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Operation Modes and Control Strategies for Solar Cooling Systems

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Abstract.- The main objective of this review is to provide an overview of the operation modes and the main control and regulation strategies designed and implemented for the operation of solar thermal cooling systems, detailing their main characteristics, advantages and disadvantages. In addition, general boundary conditions that govern the functioning of the single and double effect $LiBr-H_2O$ absorption chillers driven by hot water are detailed, delving into the effects and/or reactions of these absorption machines with respect to the variations that may occur in the operating conditions of the system.

Keywords: absorption cooling; solar energy; solar thermal cooling systems; control strategies.

Modos de operación y estrategias de control para sistemas de refrigeración solar

Resumen.- El presente trabajo de revisión tiene como objetivo principal proporcionar una visión general sobre los modos de operación y las principales estrategias de control y regulación diseñadas e implementadas para la operación de sistemas térmicos de frío solar, destacando sus principales características, ventajas e inconvenientes. Además, se detallan las condiciones generales de contorno que rigen el funcionamiento de las máquinas de absorción de $LiBr-H_2O$ de simple y doble efecto accionadas por agua caliente, profundizando en los efectos o reacciones que se producen en este tipo de equipos con respecto a las variaciones que puedan ocurrir en las condiciones de funcionamiento del sistema.

Palabras clave: enfriamiento por absorción; energía solar; frío solar; estrategias de control.

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1. Introduction

Controlling a solar thermal cooling system essentially consists of the simultaneous regulation of each of its components based on the operating conditions of their respective circuits.

Depending on the purpose of the installation and the approach under which it has been designed, the control system can have very different objectives: optimization of the electrical consumption of the general system, maximization of the cooling generation or optimization of the available solar and residual energy resources. Other factors such as climatic conditions, characteristics of the building, the type and characteristics of the components of the installation itself, the hourly profile of the cooling demand, the presence of usable residual energy, among others, condition the selection and/or definition of the most appropriate control strategy to be implemented for achieving the proposed objectives.

The implementation of an inappropriate control strategy would result in an inefficient operation of the installation, regardless of the quality of the components, the correct dimensioning of the installation and/or the implementation of appropriate hydraulic concepts and configurations. This possible low performance of the solar cooling system is usually represented by a general electrical efficiency much lower than expected and a high consumption of auxiliary energy, which is used to energize the absorption machine and be able to satisfy the cooling demand.

The high consumption of auxiliary energy is mainly caused by the implementation of control

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modes in which it is not possible to modulate the absorption machine at partial loads, leading to the generation of unnecessary cooling energy (parasitic) and with-it high-energy requirements.

This need to define and design appropriate strategies and model of control for achieving an optimum and efficient operation of solar absorption cooling installations has been reflected in the growing increase in research work aimed at this objective in recent years. In these research works various strategies and regulation techniques have been proposed and analyzed for solar thermal cooling systems of very varied configurations and constitutive characteristics, which have been used as a basis for the preparation of the present review work.

2. Objectives and scope

The main objective of this paper is to provide an overview of the various control strategies defined, designed and analyzed to date, for the operation and regulation of solar thermal cooling systems.

For a better understanding of the characteristics, advantages and disadvantages of the control strategies, the general boundary conditions that govern the functioning of the single and double effect $LiBr-H_2O$ absorption systems driven by hot water are detailed, delving into the effects and/or reactions of these absorption machines with respect to the changes that may occur in the operating conditions of the system.

The scope of the work also includes the description of the basic operation modes of solar absorption systems, and some schematics with the typical configurations and operating strategies generally used in this type of installations, proposed in research works and by the manufacturers themselves.

The determination or provision of specific indications on optimal strategies, models and policies for the operation of solar cooling systems are not part of the scope of this review.

3. Boundary conditions of absorption chillers

Considering technical manuals, catalogs and datasheets of some of the main commercial suppliers of absorption machines, the limit and nominal operating conditions of single and double effect $LiBr-H_2O$ chillers driven by hot water were collected and summarized in Table 1 and Table 2.

The nominal and limit operating conditions shown in Table 1 and Table 2 differ to some extent from one manufacturer to another, due to the design, constructive, functional and technological implemented characteristics, typical of each model and each brand. Although there is no clear and exact trend in these values, the important and essential point is to identify and know the magnitudes of the conditions under which the absorption machines can operate and thus be able to design and implement appropriate control strategies for each specific design situation.

4. Practical and general recommendations/indications about operating conditions provided by manufacturers

- Tube water velocities should not exceed 3,05 m/s in copper tubes and 3,35 m/s in cupronickel tubes.
- Cooling water flow rate should be within the limits indicated on the manufacturer selection table in order to ensure that changes in condenser water temperature should not exceed 1 °F/min.
- Special attention should be given to the cooling water temperature due to the significant effect that it produces on the operation of the absorption machine, mainly to the speed at which temperature variations can occur. Some of the effects that can occur in the absorption machine associated with the temperature of the cooling water are indicated below:
    - Chiller capacity increases with the decreasing of the inlet cooling water temperature.
    - Very fast and sudden changes in the inlet cooling water temperature can cause the absorbent solution to carry over from the generator into the condenser, provoking on the one hand a reduction in the cooling capacity of the absorption

Table 1: Operating conditions of $LiBr-H_2O$ single effect hot water fired absorption chiller

