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Quality for solar cooling on component level

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Abstract

Within IEA-SHC Task 48 "Quality assurance and support measures for Solar Cooling" the most crucial components of solar thermal cooling plants have been analyzed in detail aiming at improving their quality. Test procedures for characterizing continuous and discontinuous chillers have been developed; market available heat rejection devices have been investigated, rating their performance through monitoring data and comparing them; pump efficiency has been also investigated and design guidelines for pump selection and hydraulic configuration are now available; a detailed and updated database of medium temperature collectors has been built.

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Keywords: Solar cooling; chiller characterization; heat rejection devices; pump efficiency; medium temperature collectors

1. Introduction

Solar cooling used to be considered as a promising technology and has always attracted huge interest among designers, policy makers and even private citizens. Nevertheless, so far it did not boom due to several reasons, among them for sure the complexity of systems, which led sometimes to high maintenance needs and/or low performance. That is why IEA Task 48 targets quality issues. Subtask A is considering the component level (while subtask B addresses the system level).

In order to ensure quality in solar cooling systems, most crucial components have been analyzed in detail: sorption chillers, heat rejection devices, circulation pumps and solar thermal collectors have been investigated. Objectives were mainly of two kinds: retrieving market available products and defining quality characteristics. For

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what concerns sorption chillers, since their application to solar cooling is relatively recent and little standardization work has been done so far, special care has been given to the definition of specific test procedures.

2. Chiller characterization

2.1. Overview

An analysis on the current normative scenario and EU regulations has revealed that, for the solar cooling technology and in particular, for one of its core components, i.e. sorption chillers, few reference standards exist and do not seem adequate and coherent. The major remarks emerged from this study were:

- The standards don't cover all sorption technologies and applications and they are not exhaustive;
- No specific prescription on the basis of the sorption chillers working operation;
- 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 American and Asiatic Standards concerning test conditions and test procedures (e.g. sampling time, tolerances);

In order to overcome all these lacks, two test procedures – one for continuous chillers and one for discontinuous chillers – 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 [1].

2.2. Approach

For the drafting of the two procedures, the protocols included in the standards EN 12309, EN 14511, EN 14825 [2], [3], [4] focused respectively on the gas-fired sorption heat pumps and chillers and on electrically driven heat pumps and chillers, have been taken as reference. 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.

Finally, in order to make such procedures suitable for being included in a standard, they have been structured according to HVAC standards i.e. they include: definitions, test conditions (only for "full load"), performance figures, test protocol, data to be recorded, test apparatus and basic rules for the uncertainty calculation.

2.3. Test conditions

Test conditions have been selected starting from 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 to the full loads. 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 mediums at the heat rejection circuit, i.e. air, water and brine. Fig. 1Fig. summarizes the standard and application conditions suitable for solar cooling applications.

Since in solar cooling applications the sorption chillers often operate at conditions which are different from the design (or nominal) ones, the two procedures prescribe to test the machine at off-design conditions, i.e. at those 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.

2.4. Performance figures

The test procedures provide separate thermal and electrical performance figures calculated taking as control volume that one around the machine, including the “virtual” internal pumps used to win the losses through the main heat exchangers. Accordingly, for each rated quantity the effective quantity will be calculated by correcting the measured quantity with the parasitic contribution (both, electrical and thermal). The main capacities and ratio calculated in the developed procedures are:

- **Effective Cooling Capacity** *(*$Q_{el,cooling}$*)* which is the cooling capacity corrected of the capacity due to the pumps at the evaporator circuit and expressed in kW;
- **Effective Heat Input** *(*$Q_{el,input}$*)* which is the heat input corrected of the capacity due to the pumps at the generator circuit and expressed in kW;
- **Effective Electrical Power Input** *(*P_{el}*)* which is 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);
- **Thermal Energy Efficiency Ratio** *(*EER_{th}*)* which is 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}) which is the ratio of the effective cooling capacity to the effective electrical power input of the unit, expressed in kW/kW.

