SOLAR COOLING WITH SMALL-SIZE ABSORPTION CHILLERS: DIFFERENT SOLUTIONS FOR SUMMER AIR CONDITIONING

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ABSTRACT

Absorption refrigerating machines represent an interesting alternative to compression machines, especially when waste heat or heat produced by solar energy is available; the market is beginning to propose small-size absorption machines especially designed for air conditioning in residential buildings. A survey of small-size absorption refrigerators is presented, with particular emphasis on their performance when the heat source comes from solar energy. The machines examined cover a range of chilling powers (4 to 15 kW) and have different working principles. The study is conducted using data supplied by manufacturers and collected in an experimental set-up realized by the University of Perugia; different refrigerators are compared taking into account the most significant parameters, such as heat source and chilled water temperature, cooling circuit characteristics, coefficient of performance, dimensions and weight. Energy and environmental advantages deriving from the solar supply are also evaluated.

1. INTRODUCTION

The summer air conditioning demand is growing continuously, not only in the tertiary sector but also in residential applications; the corresponding demand for electric power may cause failures in the electricity supply network, which must cover increasingly higher peak loads. Heat assisted cooling systems represent a fascinating solution, especially when waste heat or heat produced by solar energy is available, also considering that they do not use CFCs, but solutions with low environmental impact; therefore, they could represent one solution to the energy-environmental issues linked to international agreements, such as the Kyoto Protocol for CO_2 emissions reduction, or the United Nations Framework Convention on Climate Change (FCCC) and the Montreal Protocol, whose aim is to abandon the use of CFCs in cooling cycles. The most common techniques that nowadays permit cold production starting from heat could be grouped into two categories: desiccant cooling systems, which produce directly cooled air with an open cycle, and thermally driven chillers, which deliver cooled water [1]. In the latter case, absorption machines represent the most common solution in actual installations, though adsorption chillers are becoming more and more interesting. As a matter of fact, adsorption machines guarantee higher efficiency at low driving temperatures, but they should be considered still at the research level. Absorption chillers can work with a single or double stage cycle, the latter being more efficient but at the same time employing a hot fluid temperature between 140°C and 160°C. These considerations focus the market's attention basically on small-size absorption machines, especially designed for air conditioning in residential buildings, employing low temperature heat [2 and 3]. This work is aimed at giving a survey of these available solutions, with particular emphasis on variations in their performance depending on external conditions.

2. DRIVING ABSORPTION MACHINES WITH SOLAR ENERGY

At present, the huge potential of the residential building cooling market is almost completely covered by electric chillers, heat pumps and (with less success) gas-fired absorbers. The main problems linked to solar-driven absorption plants can be summarized as follow:

- strict plant dependence on environmental parameters such as external air temperature, solar irradiation level and wind speed;
- high initial cost;
- efficiency of solar contribution limited to the central hours of the day.

It should be underlined that the plant has to be connected to an evaporative cooling tower removing the heat released by the condenser and by the absorber of the chiller; the amount of this energy is approximately the sum of the heat sent to the generator and the heat released in the evaporator.

Besides, an intrinsic characteristic of the plant limits its overall performance: although absorption cycles reach highest efficiencies when heat sources are available at a high thermal level, solar panels behave in the exact opposite manner: both flat and evacuated-tube collectors have efficiencies that decrease with the rising of the circulating fluid temperature.

Lastly, even though the cooling load and the solar irradiation take place more or less at the same time of day, there can be many occasions when the ideal match between the sun and the absorption machine does not occur: hot days with little irradiation, morning or late evening cooling loads and sunny days without cooling demand.

Control strategies must tend towards reaching the highest efficiency, combining flexibility, inexpensiveness and ease of installation. Two main control modes can be adopted: the solar-guided mode and the cold-guided mode. With the first approach, solar collectors are linked directly (or by an external heat exchanger) to the generator of the absorption machine; this solution makes it possible to transfer all of the energy gathered by the collectors straight to the machine, without passing through a storage tank.

Choosing this alternative, although the generator is fed with high level thermal energy, the control possibilities remain greatly limited; therefore, each variation of the solar input is transmitted to the chilled water and then to the user. Besides, in case of low irradiation, there is a transient effect characterized by continuous ON-OFFs, resulting in a decrease in efficiency and unwanted intermittent absorption cycle behavior. The plant does not follow building cooling loads, so its applications are limited to users without steady cooling requirements.