Parameter	Manufacturer/series model			
	Yazaki WFC (Link)	Carrier 16JLR (Link)	Broad BDH (Link)	Carrier/Sanyo 16LJ Link
Cooling capacity regulation range [%]	HWTR[2]	HWTR[2]	5-115	20-100
Chilled water				
Nominal Inlet/Outlet temperature [°C]	12,5/7	12/7	12/7	12,2/6,7
Outlet temperature working range, min-max [°C]	5,5-15,5	5-15	$\geq$ 5	6-12
Flow rate adjustable range, min-max [%]	80-120	50-120	50-120	0,043 l/s · kW
Maximum working pressure [MPa]	0,588	0,8	0,8	1,034
Cooling water				
Nominal Inlet/Outlet temperature [°C]	31/35	32/40	30/37	29,4/38,4
Inlet temperature working range, min-max [°C]	27-32	15-35	$\geq$ 10	19-34
Flow rate adjustable range, min-max [%]	100-120	50-120	30-140	0,065 l/s · kW
Maximum working pressure [MPa]	0,588	0,8	0,8	1,034
Hot water				
Nominal Inlet/Outlet temperature [°C]	88/83	95/80	98/88	95/86
Inlet temperature working range, min-max [°C]	70-95	95-125	CCOR[1]	80-98
Flow rate adjustable range, min-max [%]	30-120	50-120	CCOR[1]	0,039 l/s · kW
Maximum working pressure [MPa]	0,588	0,8	0,8	1,034

[1] CCOR: The cooling capacity operation range is provided.
[2] HWTR: The hot water temperature operation range is provided.
Nominal flow rate in each circuit=100 %

Table 2: Operating conditions of $LiBr-H_2O$ double effect hot water fired absorption chiller

Parameter	Manufacturer/series model			
	Ebara RFH-Y (Link)	Shuangliang HSB/HSC (Link).	Thermax HD (Link)	Broad BDH (Link)
Cooling capacity regulation range [%]	20-100	20-100	87,5-120	5-115
Chilled water				
Nominal Inlet/Outlet temperature [°C]	7/12	12/7	12/7	12/7
Outlet temperature working range, min-max [°C]	$\geq$ 5	$\geq$ 5	4,5/11	$\geq$ 5
Flow rate adjustable range, min-max [%]	60-100	60-120	NS[1]	50-120
Maximum working pressure [MPa]	0,8	0,8	0,785	0,8
Cooling water				
Nominal Inlet/Outlet temperature [°C]	32/38	32/38	29/34	30/37
Inlet temperature working range, min-max [°C]	$\geq$ 15	18-34	20-34	$\geq$ 10
Flow rate adjustable range, min-max [%]	60-100	60-100	NS[1]	30-140
Maximum working pressure [MPa]	0,8	0,8	0,785	0,8
Hot water				
Nominal Inlet/Outlet temperature [°C]	98/88	130/68	180/160	170-155
Inlet temperature working range, min-max [°C]	CCOR[2]	CCOR[2]	160-185	CCOR[2]
Flow rate adjustable range, min-max [%]	CCOR[2]	CCOR[2]	NS[1]	CCOR[2]
Maximum working pressure [MPa]	0,8	0,8	0,785	0,8

[1] NS: not specified in the datasheet. Manufacturer should be consulted .
[2] CCOR: The cooling capacity operation range is provided.
[3] HWTR: The hot water temperature operation range is provided.
Nominal flow rate in each circuit =100 %

machine and on the other increasing the risks of corrosion in the condenser and the evaporator.

- Very low inlet cooling water temperatures can lead to crystallization.

- The room temperature, where the absorption machine is installed, should be controlled within the range of (5-40) °C.

5. General aspects of absorption chiller functioning and control

The modern absorption machines available on the market today have been designed with the necessary control measures to offer stable and fault-free operation, even for one of the main problems that afflicts them, such as crystallization. Through these control systems is possible the monitoring and regulation of concentrations and temperatures inside the machine not only to prevent the crystallization but also for the benefit of capacity control, thus enabling it to function safely in a wide range of conditions.

The current control systems provided with the chiller also permit a wide set of functions to be performed, such as: one-key startup/ shutdown, timing on/off, mature safety protection system, multiple automatic adjustment, system interlock, expert system, human machine dialogue (multi languages), building automation interfaces, among others. The control elements are factory mounted, wired and tested to ensure a protection of the chiller and efficient capacity control.

Crystallization

As previously mentioned, a common problem in absorption machines is the crystallization, which is nothing more than the process through which the salt present in a saline solution at a temperature below the saturation temperature of a given concentration, begins to solidify.

The crystallization occurs depending on the temperature and concentration of the concentrated solution inside the heat exchanger, which could be obstructed by accumulation of salt crystals due to a prolonged operation under this condition, finally affecting the operation of the chiller. Some of the main causes of crystallization in absorption machines are: air and other non-condensables leaking into the chiller, too low cooling water temperature and sudden/abrupt fluctuations of cooling water temperature.

The presence of air and other non-condensables inside the chiller causes an increase of the pressure in the evaporator and thus an increase in its temperature, with a consequently decrease in the cooling capacity. When the control system detects an increase in the evaporator outlet temperature, and in an attempt to solve this situation, it reacts by increasing the amount of solution and heat supplied to the generator, causing that more refrigerant boils off at the generator and a more concentrated solution to be delivered to the heat exchanger. If this situation occurs under higher load conditions, can lead to increasing the concentration of the solution to such an extent that crystallization occurs in the heat exchanger.

To prevent air and other non-condensable leaks, manufacturers have successfully implemented high-quality construction, smart microelectronic controls, and automatic purge systems in modern absorption chillers.

As mentioned above, another possible cause of crystallization is the supply of cooling water with a very low temperature, due to the fact that the low temperature of the cooling water reduces the temperature of the diluted solution that subsequently enters the heat exchanger. In this, the low-temperature diluted solution absorbs a greater amount of heat from the concentrated solution, causing a decrease in its temperature at the heat exchanger outlet, with the risk that if the temperature drops sufficiently it may result in crystallization of the concentrated solution.