			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							

Fig. 1. Full load Test Conditions

2.5. Test procedures

The developed procedures include protocols to perform stationary tests at full and partial load. Concerning the tests at part loads, two distinct types of tests are foreseen: continuous tests or ON-OFF tests. ON-OFF tests are those tests that shall be performed when at specific part lad 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. However all these protocols consist of four main phases:

1. “Set-up of the machine”: the chiller is installed into the test bench following the manufacturer’s instructions;
2. “Test Set-up”: the desired test conditions, i.e. the flow rates and the inlet temperatures at the three heat exchangers, are set;
3. “Equilibrium phase”: it is verified that the stationarity is reached, i.e. all quantities under control lay 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). These intervals (or tolerances) 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);
4. “Data collection period” during which all meaningful data is collect. Such period lasts 30 minutes for continuous machines and 2 cycles for the discontinuous machines.

2.6. Test apparatus

In order to be able to fulfill all stability criteria and to measure in the same way and with the same quality, the test procedures provide specifications about the design of the test apparatus and about minimum requirements in terms of uncertainty, that the measurement equipment must meet. An example of one of the “suggested test rig” is given in Fig. 2, where a test apparatus (*or compensation system*) for testing air-to-water/brine chillers at full and partial load is shown. As it is possible to see, it consists 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 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).

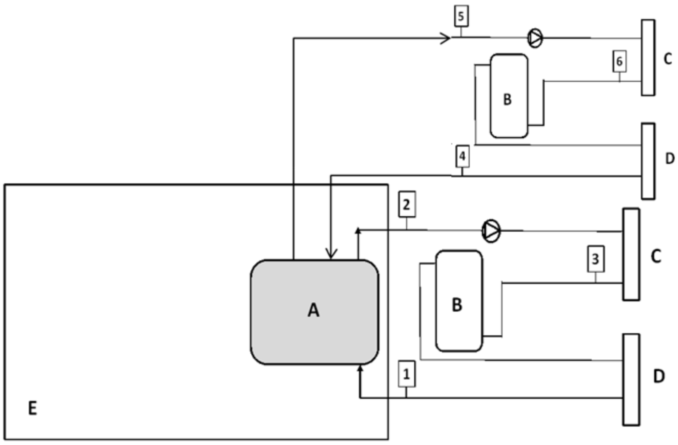

Fig. 2. Compensation systems for air-to-water/brine chillers

2.7. Test validation

A first validation of the developed test procedures has been carried out. Tests performed by IEA Task48 partners in their laboratories according to their internal procedures (post-validation process) or by using the procedures described in this paper (validation process) have been used. In total, data have been achieved from 17 continuous tests, carried out respectively on 3 continuous chillers (one on-sales machine and two prototypes), and 3 discontinuous chillers (two on-sales machines and one prototype). No data from ON-OFF tests is available. An analysis on available data has shown that:

- The conditions at which the chillers are rated depend on the specific application;
- Pressure drops are often not measured, therefore no Effective Cooling Power and Electric Power can be measured (and effective EER consequently);
- The defined "stationary criteria" work for continuous chillers but some modifications are needed for discontinuous ones;
- Often, when stationary criteria are not satisfied, it is due to test apparatus: controls and devices are not adequate for this kind of tests. Usually this problem could be solved by using storages and by improving control strategies.

3. Heat rejection

3.1. Overview

A detailed market survey on about 1300 available "recoolers" (wet cooling towers, dry coolers and hybrid cooling towers) has been carried out using the technical documentation publicly available on the manufacturers' websites. From this activity, an exhaustive database on heat rejection components was created. The database comprises heat rejection components ranging from small capacities, typical of residential applications, to large capacities adopted in industrial or tertiary applications.

Scope of the activity has been to give an overview of existing and novel concepts for heat rejection devices in solar cooling systems in terms of 1) investment & operation costs and 2) re-cooling performance and efficiency.