In the case of cold-guided mode control, the whole system has to guarantee a defined cooled water temperature or a fixed cooling load; therefore it is necessary to put a hot storage tank between the collectors and the absorption machine, thus allowing a minimum of control, storing the energy when the production exceeds the cooling load and also feeding the generator at the desired temperature when the solar radiation is not sufficient.

With this solution a series of heat losses is introduced: the dispersion through the tank surface, the energy wasted in the heat exchanger between the solar circuit and the hot storage, and the coils between the generator feeding circuit and the hot storage. There is also the possibility of installing a cold storage, with the effect of giving a higher inertia to the load, avoiding the intermittent functioning of the absorption machine.

3. INVESTIGATED SMALL-SIZE ABSORPTION CHILLERS

The market for small-size absorption chillers seems to be barely developed, probably because of the cutthroat competition of electric chillers and heat pumps; nevertheless, it was possible to find and analyze five absorption machines, built by different manufacturers, even though most of them should be considered more as prototypes rather than as commercially available items.

3.1. Machine A

The first sample is made up of two separate steel units in which the evaporator-absorber and generator-condenser pairs are placed respectively (Fig. 1).

The refrigerant-absorbent pair is Water/Lithium Bromide, evolving inside a classic single stage absorption cycle with a regenerator (plate heat exchanger) between the absorber and the generator. Two electric pumps provide circulation between the absorber and the generator, and the periodic suction of incondensable gases is done by a built-in vacuum pump. The cooling capacity under fixed conditions (see paragraph 4) is approximately 11 kW, and the heat extraction is carried out under all conditions by a 35 kW evaporative cooling tower [4 and 5].

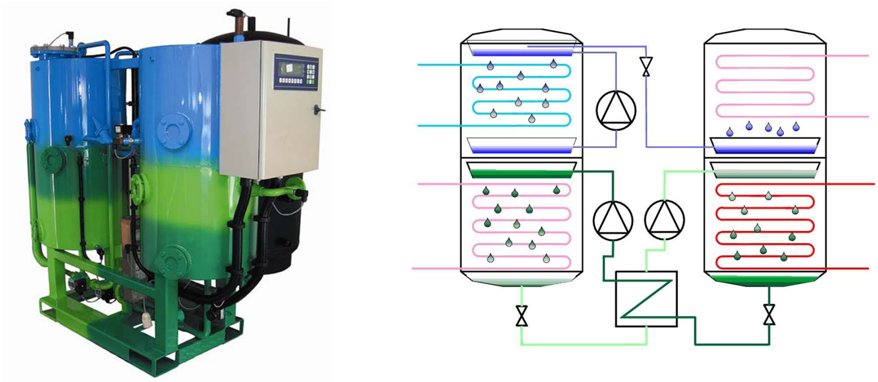


Figure 1. External and internal view of sample A.

3.2. Machine B

The second absorption machine examined was found to be similar in construction to the previous one: it follows the normal Water/Lithium Bromide single stage absorption cycle, with only one electric solution pump to overcome the pressure difference between the absorber and the generator, divided by the heat regenerator (Fig. 2). According to the manufacturer, the machine could work with a wide range of generator temperatures (from 55°C to 105°C); the cooling capacity under fixed conditions is about 10 kW, and a 25 kW evaporative cooling tower is necessary [6, 7].

Figure 2. External and internal view of sample B.

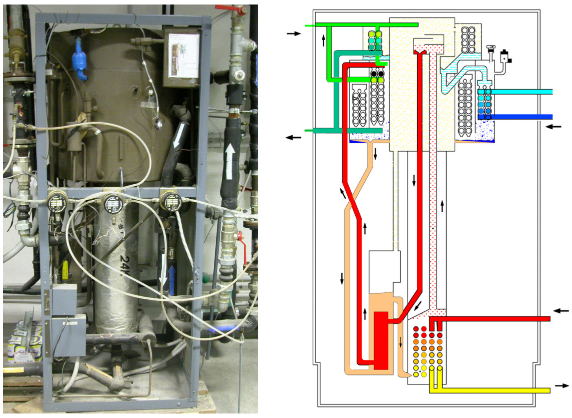


Figure 3. External and internal view of sample C.