To avoid the aforementioned, manufacturers designed absorption machines to operate with a constant cooling temperature. However, at the present time, control elements are being implemented for enabling to modern absorption machines operate in a wide cooling temperature range and even that this temperature can vary depending on the cooling demand and the environmental conditions.

In addition, sudden and rapid changes in the temperature variation of the cooling water must be avoided.

Capacity control of the absorption machine

The principals used methods to carry out the control of the capacity of an absorption machine consist of the solution temperature variation, solution concentration variation or in some cases the simultaneous application of the previous two.

One of the main tasks of the control system is to regulate and control the capacity of the chiller, for which it constantly monitors the evaporator outlet water temperature, compares it with the setpoint, and according to the obtained results, implements some of the methods indicated above.

- Solution temperature variation
  For varying the temperature of the solution, it is usually resorted to the variation of the supplied solution quantity to the generator. For example, in a partial load situation, when the control system detects a variation in the evaporator outlet water temperature, it sends a less diluted solution to the generator, which would reduce the amount of thermal energy required to boil off the refrigerant. Due to this lower amount of thermal energy supplied to the generator, the amount of refrigerant evaporated in it decreases, causing a less concentrated solution to return to the absorber. This less concentrated solution in the absorber leads to an increase in pressure in the evaporator-absorber section and with it an increase in the evaporation temperature, finally decreasing the cooling capacity of the machine due to the reduction of the temperature difference between the chilled water and the refrigerant.
  Traditional chillers used to implement a throttling valve or a bypass valve for varying the solution flow to the generator. The throttling valve increases the pressure loss in the circuit, forcing the pump to work at a higher point on the curve, which leads to a decrease in the pumped flow rate. Through the by-pass valve, part of the pumped solution is returned to the absorber, thereby reducing the amount of solution finally sent to the generator.
  Modern absorption machines work with variable flow pumps controlled by frequency inverters, achieving not only adjust the quantity of the pumped solution to the generator but also reducing the energy consumption.
- Solution concentration variation
  The variation of the solution concentration for the adjustment and control of the capacity of the absorption machine is achieved through the variation of the supplied thermal energy to the generator according to the variation of the cooling demand on the chiller. This effect is achieved by adjusting the thermal energy supplied to the generator through a modulation valve in indirect fired absorption chillers or by the burner modulating in direct-fired absorption chillers, when the control system detects changes in the evaporator outlet water temperature.
  Due to the lower supply of thermal energy to the generator, the solution that reaches the absorber will be less concentrated since it will contain some refrigerant, having less capacity to absorb refrigerant vapor. Due to the foregoing, a greater amount of refrigerant vapor will remain in the evaporator causing an increase in pressure in the evaporator-absorber section and with it an increase in the evaporation temperature, finally decreasing the cooling capacity of the machine due to the reduction of the temperature difference between the chilled water and the refrigerant.
  In traditional absorption machines, the method described above used to be implemented to maintain the evaporator outlet water temperature at the desired values, however, by itself, it does not constitute an optimal solution due to the slow response times necessary for the adjustment of temperature and the capacity.
  Some modern absorption equipment combines the adjustment of the concentration and the temperature of the solution at the generator, to reach an optimal control of the capacity of the machine and for maintaining the evaporator outlet water temperature at the desired values.

6. Analysis of the absorption chiller components in accordance with the operating conditions

In some consulted research works, such as those performed by Herold *et al.* [1], Wang *et al.* [2], Zaidan *et al.* [3], Mohanty *et al.* [4], and Abdulateef *et al.* [5], the effects in the thermodynamic behavior of a simple effect $LiBr-H_2O$ absorption refrigeration cycle were studied through simulations, regarding changes and variations done in some of its operating conditions. Considering these studies, this section provides information about the behavior of the absorption machines regarding to those operating conditions that can be modified and/or adjusted to a certain extent by the strategies and control systems implemented.

In the works indicated above, simulations of practical study cases were carried out in which the parameter that was intended to be studied was varied and the rest of the parameters and input data were kept constant.

Generator inlet water temperature variation

The curves in Figure 1 show the effects of the generator inlet water temperature variation on the coefficient of performance (COP) and on the heat transfer rates at the evaporator, generator, condenser, and solution heat exchanger

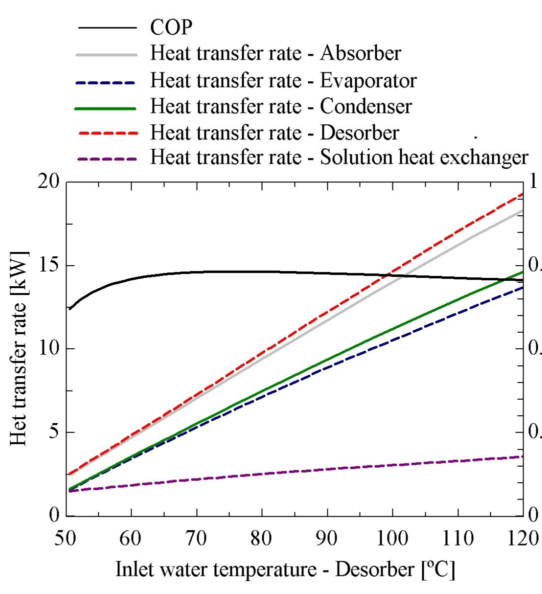

Figure 1: Effect of the generator inlet water temperature variation on the performance of $LiBr-H_2O$ absorption machine [1].

