Test apparatus for testing air-to-water/brine chillers at full load and partial load

The test apparatus (*or compensation system*) used for testing air-to-water/brine chillers at full and partial load should consist of:

- a closed climatic test room where the condenser rejects the air energy;
- a test rig connected to the chiller's evaporator consisting of:
  - heating and cooling heat exchangers, to compensate for the cooling and the heating capacity of the appliance;
  - one or more storage tanks to avoid large inlet temperature deviations (about 10 l/kW to 30 l/kW).

An example of this compensation system is shown Figure 8

Concerning the climatic test room, according to the prescriptions of the standard EN14511, the size shall be selected such that any resistance to air flow at the air inlet and air outlet orifices of the chiller is avoided. The air flow through the room shall not be capable of initiating any short circuit between these two orifices, and therefore the velocity of the air flow through the room at these two locations shall not exceed 1.5 m/s when the appliance is switched off. Unless otherwise stated by the manufacturer, the air inlet or air outlet orifices shall be not less than 1 m distant from the surfaces of the test room.

Any direct heat radiation by heating device (appliance, equipment...) in the test room onto the appliance or onto the temperature measuring points shall be avoided.

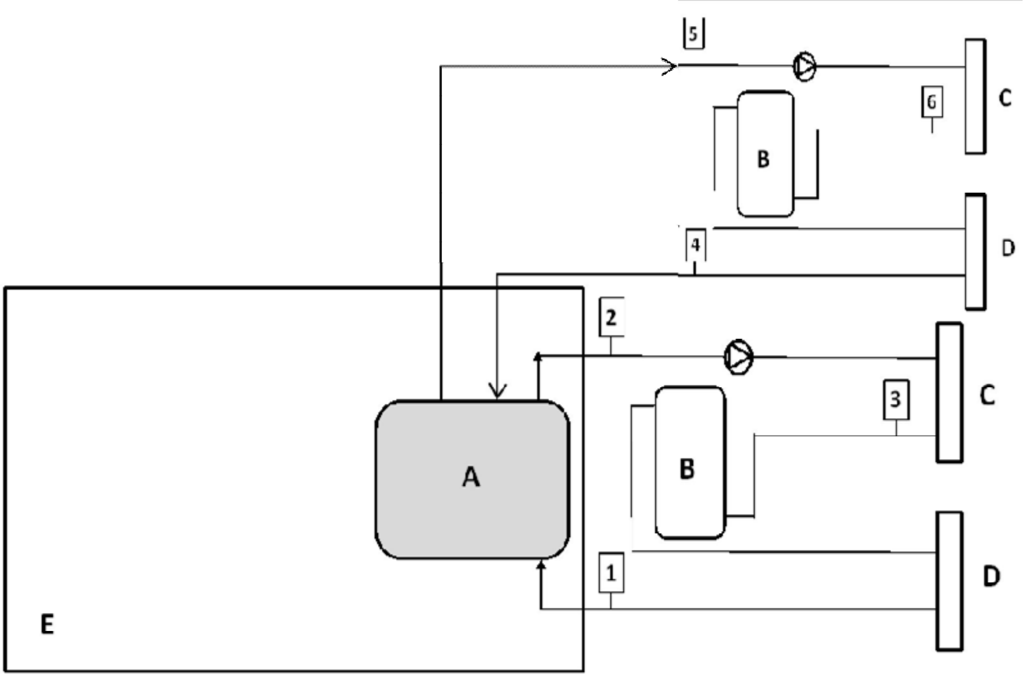


Figure 8 Compensation systems for air-to-water/brine chillers

Key

A chiller under test

B storage tank

C Primary compensation heat exchanger

D Secondary compensation heat exchanger

E climatic test room

1 inlet temperature of the chiller's evaporator

2 outlet temperature of the chiller's evaporator

3 intermediate temperature for test rig control with 3 < 2 and 3 < 1

3.7.2 Test apparatus for testing water/brine-to-water/brine chillers at full load and partial load

For testing water/brine-to-water/brine chillers at full and partial load, the chillers shall be installed in compensation system that includes:

- heating and cooling heat exchangers to compensate the cooling and the heating capacity of the appliance
- one or more storage tanks to avoid large inlet temperature deviations (10 l/kW to 30 l/kW).

as shown in the Figure 9.