3.2. Market survey

An important feature to be analyzed for heat rejection systems is their size, and in particular the weight-to-volume and weight-to-area ratios of the different components. For this comparison the base gross area, defined as the frontal area of the heat rejection device casing, is employed. Fig. 3 shows the resulting trends:

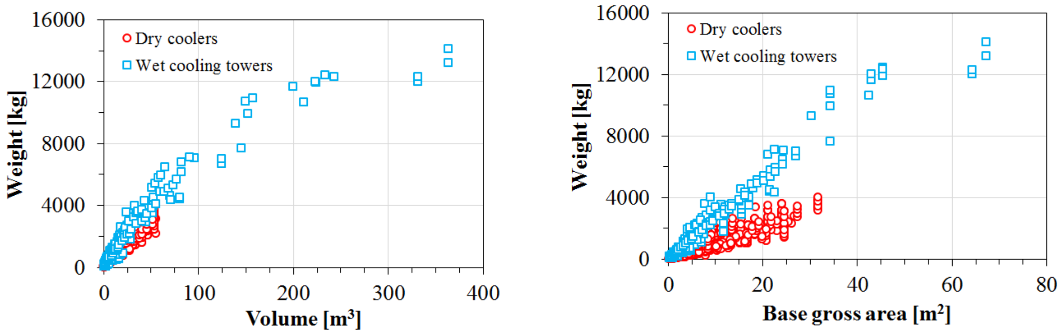

Fig. 3. Wight to Volume (a) and Weight to Area ratios distributions (b)

Dry coolers and wet cooling towers have almost the same weight-to-volume ratio. For dry coolers the average ratio is between 45-126 kg/m^3, while for wet cooling towers is 41-101 kg/m^3. For volumes above about 70 m^3, only wet cooling tower systems can be found, and a more dispersed weight-to-volume trend is recorded.

For the same base gross area, the weight of a wet cooling tower is larger than that of a dry cooler and the difference increases with the surface. For a fixed base gross area the weight of a wet cooling tower is about 60 % greater than that of a dry cooler.

When limitations on the available space are present, the relationship between the device size and the provided rejected heat is noteworthy to consider. This relationship is shown in Fig. 4 for the two investigated heat rejection device categories, with respect to volume (a) and base gross area (b). The rejected heat-to-volume ratio for dry coolers and wet cooling towers ranges between 10-40 kW$_{rejected}$/m^3 and 8-47 kW$_{rejected}$/m^3, respectively. An analogous trend is noticed when the rejected heat is plotted as a function of the gross area. This ratio rages between 13-80 $kW_{rejected}/m^2$ for dry coolers and between 60-163 $kW_{rejected}/m^2$ for wet cooling towers.

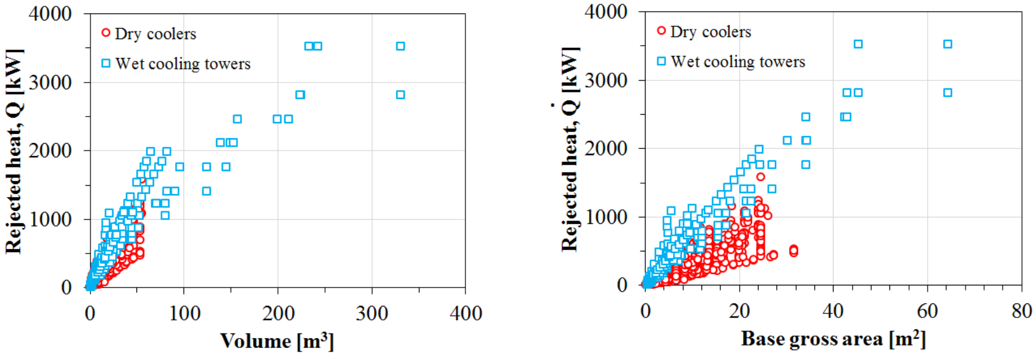

Fig. 4. Rejected heat versus volume (a) and versus gross area (b)

Fig. 5 shows the ratio between electric power consumption and rejected heat. The specific consumption values ($kW_{el}/kW_{rejected}$) of dry coolers are in general higher than those of wet cooling towers, type (open or closed) and the fan function (induced or forced draft towers) deeply influencing the performance of the latter. The ranges of specific consumption that have been found are between 0.0125-0.091 $kW_{el}/kW_{rejected}$ for dry coolers, and between 0.005-0.060 $kW_{el}/kW_{rejectedd}$ for wet cooling towers. In particular, the average specific consumption for dry coolers is about 0.033 $kW_{el}/kW_{rejected}$, while for wet cooling tower is about 0.017 $kW_{el}/kW_{rejected}$. This last trend is obtained for the open cooling towers and it is in very good agreement with Saidi [6] and Eicker´s [5] results.