In the figure above, almost a linear increase in the cooling capacity of the chiller is observed as the inlet temperature of the generator water rises. Also, the heat transfer rate in the rest of the heat exchangers of the absorption machine experiment a significant increasing as the temperature of the water entering the generator increases.

The COP curve is characterized by having a flattened shape as the water inlet temperature to the generator increases, which according to [1] is due to the fact that the absorption machine is a three-temperature device whose variations significantly affect cycle performance, so the effect generated in the COP is not at all obvious.

Evaporator inlet water temperature variation

The effects of the variation of the inlet water at the evaporator on the absorption chiller coefficient of performance (COP) and on the evaporator heat transfer rate are illustrated in Figure 2. In this, a slight variation in the COP and in the cooling capacity of the machine is observed as the temperature of the water entering the evaporator increases.

The pressure in the evaporator increases as a consequence of the rising of its temperature, causing a slight increase in the heat transfer driving potential.

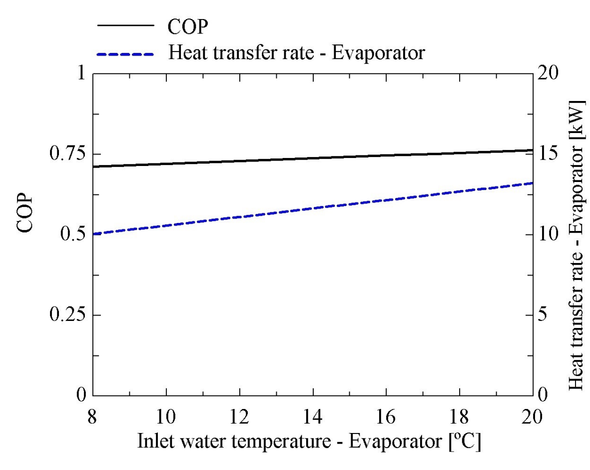

Figure 2: Effect of the evaporator inlet water temperature variation on the performance of $LiBr-H_2O$ absorption machine [1].

Cooling inlet water temperature variation

The effects of the cooling water temperature variation on the coefficient of performance (COP) and on the cooling capacity of the absorption chiller are shown in Figure 3. In this, a decreasing in the cooling capacity of the absorption machine is observed as the cooling inlet temperature increases.

A slight variation in the COP value is observed, due to the combined and palliative effect of changes in temperature and capacity experienced in the evaporator.

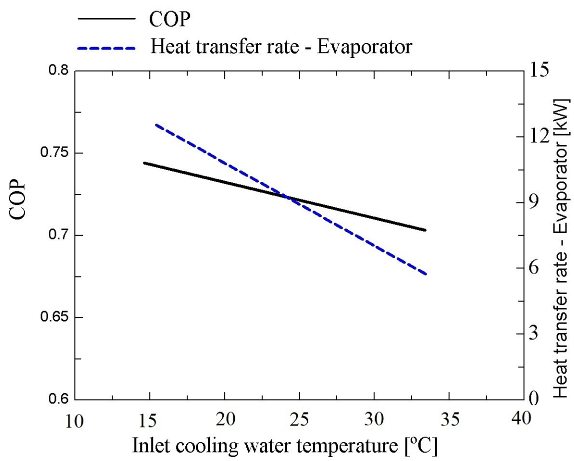

Figure 3: Effect of the cooling inlet water temperature variation on the performance of LiBr – H_2O absorption machine [1].

Water flow rate variation at the generator

The graphs in Figure 4 show the effects of the variation of the water flow rate supplied to the generator on the coefficient of performance (COP) and on the cooling capacity of the absorption machine. In this, it is observed a low sensitivity of both the COP and the heat transfer rate of the evaporator to the variation of the mass flow of hot water supplied.

7. Basic operation modes of solar thermal cooling system driven by solar collectors

The configurations of solar cooling systems driven by solar collectors are designed to work in one of the two typical operating modes commonly used in this kind of solutions, such as: direct coupling and indirect coupling.

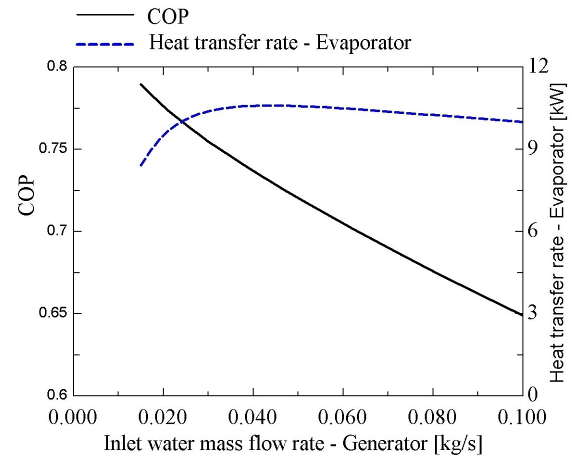

Figure 4: Effect of the hot water mass flow rate variation at the generator on the performance of LiBr – H_2O absorption machine [1].

Mode direct coupling

This mode of operation consists of the direct and simultaneous use of the available solar energy for the generation of refrigeration in the treatment of an air-conditioned building, coupling the solar collector system and the absorption machine directly or through an inertia tank, but without including a hot water storage, as shown in Figure 5.

Without going into details related to the operation of the control system, the main characteristics of this type of operating mode are listed below:

- The absorption machine is activated only if the provided solar energy is sufficient and within the values of the boundary conditions.
- Cooling generation occurs regardless of the cooling demand of the building.
- The cooling supply is fast, but without a precise control over the generated cooling capacity and chilled water temperature, because any amount of available solar energy will be transformed into cold.
- When a buffer tank is not included, the operation of the system becomes more unstable, especially in relation to the temperature of the chilled water, since any variation in

the available solar energy directly affects the cooling generation.