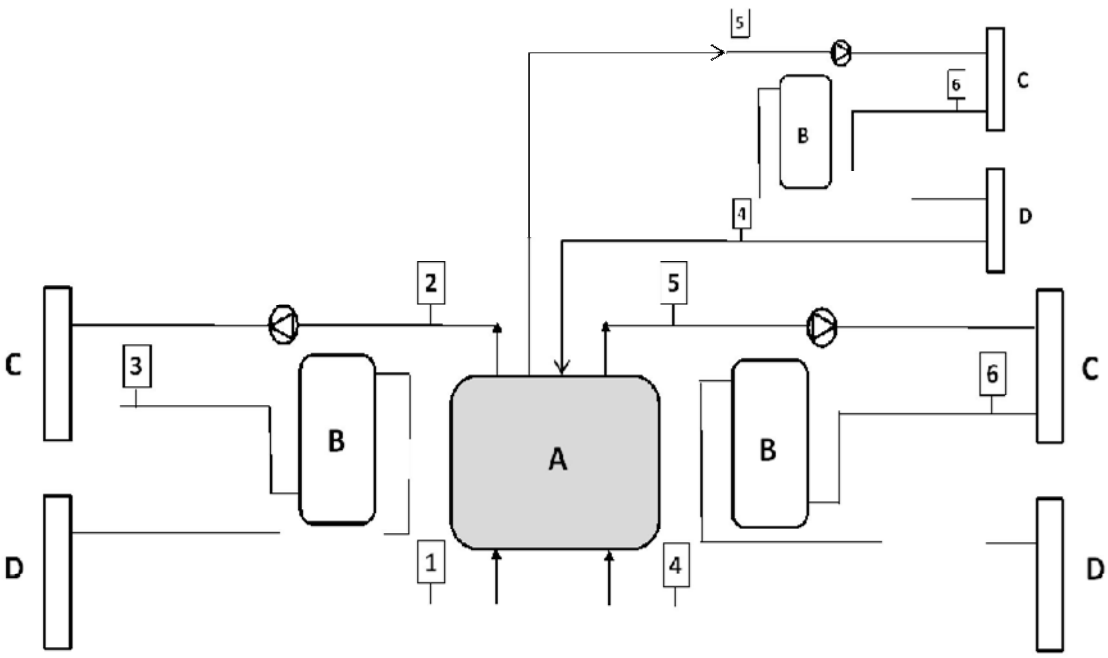


Figure 9 Compensation systems for water/brine-to-water/brine chillers

Key

A chiller under test

B storage tank

C Primary compensation heat exchanger

D Secondary compensation heat exchanger

1 inlet temperature of the chiller's condenser

2 outlet temperature of the chiller's condenser

3 intermediate temperature for test rig control with 3 < 2 and 3 < 1

4 inlet temperature of the chiller's evaporator

4 outlet temperature of the chiller's evaporator

6 intermediate temperature for test rig control with 6 < 5 and 6 < 4

3.7.3 Specification for the measurement equipment position

Concerning the position of the measurement equipment:

- The temperature and pressure measuring points shall be arranged in order to obtain mean significant values.
- For the free air intake temperature measurements, it is required:
  - either to have at least one sensor per square meter and not less than four measuring points and by restricting to 20 the number of sensor equally distributed on the air surface;
  - or to use a sampling device. The sampling device shall be completed by four sensors for checking uniformity if the surface area is greater than 1 m²;
- Air temperature sensors shall be placed at a maximum distance of 0.25 m from the free air surface;
- The water density used to calculate the mass flow rate from the volume flow rate shall be determine in the temperature conditions measured near the flow measuring device.

3.7.4 Measurement equipment and uncertainties

Measuring in the same way and with the same quality in all test facilities is an important prerogative to obtain comparable results.

This section aim at provide the minimum requirements in terms of uncertainty that measurement equipment shall satisfy.

Specifically Table 7 lists the uncertainties of individual measurements. They can be used as criteria for the selection of the measuring apparatus.

For measurements requiring a combination of individual measurements (e.g. efficiency measurements), the lower uncertainties associated with individual measurements may be necessary to limit the overall uncertainty.