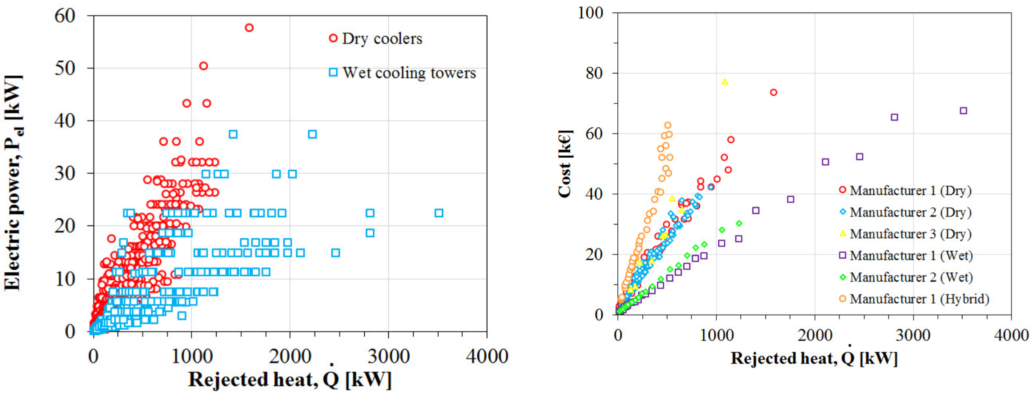

Fig.5. Electric power to rejected heat (left) and investment cost to rejected heat ration (right)

For the present analysis, a primary classification has been drafted in terms of investment costs. The cost figures reported only include the heat rejection device itself, while additional components (e.g. filtration system, working platform and ladder for large towers, chemical treatment system, wiring, etc.) are usually not included in the datasheets and strongly depend on the specific installation under consideration.

For a specific heat rejected, the investment costs for dry coolers are typically higher than for wet cooling towers. In particular, the average cost per unit of rejected heat power ranges for dry coolers between 49 and 107 €/$kW_{rejected}$, (i.e. between 61 and 134 US$/ $kW_{rejected}$) and for wet cooling towers between 22 and 27 €/$kW_{rejected}$ (i.e. between 28 and 34 US$/$kW_{rejected}$).

From Fig. 5 it is evident that, while wet cooling towers present a good linear cost-to rejected heat relationship, for dry coolers two different trends can be distinguished. Of the two recognizable linear trends for dry coolers, the one at higher costs represents hybrid components, for which the cost of the spray system has to be included. All other dry cooler models follow a common linear trend (at lower investment costs).

4. Pump efficiency and adaptability

Auxiliary electricity consumption in SHC systems is not negligible and, besides the cooling tower, mainly caused by the pumps in the different hydraulic circuits, mostly the heat rejection system. In order to achieve high seasonal energy efficiency ratios (SEER) it's essential to minimize the overall hydraulic pressure drops and select all pumps of the different hydraulic circuits properly to operate in Best Efficiency Point (BEP) under any load condition.

4.1. State of the art

Since 2010 great improvements in overall pump efficiency have been obtained, in particular due to legislative restrictions and manufacturer initiatives. Thus, the efficiency of converting electric power into hydraulic work increased from former less than 30% up to more than 60% for medium-scale, variable speed & high-efficiency single-stage canned circulators. Fig. 6 provided by Europump Association shows the theoretical limit and the results of several market surveys on pump efficiency with a flow rate up to 200 m³/h. In general, bigger pumps achieve higher efficiencies even up to 85 %.