- The cooling demand meeting is not guaranteed due to the absence of an auxiliary heating supply system
- The operation mode of direct coupling should not be implemented in applications with a constant cooling demand. Some applications of this type of system are found in single-family homes or as support for conventional refrigeration systems.

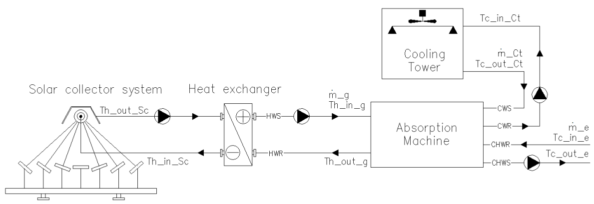

Figure 5: Typical schematic diagram of solar driven absorption cooling system with direct coupling

Table 3 includes information on some existing solar absorption installations and research work carried out with the direct coupling operation approach. This table includes information on the type of collector, type and cooling capacity of the absorption chiller, location, among other data of interest.

Mode Indirect coupling

This mode of operation consists of including a hot water storage tank and an auxiliary heating system in the coupling between the absorption machine and the solar collector system, with sufficient capacity to enable constant and stable operation of the system and the cooling demand meeting. This mode of coupling is illustrated in Figure 6. It is the most used operation mode in the solar thermal cooling systems built and installed to date, and the most frequently implemented in the research works performed in this field of engineering.

Depending on the capacity of the hot water storage tank, the solar cooling system can work in basically two differents ways:

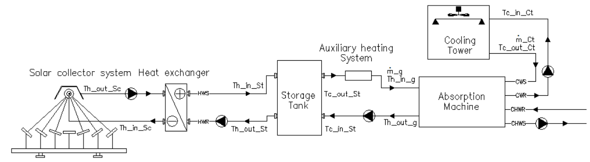

Figure 6: Typical schematic diagram of solar driven absorption cooling system with indirect coupling

- If the tank has a low storage capacity, the absorption machine will start up once it has been charged with a certain amount of energy and the minimum operating temperature of the chiller has been reached inside. The loading and unloading of the tank occur constantly.
  Only the absorbed solar thermal energy necessary to satisfy the momentary cooling demand will be used and the rest is stored. If the solar thermal energy absorbed is not sufficient to satisfy the thermal demand, then the auxiliary heating system comes into operation.
- When the hot water storage tank has a large capacity, then, it is usually charged with the solar energy absorbed by the collectors during the start-up of the installation, and then kept at a minimum temperature for long periods of time. Daily, in the tank, processes of charging (storage of thermal energy from the absorption of the collectors) and partial discharge are carried out. In this way, the previously stored energy as well as the daily absorbed and stored energy can be used in the stable generation of refrigeration.
  Thus, not only a stable operation of the installation is guaranteed, but also the satisfaction of the thermal load of the building regardless of the coupling of the simultaneity between available solar energy and required thermal load.

Some existing solar absorption installations and research works in which the indirect coupling operation approach was used are included in Table 4.

Table 3: Solar absorption installations functioning with the direct coupling operation approach

City	Owner/client	Type of work		Solar collector technology					Absorption Technology		Collector area	Cooling Capacity	Reference
		(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	m^2	kW	
Newcastle	CSIRO energy center		X			X			X		60	17,5	[6]
Graz	FA. Solid		X	X					X		7	2	[6]
Stuttgart	University Stuttgart		X	X					X		32	10	[6]
Miñao	Domolab		X	X					X		22,7	4,5	[6]
Freiburg	PSE workshop	X	X					X		X	88	2 ut of 12 kW	[7]
Bergamo	Robur factory	X	X					X		X	132	2 ut of 12 kW	[7]
Freiburg	PSE workshop	X	X					X		X	88	2 ut of 12 kW	[8]
Curicó	Miguel Torres winery	X	X	X					X		80	17,5	[9]
Seville	-	X						X		X	352	174	[10]
Seville	-	X						X		X	352	174	[11]
Gabes	-	X			X				X		21	8	[12]
Seville	-	X						X		X	352	174	[13]
Las Vegas/Seville	-							X		X	500-1000-2500	233-1454	[14]
Seville	-	X						X		X	352	174	[15]
Grombalia	Winery Grombalia		X					X	X		88	12,8	[16]
Marrakech	Le bonlait		X			X			X		70	12,8	[16]

(a):Research, (b): Commissioned
(c): Flat plate solar collector, (d): Evacuated-tube collector, (e): Parabolic trough collector, (f): Parabolic Dish collector
(g): Linear Fresnel collector, (h):Single effect, (i): Double effect

8. Basic control techniques for hydronics circuits

Considering the information consulted in various research works ([23, 24, 25, 26, 27]), doctoral theses ([28, 29]), manufacturers technical manuals:

- Yazaki WFC- SC(H) Chiller and Chiller-Heater Available online: (Link).
- Cention Technical catalogue Available online: (Link).
- Carrier Manufacturer - General information and technical manual Available online: (Link).
- WorldEnergy Absorption Chiller Heat Pump Available online: (Link).
- MAYA-Yazaki Water fired absorption chiller WFC series Available online: (Link).
- LG Absorption chiller Available online: (Link).
- Thermax Hot water vapour absorption chiller Available online: (Link).
- Cogenie-Prochill Hot Water Driven Vapor Absorption Machine Available online: (Link).
- Yasaki Plantas enfriadoras de agua por ciclo de absorción, alimentadas por agua caliente Available online: (Link).
- Trane Trane Classic. Absorption Series Available online: (Link).
- Trane Trane Horizon. Absorption Series Available online: (Link).

and others documents, some basic techniques commonly used for the control and regulation of hydronic systems have been identified and briefly described below.