- The cooling capacity and the heat input shall be determined within a maximum overall uncertainty of (20,5*ΔT- 0.89)%, independent of the individual uncertainties of measurement including the uncertainties on the properties of fluids. The ΔT is the temperature difference between inlet and outlet at the evaporator and generator.
- The total electrical power input shall be determined within a maximum overall uncertainty of 1%, independent of the individual uncertainties.

If the water flow stops during, for example, during an ON-OFF test, no maximum overall uncertainty is required for the capacity. However, the measurements tools shall fulfill the uncertainties of individual measurements required for steady state operation tests.

The same principle applies for electrical power input.

Table 7 – Uncertainties of measurement for indicated individual values

Measured parameter	Nomenclature	Unit	Uncertainty
Cooling capacity			
Outlet/inlet temperature	T_{out} T_{in}	°C	+/- 0.15 K
Temperature difference	Δt	K	+/- 0.15 K
Flow rate (volume or mass)	V_m or m	m^3/s or kg/s	+/- 1%
Static pressure difference	Δp_i	Pa	+/- 5 Pa ($p \leq 100$ Pa) +/- 5 % ($p > 100$ Pa)
Heat input			
Outlet/inlet temperature	T_{out} T_{in}	°C	+/- 0.15 K
Temperature difference	Δt	K	+/- 0.15 K
Flow rate (volume or mass)	V_m or m	m^3/s or kg/s	+/- 1%
Static pressure difference	Δp_i	Pa	+/- 5 Pa ($p \leq 100$ Pa) +/- 5 % ($p > 100$ Pa)
Outlet/inlet temperature	T_{out} T_{in}	°C	+/- 0.15 K
Heat Rejection – Air a)			
Dry bulb temperature		°C	+/- 0.2 K
Wet bulb temperature		°C	+/- 0.4 K
Flow rate		m^3/s	+/- 5%
Note a) In case, Brine or Water is used as heat transfer medium in heat rejection circuit, the value of uncertainties of measurement to be respected are those prescribed for the cooling capacity			
Electrical input			
Electrical power	P_T	kW	+/- 1%
Other			
Time			+/- 0.2 s (up to 1 h) +/- 0.1% (beyond 1 h)

3.8 Uncertainty Calculation: basic rules

The estimation of the measurement uncertainty of the quantities monitored and calculated is fundamental since it expresses the intrinsic reliability of the achieved results. Every time a quantity of interest is measured, the outcome depends on the measuring system, the measurement procedure, the skill of the operator, the environment, and other effects. Therefore, it is not thinkable to show performance figures obtained according to the test procedures here presented without stating the range where their true value can vary.

This section has the aim to provide basic rules for calculating the uncertainty of the major quantities measured and calculated. The references used are the standard ENV 13005 "*Guide to the Expression of Uncertainty in Measurement*" and the guidelines "*EA-4/02*" derived from it.

Assuming that the generic quantity **z** (test result), called *measurand*, is not measured directly but depends on *n* other inlet quantities $x_1, x_2, \ldots, x_N$ through the functional relation z, i.e. $\mathbf{z} = z(x_1, x_2, \ldots, x_n)$, the combined measurement uncertainty, u_c, is determined as follows:

$$u_c = \sqrt{\left(\frac{\partial z}{\partial x_1}\right)^2 u(x_1)^2 + \left(\frac{\partial z}{\partial x_2}\right)^2 u(x_2)^2 \ldots\ldots + \left(\frac{\partial z}{\partial x_n}\right)^2 u(x_n)^2} \qquad \textbf{Eq. 16}$$

by applying the law of propagation of uncertainty and by assuming that the inlet quantities $x_1, x_2 \ldots x_n$ are uncorrelated, i.e. independent among them.

The partial derivatives of the quantity z with respect to the n-th variable represent the sensitivity coefficients evaluated at the working point, i.e. in correspondence of the estimated value of $x_1, x_2 \ldots x_n$; while $u_{x_1}, u_{x_2}, \ldots, u_{x_n}$ are the standard uncertainties of the measurements of $x_1, x_2 \ldots x_n$.