3.3. Machine C

The main characteristic that distinguishes this machine from the others is the absence of the solution pump: the circulation from the absorber to the generator is carried out by a bubble pump that does not need electricity. The machine operates with a single stage Water/Lithium Bromide absorption cycle using a plate heat exchanger as a regenerator; the fixed-conditions cooling capacity of 15 kW requires coupling with a 45 kW evaporative cooling tower [14]. This model was tested at the University of Perugia labs, with the installation of a solar field, measurement equipment and a data acquisition system (Fig. 3), with the aim of evaluating the influence of external circuits to the overall functioning of the solar cooling plant. Experimental data obtained in the test rig at the University of Perugia (solar-driven machine) can be found in [8]; for this study, however, only data provided by the manufacturer were used.

3.4. Machine D

The fourth sample is distinctive in that it has a rotating generator: the chamber that hosts the generator rotates at a speed of about 4.3 rps; according to the manufacturer, this characteristic enhances the heat and mass transfer process inside the generator itself, permitting a consistent size reduction. The rest of the cycle reflects the normal Water/Lithium

Bromide single stage absorption cycle, with a difference in the dissipation device, which is a wet-type built into the machine (Fig. 4). The nominal cooling capacity is about 5 kW [9].

Figure 4. External and internal view of sample D.

Figure 5. External view and cross section of sample E.

3.5. Machine E

The last sample (Fig. 5) uses triple-state absorption technology with a Water/Lithium Chloride solution; this makes it significantly different from the traditional absorption processes, since it is a three-phase process (solid, solution and vapour). It works intermittently with two parallel accumulators (barrels), each comprised of a reactor and a condenser-evaporator: in the charging period, the input heat is converted into chemical energy by drying the salt (LiCl); afterwards, the cooling effect is obtained by inverting the cycle. Both sequences need a heat sink, which could consist of a standard dissipation device such as an evaporative cooling tower. The nominal cooling capacity is about 4 kW [10].

3.6. Other

Researchers and companies have developed other prototypes of small-size absorption machines; for example, a single effect ammonia/water absorption chiller equipped with a membrane solution pump is under development [11], providing nominal cooling capacities between 5 and 20 kW. This solution, as well as others not mentioned, lack complete experimental data, therefore they were not included in this investigation, except for a performance evaluation reported in Table 1, where the abovementioned chiller (sample F) is compared with the other five samples, in nominal conditions.

4. COMPARATIVE ANALYSIS

A comparison was made between the five different absorption machines starting from the manufacturers' rating and functioning curves. Performances were evaluated in terms of cooling capacity and global coefficient of performance (the ratio between cooling capacity and the sum of the heat given to the generator plus the electric energy absorbed). The machine components requiring electric energy are the generator-absorber pumps (when applicable), the pumps for the circulating fluids in the evaporative cooling tower and the solar circuit and the evaporative cooling tower engine; in addition, for sample D, energy is needed for the generator rotation.

The energy consumption of the external circuits pumps was considered equal to 20 W/kW of fluids transported in nominal conditions (considering a direct connection between solar collectors and absorption machine, without cold storage) plus 10 W/kW processed by the evaporative cooling tower engine; these values were considered the same for each absorption machine analyzed, so that they did not influence relative performances.

Table 1 summarizes the results for a common nominal condition (except for sample F); taking into account that the devices are driven by solar collectors; the values were set as follows:

- generator inlet temperature $T_{g,i} = 85°C$;
- machine outlet cooling fluid temperature $T_{c,o} = 9°C$;
- evaporative cooling tower outlet re-cooling fluid temperature $T_{t,o} = 30°C$.

Position	Parameter	M.U.	Sample A	Sample B	Sample C	Sample D	Sample E	Sample F
Cooling circuit	Capacity	kW	11.4	8.4	9.3	5.2	4.8	10.0
	$T_{c,o}$	°C	9.0	9.0	9.0	9.0	9.0	16.0
Heating circuit	Power	kW	16.6	13.0	16.0	7.6	7.1	15.6
	$T_{g,i}$	°C	85.0	85.0	85.0	85.0	85.0	75.0
Re-cooling circuit	Power	kW	28.0	21.4	25.3	12.8	11.9	25.6
	$T_{t,o}$	°C	30.0	30.0	30.0	30.0	30.0	24.0
Electric absorption		kW	1.4	1.1	1.8	0.7	0.7	1.3
Global COP		-	0.64	0.59	0.52	0.63	0.62	0.59
Weight		kg	700	350	325	240	740	350
Overall dimensions	Length	mm	1500	855	750	1130	700	800
	Width	mm	750	653	716	720	680	600
	Height	mm	1600	1847	1750	790	1850	2200
Volume		m^3	1.800	1.031	0.939	0.643	0.881	1.056
Norm. cooling capacity		kW/m^3	6.4	8.1	9.9	8.1	4.8	9.5

Table 1. Comparison among the characteristics of the investigated absorption machines.