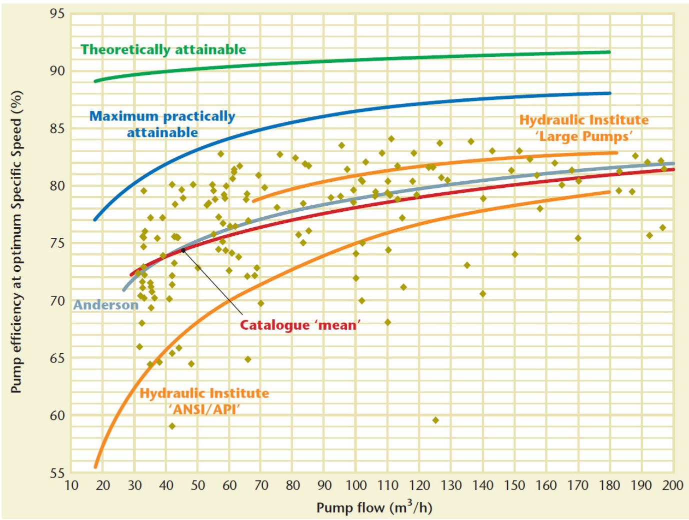

Fig. 6. Results of different surveys on single stage circulator efficiency by Europump Association [7]

Even though the investment costs of variable speed high-efficiency pumps often are twice as high compared to a cheap, but inefficient fixed speed pumps, the overall share of pumps on the total investment costs of SHC system components are commonly below 5 % as depicted in Fig. 7.

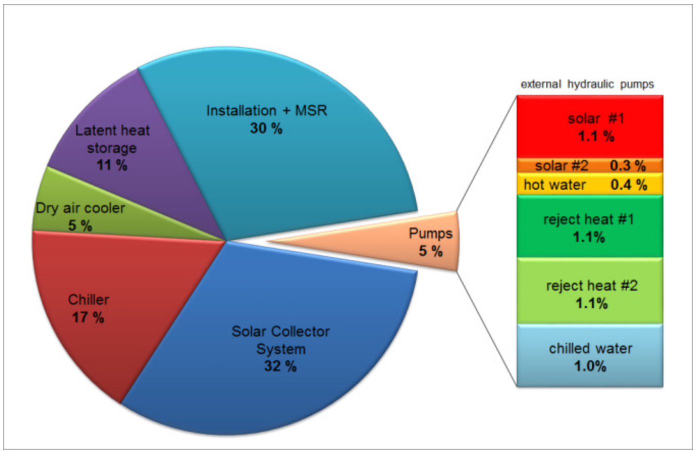

Fig. 7. Share of Pumps costs in comparison to overall investment costs for a SHC System

But, the adaptability to part load conditions offers high energy savings and operational cost reduction. Furthermore these intelligent high-efficiency pumps are often featured with additional internal flow, pressure, temperature sensors as well as an electric power meter. This offers a great opportunity for advanced system evaluation at concurrently reduced measuring equipment costs. Especially in the hydraulic circuits of solar collector, chilled water and reject heat, which represents the main electricity consumers (see Fig. 8) the use of efficient pumps is mandatory in order to achieve good system performance.

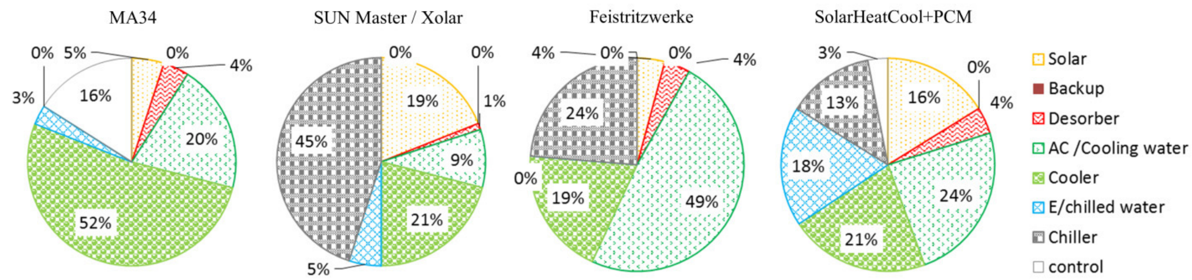

Fig. 8. Proportion of electricity consumption in the different sub-systems of selected SHC Systems