Such uncertainties are obtained as a combination (*i.e. sum*), under root square, of two types of uncertainty: uncertainty *Type A* and uncertainty *Type B*, which differ on the basis of the calculation methods. In details:

- The uncertainty Type A is the uncertainty evaluated by statistical methods. It is calculated on a series of repeated independent measurements of the quantity x_i that it is assumed to have a Gaussian distribution. In this case, the expected value or true value is the average of the measured values; while the associated uncertainty is the standard deviation of the average, σ_i, equal to the positive square root of the statistically estimated variance $\sigma_i^{\,2}$. When the uncertainty is evaluated from a small number of measured values (regarded as instances of a quantity characterized by a Gaussian distribution), the corresponding distribution can be taken as a t-distribution. This kind of uncertainty allow taking into consideration random errors.

- The uncertainty *Type B* is the uncertainty evaluated by methods different from statistical ones. It is usually based on scientific judgment using all of the relevant information available, which may include:
    - previous measurement data;

- experience with, or general knowledge of, the behavior and property of relevant materials and instruments;
- manufacturer's specifications;
- data provided in calibration and other reports and uncertainties assigned to reference data taken from handbooks.

Broadly speaking, this type of uncertainty is obtained either from an outside source or from an assumed distribution and it represents systematic errors.

From the statistical law of the propagation of uncertainties, it follows that there are three basic relations for which the resulting deviations become quite simple.

1. For equation of measurand involving only sum or differences

$$y = x_1 + x_2 + \ldots\ldots + x_n \qquad \text{it follows}$$

$$u_c = \sqrt{u(x_1)^2 + u(x_2)^2 \ldots\ldots + u(x_n)^2} \qquad \textbf{Eq. 17}$$

2. For equation of measurand involving only product or quotients

$$y = x_1 \cdot x_2 \ldots\ldots \cdot x_n \qquad \text{it follows}$$

$$\frac{u_c}{|y|} = \sqrt{\frac{u(x_1)^2}{x_1^2} + \frac{u(x_2)^2}{x_2^2} \ldots\ldots + \frac{u(x_n)^2}{x_n^2}} \qquad \textbf{Eq. 18}$$

3. For equation of measurand involving only exponents

$$y = x_1^a \cdot x_2^b \ldots\ldots \cdot x_n^z \qquad \text{it follows}$$

$$\frac{u_c}{|y|} = \sqrt{\frac{a^2 \cdot u(x_1)^2}{x_1^2} + \frac{b^2 \cdot u(x_2)^2}{x_2^2} \ldots\ldots + \frac{z^2 \cdot u(x_n)^2}{x_n^2}} \qquad \textbf{Eq. 19}$$

The uncertainties $u(x_i)$ are defined "absolute uncertainties"; the uncertainties $\frac{u_i^2}{x_i^2} = u^2{}_{rel,i}$ are also defined as the relative uncertainties which are usually written as a percentage.

Once the combined uncertainty, u_c, has been determined, it is possible calculated the expanded uncertainty by multiplying it by the coverage factor k assumed in this case equal to 2 and corresponding to a confidence level equal to 95%,

Using the notions just introduced, the procedures for the calculation of the uncertainty of the quantities result of the test are following described in details.

Starting from the equations for the calculation of the *Cooling Capacity* and *Heat Input* of the unit under test, their measurement uncertainty is obtained by using the law of the propagation of uncertainty as follow:

$$u_{c,REL}(Q_{cooling/input}) = \sqrt{u^2(\dot{V})_{REL} + u^2(\rho)_{REL} + u^2(c_p)_{REL} + u^2(\Delta T)_{REL}} \qquad \textbf{Eq. 20}$$

Where:

- $u_{c,REL}(Q_{cooling/input})$ is the relative uncertainty of the measured cooling capacity/heat input of the unit under test;
- $u^2(\dot{V})_{REL}, u^2(\rho)_{REL}, u^2(c_p)_{REL}, u^2(\Delta T)_{REL}$ are the relative uncertainties of the inlet quantities, i.e.: volume flow $\dot{V}$, density ρ, specific heat c_p and difference between inlet and outlet temperatures of the heat transfer medium at the evaporator/generator ΔT.

The combined uncertainties of the *Effective Cooling Capacity*, $Q_{Ecoolin}$ and *Effective Heat Input*, Q_{Einpu}, are calculated as follow:

$$u_c(Q_{E\,cooling/input}) = \sqrt{u^2(Q_{cooling/input}) + u^2(\varepsilon_{pump,eva/gen})} \qquad \textbf{Eq. 21}$$

where:

- $u(Q_{E\,cooling/input})$ is the absolute uncertainty of the effective cooling capacity/heat input of the unit under test;
- $u(Q_{cooling/input})$ is the absolute uncertainty of the measured cooling capacity/heat input of the unit under test;
- $u(\varepsilon_{pump,eva/gen})$ is the absolute uncertainty of capacity correction due to the pump(s) responsible for circulating the heat transfer medium through the evaporator/generator.