The table also gives overall dimensions and the weight of each absorption machine, together with the unitary cooling capacity as the ratio between the nominal cooling capacity and the volume of the parallelepiped circumscribed about the machine. The volume was chosen as the normalization parameter, taking into account that the small-size absorption machine target consists mainly of residential applications, where space saving could represent an important feature.

A more in-depth comparative investigation was conducted varying the three external inlet temperatures and consequently evaluating the COP and the normalized cooling capacity. When data are not directly available, the following hypothesis was assumed: if the variation of the cooling capacity with the chilled water temperature is known, at a fixed re-cooling water temperature, the trend of the cooling capacity at another re-cooling water temperature is obtained simply by scaling the previous trend. The scaling factor was derived from the cooling capacity trend vs. the re-cooling water temperature at a fixed cooling water temperature. In Fig. 6 and 7 the normalized cooling capacity and the global COP are sketched respectively as a function of the cooling circuit outlet temperature, setting the generator inlet temperature at 85°C and the evaporative cooling tower outlet re-cooling fluid temperature at 30°C.

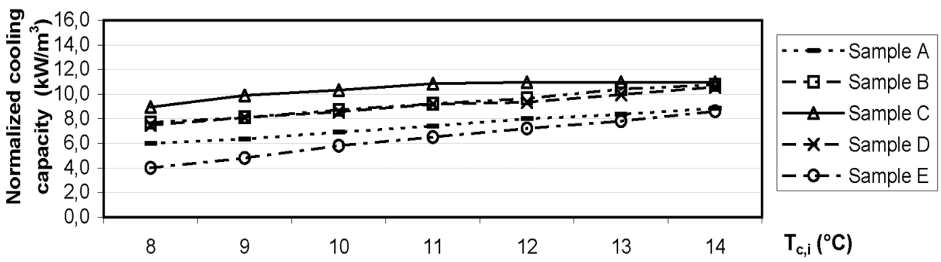


Figure 6. Samples' normalized cooling capacity as a function of $T_{c,i}$ ($T_{t,o}$ = 30°C, $T_{g,i}$ = 85°C).

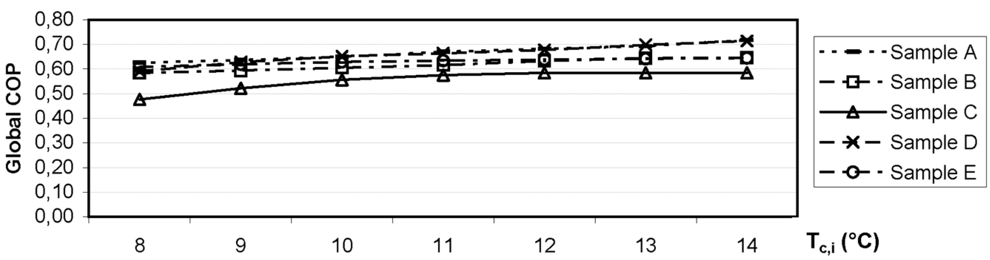


Figure 7. Samples' COP as a function of $T_{c,i}$ ($T_{t,o}$ = 30°C, $T_{g,i}$ = 85°C).

The first couple of graphs shows how sample C proves to be the most powerful machine varying $T_{c,i}$ but, at the same time, it suffers in terms of performance; sample E shows the lowest normalized cooling capacity; the global COP of samples A, B, D and E are very close to each other, showing weak variations with the cooling circuit outlet temperature. In Fig. 8 and 9 the normalized cooling capacity and the global COP are sketched respectively as a function of the generator inlet temperature, setting the cooling circuit outlet temperature at 11°C and the evaporative cooling tower outlet re-cooling fluid temperature at 30°C. The same considerations for sample C can be repeated for the $T_{g,i}$ variation; the normalized cooling capacity of samples B and D seem higher than the remaining two chillers, while sample E confirms its weakest performance; the global COP shows to be scarcely influenced by the generator inlet temperature.