Heating system control techniques

The control and regulation of hydronic hot water systems can be performed through any of the techniques shown in Figure 7.

- Differential ON/OFF control
  This technique basically consists of start/stop the circulation pump of a heating circuit, according to the comparison of the temperature

Table 4: Solar absorption installations functioning with the indirect coupling operation approach

City	Owner/client	Type of work		Solar collector technology					Absorption Technology		Collector area m^2	Cooling Capacity kW	Hot water Storage tank L	Reference
		(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)				
Maclas	Résidence du Lac / SIEL		X		X				X		24	10	500	[6]
Erlangen	Siemens Erlangen		X		X				X		50	10	1000	[6]
Kalkhara	Retirement home Kalkhara		X	X					X		38	10	1000	[6]
Kording	Headquarter of Eco Group		X	X	X				X		30,5 / 7	10	400	[6]
Canary Island	ITC [1]		X	X							68,4	35,2	2 x 3000 L	[17]
Nicosia	L' Amor Rouge Bakery		X		X				X		120	70,3	6800	[17]
Doha	-		X					X		X	1400	700	40000	(Link)
Johannesburg	MTN HD[2]		X					X		X	484	330	NS [5]	(Link)
Newcastle	CSSC[3]		X			X				X	350	233	2000	[16]
Queensland	Ipswich Hospital		X			X				X	574	295	5000	[16]
Dalaman	The TUI Iberotel Hotel		X				X				360	116	6000	[16]
Baja California	-	X	X		X				X		110	35	12000	[18]
Various[4]	-	X		X					X		70-110	35	5000	[19]
Depok	MRC	X	X		X				X	X	181	239	1000	[20]
Ningbo	-	X	X		X				X		120	35	4000	[21]
Casaccia	Enea Research Center	X	X		X				X		99	70	NS [5,6]	[22]

[1] ITC: Technological Institute of Canary Islands.
[2] MTN Headquarters Datacenter.
[3] CSSC: Charlestown Square shopping center.
[4] Ahmedabad/ Bangalore/ Chennai/ Delhi.
[5] NS: not specified.
[6] The charge/discharge time is of the order of 10 minutes
(a):Research, (b): Commissioned
(c): Flat plate solar collector, (d): Evacuated-tube collector, (e): Parabolic trough collector, (f): Parabolic Dish collector
(g): Linear Fresnel collector, (h):Single effect, (i): Double effect

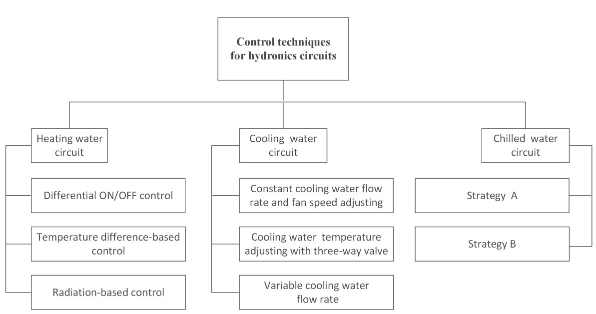

Figure 7: Basic control techniques according to the hydronic system type

reached at some point or element of the circuit with a previously defined target value.

As illustrated in Figure 8, the controller compares the collector fluid outlet temperature with the temperature of the tank. If the temperature at the outlet of the collector is higher than temperature inside the tank, and the temperature of the tank is lower than the maximum storage limit temperature, then the pumps are started.

When the temperature at the collector outlet drops to a certain value or the temperature inside the tank exceeds the defined boundary conditions, the pumps are turned off.

This technique is one of the most utilized in various domestic and commercial applications

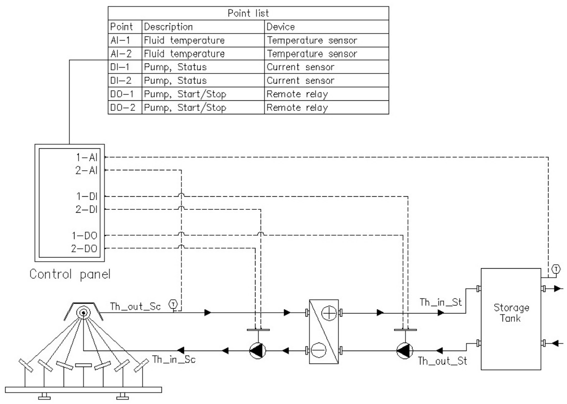

Figure 8: Differential ON/OFF strategy simplified representation

to regulate hot water systems. Low cost, reduced number of components and simplicity constitute its main advantages.
The drawbacks found in the differential ON/OFF control are: continuous periods of stops, constant fluctuations in the temperature of the loop, and the high consumption of the pumps due to their operation at fixed speed.