The combined uncertainties of the *Effective Electric Power Input*, P_E, instead are calculated as follow:

$$u_c(P_E) = \sqrt{u^2(P_T) + u^2(\varepsilon_{pump,eva}) + u^2(\varepsilon_{pump,gen}) + u^2(\varepsilon_{pump,cond})} \quad \textbf{Eq. 22}$$

Where:

- $u(P_E)$ is the absolute uncertainty of the effective electrical power input of the unit under test;
- $u(P_T)$ is the absolute uncertainty of the measured (total) electrical power of the unit under test;
- $u(\varepsilon_{pump,eva})$ is the absolute uncertainty of capacity correction due to the pump(s) responsible for circulating the heat transfer medium through the evaporator;
- $u(\varepsilon_{pump,gen})$ is the absolute uncertainty of capacity correction due to the pump(s) responsible for circulating the heat transfer medium through the generator;
- $u(\varepsilon_{pump,cond})$ is the absolute uncertainty of capacity correction due to the pump(s) responsible for circulating the heat transfer medium through the condenser.

Finally, from the definitions of the *Thermal Energy Efficiency Ratio*, EER_{th}, and **E***lectrical Energy Efficiency Ratio*, EER_{el}, the combined measurement uncertainties are calculated as follow:

$$u_{REL}(EER_{th}) = \sqrt{u_{REL}{}^2(Q_{Ecooling}) + u_{REL}{}^2(Q_{Einput})} \quad \textbf{Eq. 23}$$

Where:

- $u(EER_{th})$ is the relative uncertainty of the Thermal EER;
- $u_{REL}(Q_{E\,cooling})$ is the relative uncertainty of the effective cooling capacity of the unit under test;
- $u_{REL}(Q_{E\,cinput})$ is the relative uncertainty of the effective heat input of the unit under test;

$$u_{REL}(EER_{el}) = \sqrt{u_{REL}{}^2(Q_{Ecooling}) + u_{REL}{}^2(P_E)} \quad \textbf{Eq. 24}$$

Where:

- $u(EER_{el})$ is the relative uncertainty of the electrical EER;
- $u_{REL}(Q_{E\,cooling})$ is the relative uncertainty of the effective cooling capacity of the unit under test;
- $u_{REL}(P_E)$ is the relative uncertainty of the effective electrical power input of the unit under test.

4 Test Validation

A validation process on the test procedures here presented has been started with the aim to demonstrate their fitness for the intended purposes and to verify their representativeness, reproducibility and repeatability in the application range.

It touched mainly the protocol for performing continuous tests at full load and partial load, the criteria for establishing the stationary operation of the chillers and the formulas for the calculation of the performance figures according to the defined control volume.

For the purpose, the tests carried out by the project partners in their laboratories have been used. Specifically, the validation has been done through:

- tests already carried out by the project partners according to their internal procedures (post-validation process);
- And tests carried out ad-hoc by the project partners by using the procedures here present (validation process).

For the collection of the test data, a file excel consisting of several sheets, each requiring specific information, have been distributed among the project partners. It includes:

- The sheet “TEST DATA”, in which the information related to the type of the machine tested (e.g. if continuous or discontinuous), the type of the data monitored and recorded during the test, the duration of the equilibrium period and the data collection period have been provided;
- The sheet “RATING CONDITIONS”, in which the conditions at which the project partners typically test the appliances for solar cooling applications shall be provided;
- Two sheets named respectively “TOLERANCES Continuous Test” and “TOLERANCES ON-OFF Test”, in which, next to the tolerances prescribed in the developed procedures per each test type, the tolerances used by the project partners for establishing the stationary of the machine and acceptability of tests shall be provided;
- The sheet “UNCERTAINTIES”, in which the uncertainties of the measurement equipment used by the project partners to monitor the test are required;
- The sheet “DATA”, where the data recorded during the specific test shall be provided. In details the data to provide are: inlet and outlet temperatures at the three heat exchangers (generator, absorber/condenser and evaporator), the flow rates, and where measure the pressure drops at the three circuits and the electrical power consumption.