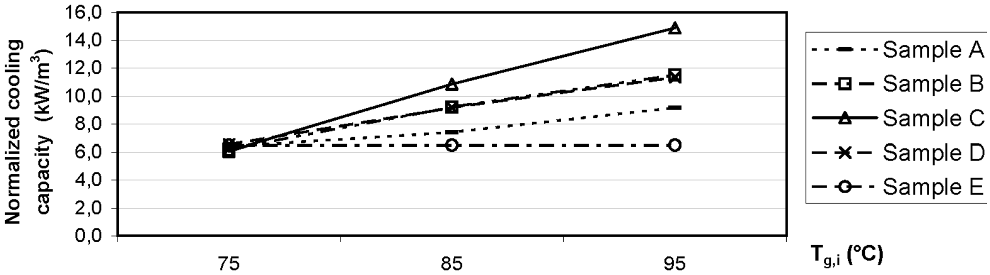
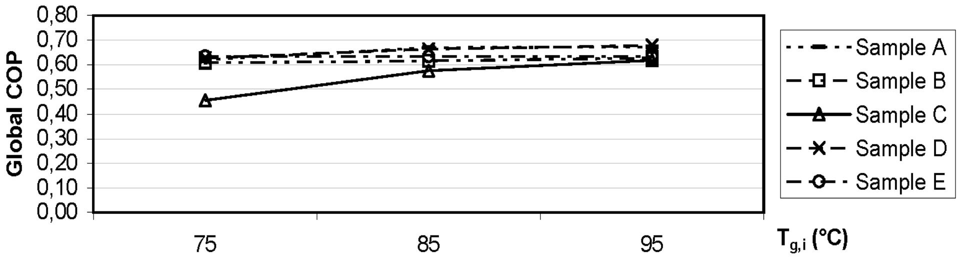


Figure 8. Samples' normalized cooling capacity as a function of $T_{g,i}$ ($T_{t,o}$ = 30°C, $T_{c,i}$ = 11°C)



.Figure 9. Samples' COP as a function of $T_{g,i}$ ($T_{t,o}$ = 30°C, $T_{c,i}$ = 11°C).

Finally, in Fig. 10 and 11 the normalized cooling capacity and the global COP are respectively sketched as a function of the evaporative cooling tower outlet re-cooling fluid temperature, setting the cooling circuit outlet temperature at 11°C and the generator inlet temperature at 85°C. All machines show bad performance at re-cooling temperatures higher than 35°C, especially samples C and D.

The differences between the cooling capacity of the samples depend on the manufacturers' construction choices. Samples A and E are those the most influenced by their volumes, which considerably diminishes the relative capacity. Sample E shows poor performance at low cooling temperatures because of its intermittent functioning, which decouples the heat feeding and cooling production environments. Samples A and B behave similarly in terms of global COP, reflecting their common construction philosophy; it should be pointed out that samples A and E weigh twice as much as all the other absorption machines investigated.

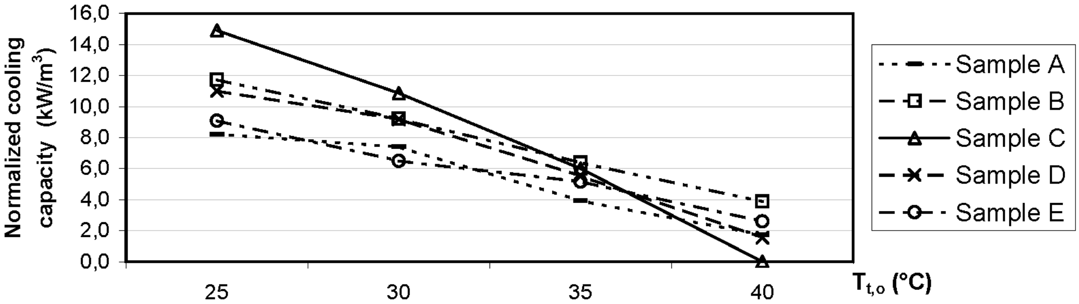


Figure 10. Samples' normalized cooling capacity as a function of $T_{t,o}$ ($T_{g,i}$ = 85°C, $T_{c,i}$ = 11°C)