4.2. Pump adaptability and control - practical

But the utilization of high-efficiency pumps in solar cooling installations does not implicate an efficient pumping automatically. The strong relationship between characteristic pump and system curve demands a proper system design as well as pump selection and adaptability to part load conditions.

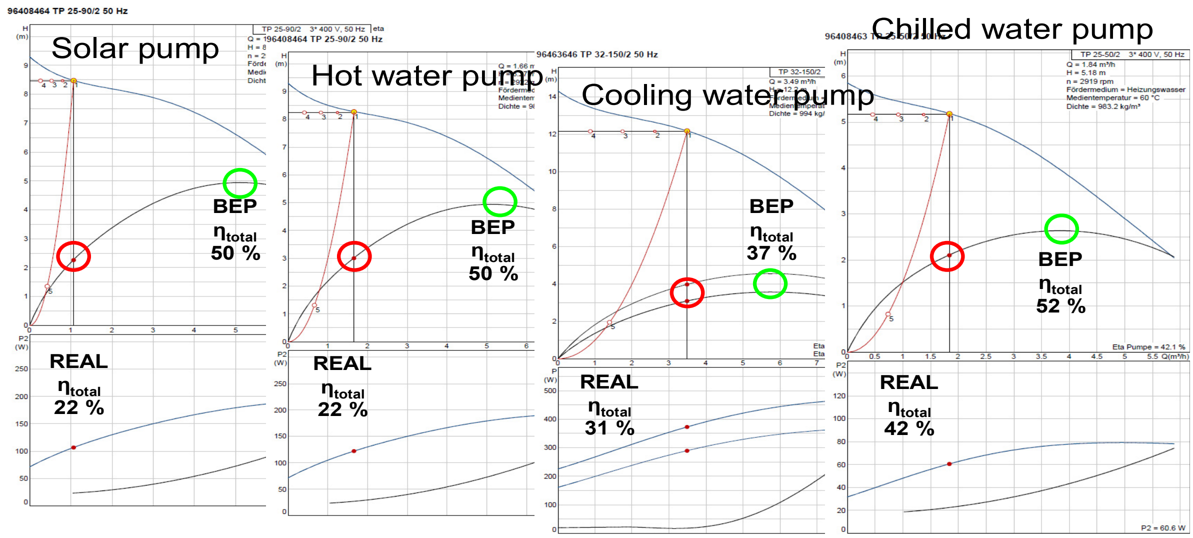

Fig. 9. Typical characteristic diagrams with theoretical Bestpoint (BEP) and real operation point (REAL)

Although, even the characteristic diagram [9] of small high-efficiency pumps feature high conversion efficiency (BEP) between electricity and hydraulic power of more than 50% the practical operating point in the different hydraulic circuits (REAL) is often far away from that optimum as illustrated in Fig. 9. A proper match of characteristic system and pump curve during design phase is essential. In order to obtain good system performance over a wide chilled water capacity range a proportional adaption to part load conditions is highly recommended for at least cooling water and chilled water pump.

4.3. Design guidelines

Notwithstanding various design guidelines most notably the Solar Cooling Handbook: A Guide to Solar Assisted Cooling and Dehumidification Processes [10] and simplified system schemes [11] dealing with optimized hydraulic design in SHC systems a proper and well performing installation is still a question of experience or pre-fabrication. The complexity and interaction of many different units cause still a high on-site planning effort including multiple error sources. Determinative aspect is a correct pressure loss calculation and repetitive review of the overall auxiliary electricity consumption as well as control strategy throughout the whole operating range. In the following main design criteria and some key figures for well-designed hydraulics and pump selection are given:

- Reduce heat carrier flow through the main components, thus prefer high temperature differences in the main circuits especially in the cooling water circuit where most of the electricity is consumed.
- Prefer chiller design with low pressure losses through internal heat exchangers and high thermal COP which reduces driving and rejected heat quantity simultaneously leading to reduced overall pumping effort.
- Reduce pipe length of water/glycol circuits to a minimum and reduce pressure losses in the pipework (sharp edges, Valves, filters, etc.). In addition to that, select pipe diameters to achieve heat carrier medium flow speed between 1 and max. 1.5 m/s for medium sized SHC-Systems
- Select the operating point of pumps lightly right from Best Efficiency Point in the Sweet or Happy zone to achieve best pump efficiency at part load conditions

The way things are an overall SEER for well-designed small scale solar cooling systems of 20 seems to be feasible. However, currently the hydraulic design of many sorption chillers does not allow a good seasonal system performance due to high pressure drops in the hydraulic circuits and a restricted adaptability to part load conditions.

5. State of the art on new collectors

The solar thermal market offers an enormous variety of technologies, especially with regard to solar collectors: different collector technologies (e.g. flat plate, evacuated tubes, parabolic trough, linear Fresnel), system concepts (e.g. forced circulation and thermosiphon), management approaches (e.g. pressurized and drain-back). Each one is more or less suitable depending on specific site conditions, such as climate, required temperature level, seasonality of application, end user typology, maintenance availability etc. When it comes to solar cooling, temperature level is always a crucial issue, thermally driven chillers requiring relatively high generator temperature in order to provide useful cooling.

For this reason an extensive market review of new collectors has been carried out. The main focus is temperature level. A first, general comment must be provided in this regard: high performance solar thermal collectors (such as concentrating one) can obviously as well provide hot water at low temperature (e.g. for domestic hot water production), but are here considered for the particular solar cooling application. Using collectors capable to reach high temperatures for low temperature applications only may indeed be economically sub optimal.

The methodology applied for developing the market review was mainly based on the knowledge of IEA Task48 participants, many of them having experience with special applications of solar thermal. Further information has been extrapolated from QAiST project [12] and IEA Task49 , which is related to solar thermal systems for industrial process heat and also investigated the market availability of high temperature collectors. Some additional information has been requested by contacting single manufacturers one by one.

The main outcome of this activity is a comprehensive database collecting 32 collectors of various typologies: Improved flat plate collectors, improved evacuated tube collectors, parabolic trough collectors, linear fresnel collectors.

Main results of the market review are summarized in the table below.

Table 1. Main results of market review.

Characteristic	Amount	Comments
Overall number of manufacturers	29	-
Improved flat plate collectors	5	Double glazing or vacuum
Improved evacuated tube collectors	3	-
Parabolic trough collectors	17	-
Linear Fresnel collectors	6	-
Maximum temperature 100-150°C	4	-
Maximum temperature 150-200°C	5	-
Maximum temperature 200-300°C	9	-
Maximum temperature > 300°C	7	-

Documented experience with solar thermal cooling was found for 15 manufacturers.

6. Conclusions

Looking at above mentioned results, one can draw several conclusions regarding the market for solar cooling.

Products are available: all component categories are well represented on the market, with large availability of solar thermal collectors, heat rejection devices, circulation pumps and relatively good choice among sorption chiller manufacturers and power ranges.

Standardization framework still has to be completed: for what concerns solar thermal collectors, indeed, a complete standardization framework is available, ISO 9806:2013 now covering as well concentrating, tracking collectors, which were not cover by EN 12975:2006.

With regard to heat rejection devices, existing standards ensure a total coverage of at least North America, Europe and Australia.

The framework condition of sorption chillers is currently less satisfactory, as no standard is available in Europe for indirect fired sorption chillers. Old standards exist in the Northern America and Asia, but are not harmonized with each other, as prescriptions are different. Furthermore, the address large power ranges and do not cover discontinuous chillers. IEA Task 48 has performed useful work by developing ad-hoc testing procedures, which should now be used a basis for creating new standards.

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