- Temperature difference-based control
  The temperature control of the hot water circuit is carried out by varying the water flow rate that circulates through it, according to the requirements and boundary conditions of the system. The flow rate variation is achieved using a proportional controller and pump speed control device (a variable speed drive or an electronic speed control) as shown in Figure 9.
  Through this technique it is possible to held the hot water circuit in continuous operation, thereby achieving a more stable behavior of the system temperature, avoiding constant stops/starts of the pump and optimizing its electrical consumption. However, the presence of the components and devices of control mentioned above, makes this solution more expensive than the Differential ON/OFF control solution.
- Radiation-based control
  In solar thermal circuits, the radiation-based control technique can be used to regulate the flow that circulates through the system. This

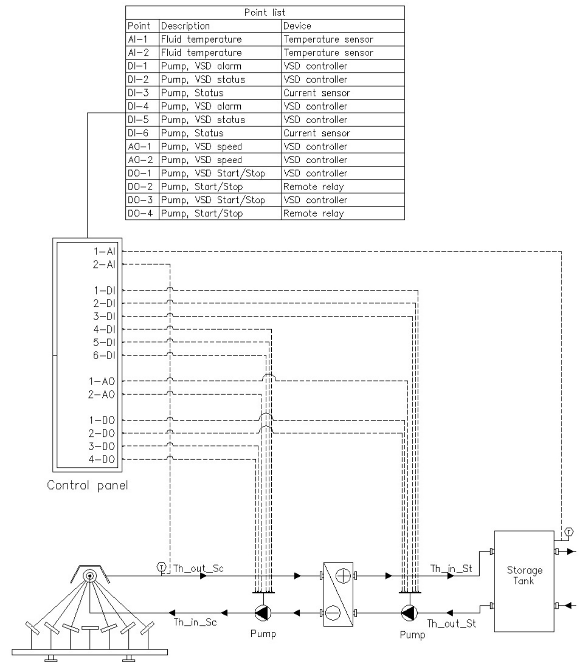

Figure 9: Heating system control strategy - Temperature difference-based control

technique is based on transiently measuring the amount of global radiation on the solar collector plane and adjusting the flow based on the required temperature and the boundary conditions of the system. A simplified representation of the radiation-based control strategy is shown in Figure 10.
The main advantage of implementing this type of control is the possibility of having a stable and constant temperature of the flow at the outlet of the solar collector. However, its implementation is limited by high costs, the absence of commercial solutions, high requirements for regulation and measurement elements, reasons why it is commonly used only in large-capacity solar thermal systems.

Cooling system control techniques

Any of the basic techniques indicated in Figure 7 for controlling cooling circuits can be implemented. These strategies with their respective control signals are illustrated in Figure 11, Figure 12 and Figure 13, for a deeper understanding of them.

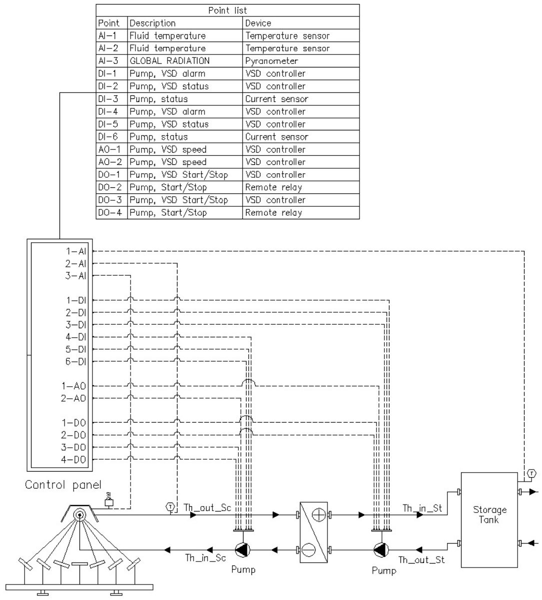

Figure 10: Heating system control strategy - Radiation-based control

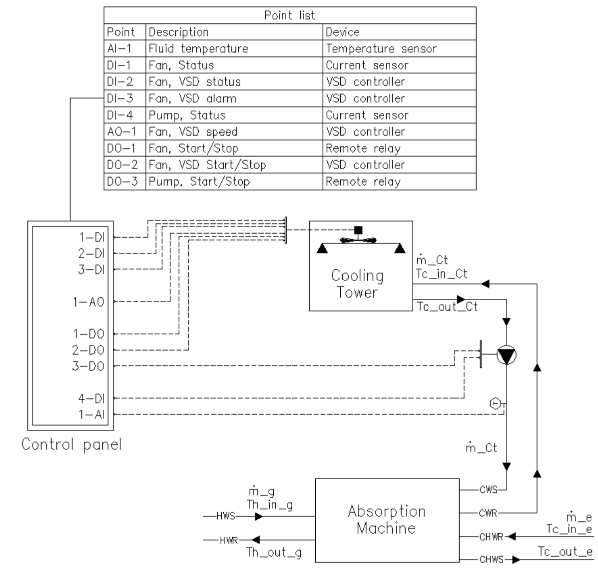

Figure 11: Cooling system control strategy– Constant cooling flow rate and fan speed adjusting

- Constant cooling flow rate and fan speed adjusting
  The cooling water temperature is controlled by varying the speed of the cooling tower fan, holding constant the flow of water in the cooling circuit. This strategy is represented simplified in the Figure 11.
  The speed adjustment of the cooling tower fan can be done with a simple two-speed controller or by means of a variable frequency drive.
  The fan speed is adjusted according to the temperature of the cooling water measured at the inlet of the absorption machine. As the fan speed increases, the air flow also increases and with it the heat exchange process in the tower, resulting in a decrease in the cooling water temperature.
  The main advantage of this regulation technique is that by maintaining a constant flow rate and controlling the temperature according to the requirements, the chiller can operate at nominal operating conditions.
- Cooling water temperature adjusting with three-way control valve (by mixing the return and supply flows)

As illustrated in Figure 12, the temperature of the cooling water supplied to the chiller is controlled through a three-way control valve, mixing the return cooling water flow (at the chiller outlet) with the cold-water flow from the cooling tower.
The water flow rate of the cooling circuit and the speed of cooling tower fan are kept constant.