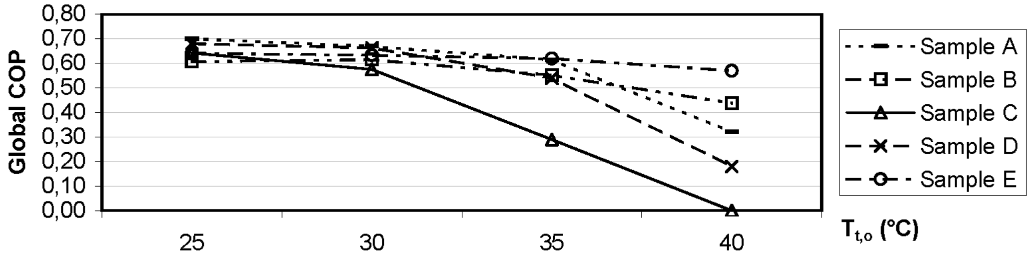


Figure 11. Samples' COP as a function of $T_{t,o}$ ($T_{g,i}$ = 85°C, $T_{c,i}$ = 11°C).

5 FIRST RESULTS OF AN EXPERIMENTAL PLANT

An experimental plant has been realized by the University of Perugia to feed an absorption chiller (D) with solar energy.

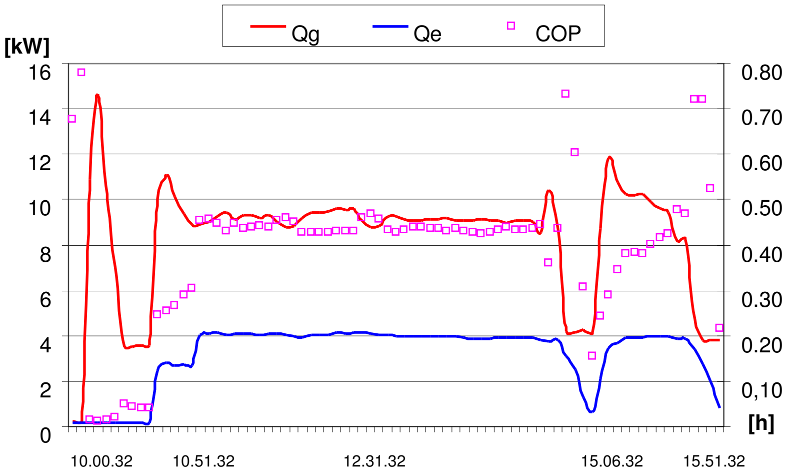


Figure 12. COP, Power supply (Q_g) and cooling power (Q_g) of Machine D ($T_{g,i}$ = 80°C, $T_{t,o}$ 26= °C).

First results highline how the machine can work with a generator inlet temperature of 80°C if cooling inlet temperature is less than 35°C, producing water chilled at 10 - 12°C with a COP of almost 0.6. If cooling inlet temperature decreases under 30°C, the chiller cools water down to 7 - 8°C but COP becomes lower than 0.5. When the cooling inlet temperature in fact is lower than 30°C, the generator is able to receive more heat than nominal one but only nominal heat is used by the evaporator to produce cooling power (Fig. 12). Extra heat is bypassed directly to the absorber in liquid form (overflow effect). Therefore, first results show that this machine can work properly (COP 0.5 – 0.6) with a generator inlet temperature lower than the nominal one (90°C), if cooling inlet temperature is over 30°C, whereas a lower cooling inlet temperature at the same conditions can decrease COP values under 0.5.

6. CONCLUSIONS

A survey of five small-size absorption chillers driven by solar energy is presented. The machines analyzed cover a range of cooling capacities (from 5 to 12 kW) and have different working principles and designs. The performance study was conducted starting from the manufacturers' rating and functioning curves, imposing the same working conditions and investigating their performance when the heat source comes from solar energy. The study has been conducted varying the three external temperatures (heat source, re-cooling water and cooling water), taking into account of the dimensions of each sample. The results consist of a group of data that allow the definition of the five samples' performance in each working condition that the cooling load, the external environment and the sun impose on these chillers.

NOMENCLATURE

COP	coefficient of performance	(-)	Subscripts	
rps	revolutions per second	(s^{-1})	c	cooling
M.U.	measurement unit	(-)	g	generator
Q	heat power	(kW)	i	inlet
T	temperature	(°C)	o	outlet
			t	evaporative cooling tower

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