Once the data have been inserted, conditional relations inside the excel cells allow showing immediately if the stationary criteria have been fulfilled or not and, consequently, if the test can be accepted.

- Finally there’s the sheet “GRAPHS”, where the data inserted in the sheet “DATA” are plotted in two graphs: one reporting the inlet ant outlet temperatures at the three heat exchangers; and the other one reporting on one axis the flow rates at the three exchangers and on the other axis the pressure drops at the three circuits.

In total, seventeen excel files have been compiled, all with data related to continuous tests carried out respectively on:

- Three continuous chillers (one on-sales machine and two prototypes), whose one series carried out ad-hoc

Three discontinuous chillers (two on-sales machines and one prototype) , whose one series carried out ad-hoc.

No excel file have been provided with data from ON-OFF tests. This means that the validation on this type of test is not possible.

An analysis executed on the received excel files has brought to following major results:

- The conditions at which the chillers usually are rated often follow those prescribed in the reference standard and those prescribed but depend most on the specific application.
- Pressure drops are often not measured so no Effective Cooling Power and Electric Power can be measured (and effective EER consequently)
- The defined “stationary criteria” work. It seems that no further modifications are needed
- When the tests don’t match the criteria is because the apparatus has controls and devices not adequate for this kind of tests. Usually this problem could be solved by using storages and by using improved control strategies

4.1 Validation Case Study: The “Itae” Testing Facility

One of the testing bench employed for the validation described above is located at “C E N T R O P R O V E ” of C.N.R. I.T.A.E. in Messina. A detailed layout of the testing rig is shown in **Erreur ! Source du renvoi introuvable.**; it allows to simulate operational conditions for thermally driven chillers. Heat source is simulated by a gas heater with nominal power of 45kW, which is connected to a 1500 liters 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 liters storage, inlet temperatures of the circuit are regulated by means of high-accuracy temperature controllers acting on motorized 3-way valves that allows mixing inlet and outlet flows in order to maintain a constant inlet temperature. Controllers managing such system applies a Proportional-Integrative-Derivative algorithm allowing a good accuracy in the control of the temperature. All 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.

Flow rates in all the circuits can be controlled by variable speed pumps.

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.

Testing procedure

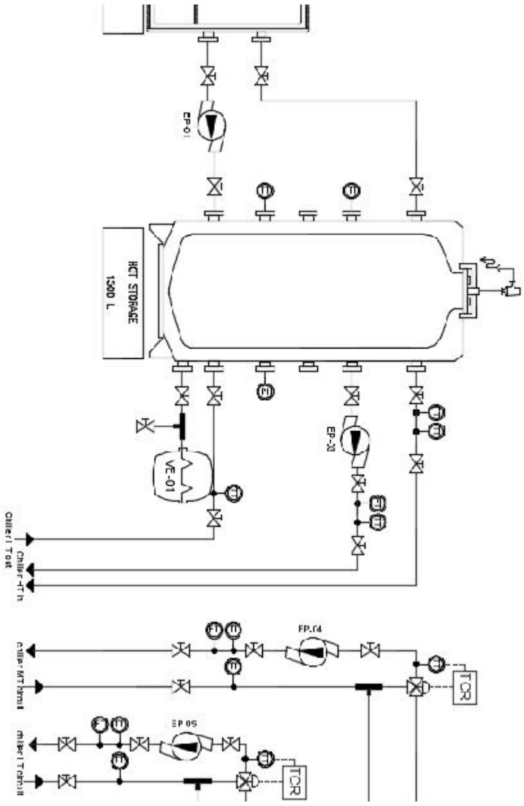
In order to verify the protocol the following testing procedure has been applied:

a. Heating of the test bench in order to reach set-point temperatures in the storages;
b. Regulation of pump speed in the test bench and LT and MT inlet temperatures;
c. Turn on of the chiller and definition of cold set point;

d. Operation of the chiller for 3 cycles;
e. Start of the recording (recording interval: 1 s);
f. 1-hour testing

The following parameters were recorded and memorised onto an excel file:

- Inlet and outlet temperatures of HT circuit in the test bench;
- Inlet and outlet temperatures of MT circuit in the test bench;
- Inlet and outlet temperatures of LT circuit in the test bench;
- Ambient temperature;
- Temperatures in the upper and lower part of hot water storage;
- Temperature in cold storage;
- Flow rate in HT circuit in the test bench;
- Flow rate in MT circuit in the test bench;
- Flow rate in LT circuit in the test bench;
- Flow rate in MT circuit of the electric chiller;
- Flow rate in MT circuit of the electric chiller;
- Pressure drop in HT circuit of the adsorption chiller;
- Pressure drop in MT circuit of the adsorption chiller;
- Pressure drop in LT circuit of the adsorption chiller;
- Electric energy consumption of the two chillers and their auxiliaries.



Typical trends

Trends in temperatures and flow rates during a test differ considerably in consideration of condensation temperature. Figure 10 depicts the temperature trends for a typical validation test with the following boundaries: HT=85°C, MTin=25°C, LT set-point=16°C.

It is possible to notice the typical tendencies for an adsorption (discontinuous) chiller, with a discontinuous evolution basing on phase cycle and cycle time. Nonetheless, curve trends are regular, thus indicating a steady-state behaviour.

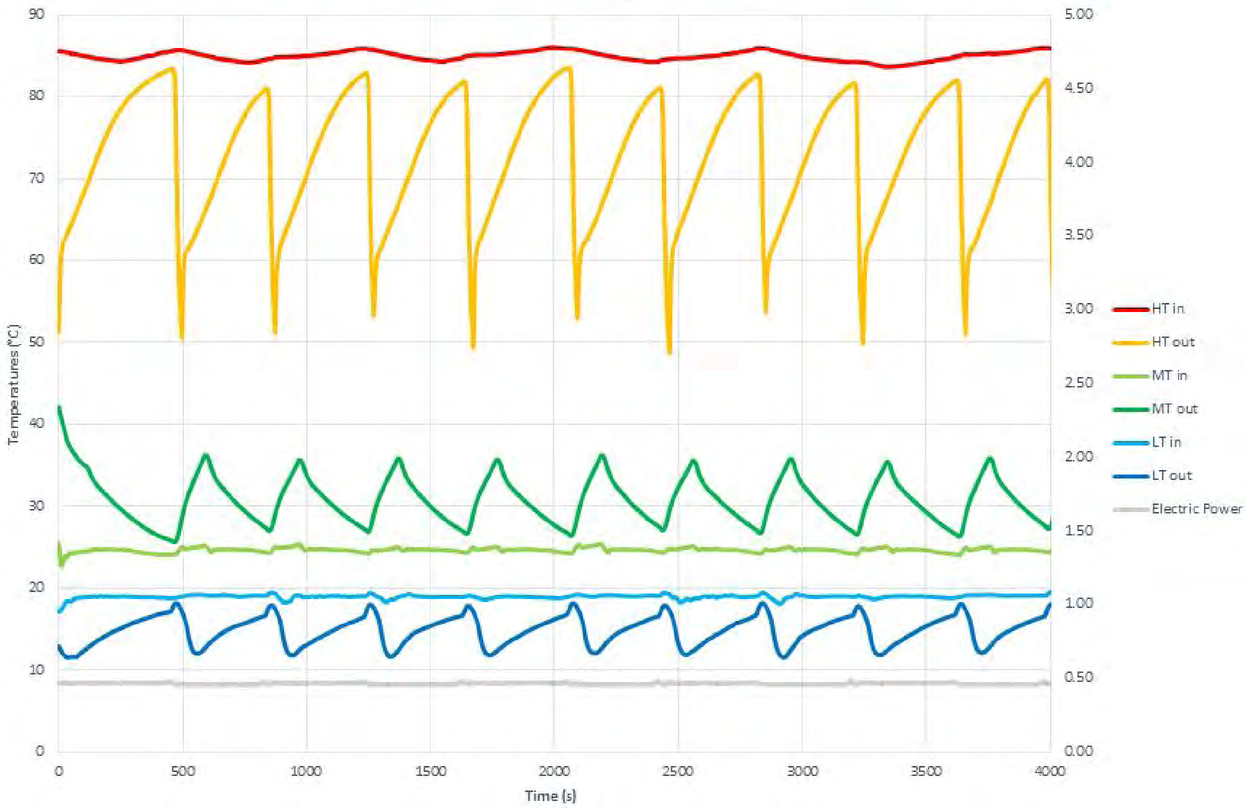


Figure 10: temperature trends for a test with low condensation temperature.

Figure 11 shows power trends during the same test: it clearly visible that power curves follow the trend of temperature curves, with peak value reached within the first 100 seconds from phase shift and a decreasing effect henceforth, the average value being the chiller nominal power (@ full load).

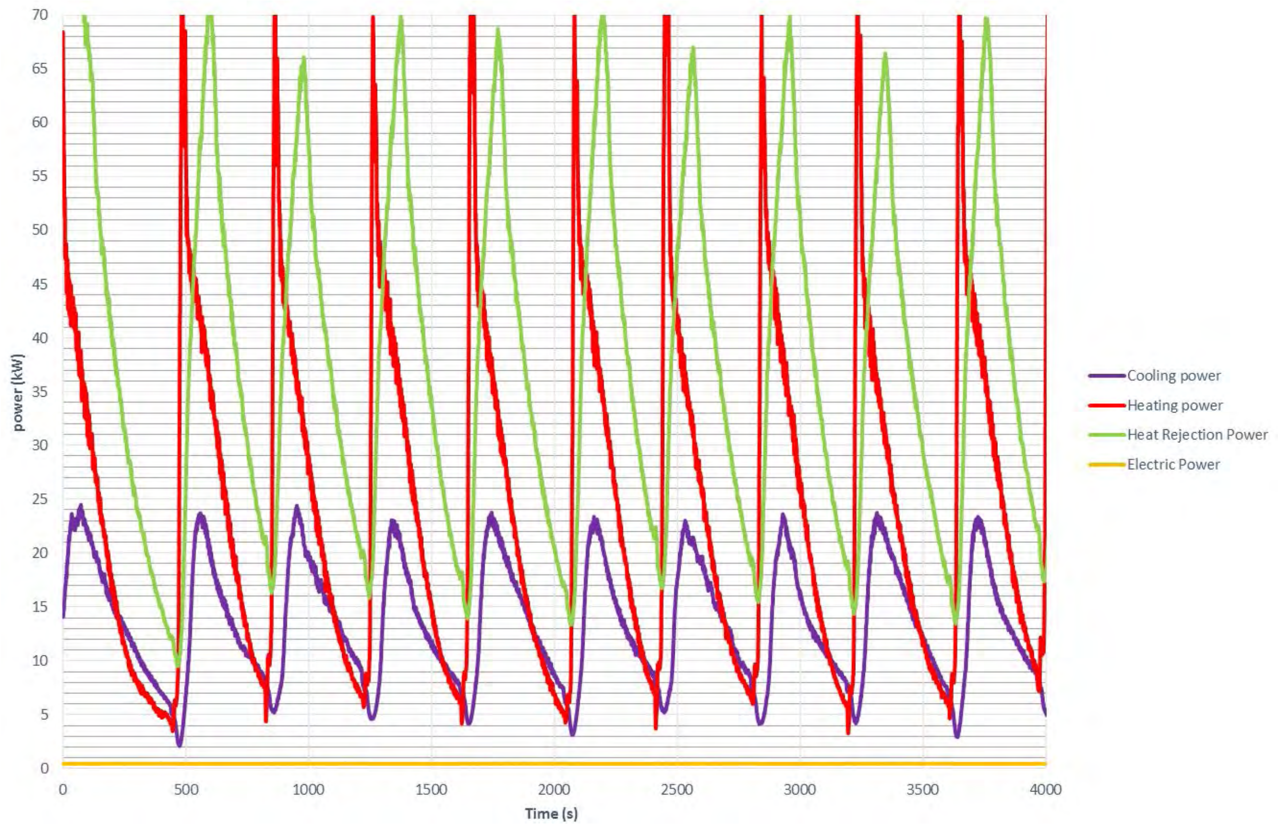


Figure 11: power trends for a test with low condensation temperature.

5 Conclusion

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 drawn up and here presented 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 fitness for the intended purposes and to verify their representativeness in the application range, a first attempt of validation on them has been carried out.
Nevertheless, since this process did not cover all parts of the procedures, further efforts shall be put in this sense. The next steps will regard the complete validation of the test procedures.

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