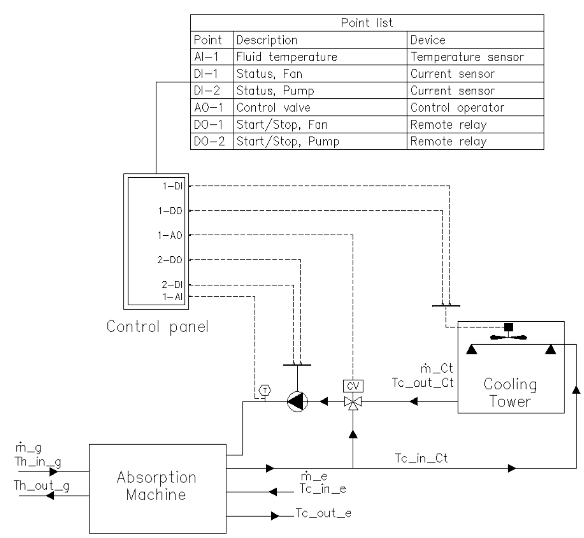

Figure 12: Cooling system control strategy– Temperature adjusting through a three–way control valve

- Variable cooling water flow rate
  The temperature control of the cooling water supplied to the chiller is carried out through the variation of the flow rate of the cooling loop, using a pump with variable frequency drive, as shown in Figure 13. The speed of the cooling tower fan is held constant.
  The main disadvantage of this technique is the slow response regarding to the changes in the cooling water temperature required by the chiller.

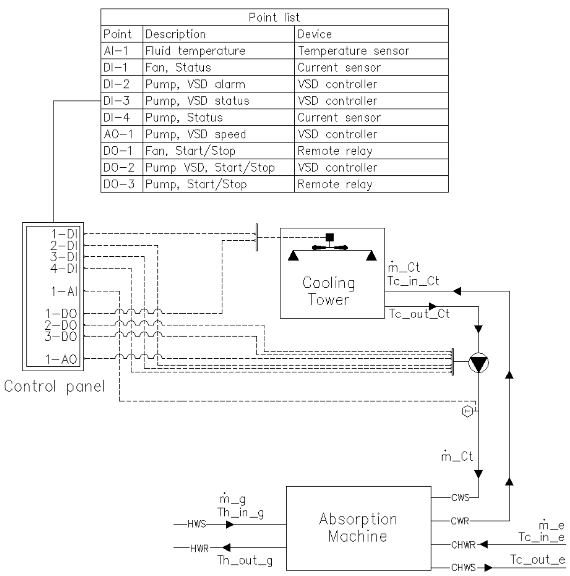

Figure 13: Cooling system control strategy–Variable flow rate

Chilled water control techniques

Chilled water distribution systems generally work at a constant flow rate, although currently, due to technological advances, conventional chillers can be implemented to work at a variable flow rate and constant temperature. The value of this temperature will depend on the types of equipment to be fed, the characteristics of the circuit and the considered criteria in the design of the chilled water distribution circuit.

The temperature of the chilled water supplied by the chiller can be controlled in different ways, through strategies that act in a combined and simultaneous way in the circuit that supplies hot water to the generator, in the cooling water circuit and in the chilled water circuit, as described below.

- Chilled water circuit control - Strategy A
  This strategy is illustrated in Figure 14 and is mainly characterized by:
  - The hot water circuit operates at a constant flow rate and variable temperature. A three-way valve is used to adjust the inlet temperature to the generator, mixing the return hot water from the absorption machine with the hot water provided from the hot water supply source (storage tank, solar circuit heat exchanger, auxiliary system, etc.).
  - The flow rate and the temperature of the cooling water supplied to the absorption machine are held at constants values.
  - In the chilled water circuit, the flow rate remains constant and the temperature is adjusted to the desired and previously defined value, by varying the temperature of the hot water at the generator inlet, using a three-way valve, in accordance to the temperature of the cooling water and the chilled water return entering the absorption machine.

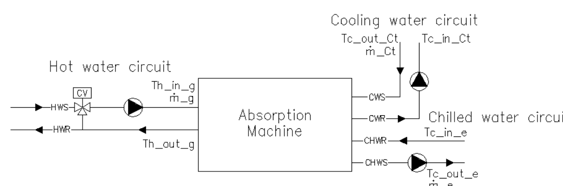

Figure 14: Chilled water circuit control–Strategy A

- Chilled water circuit control - Strategy B
  This strategy is illustrated in Figure 15 and is mainly characterized by:
  - In the hot water circuit, the temperature and flow rate of the water supplied to the absorption machine remain constant. It is essential to have a guaranteed and sufficient supply of thermal energy.
  - In the cooling water circuit, a three-way valve is used to adjust the inlet

temperature to the absorption machine, mixing the cold return water from the absorption machine with the cold water supplied from the cooling tower. The cooling water temperature adjustment can also be performed using other techniques, such as those described in the previous section.

- In the chilled water circuit, the flow rate is kept constant and the temperature will be adjusted to the desired and previously defined value through the variation of the cooling water temperature supplied to the absorption machine, depending on the temperature of the hot water at the generator inlet and the return temperature of the chilled water.

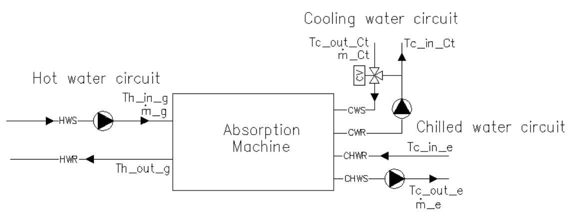

Figure 15: Chilled water circuit control–Strategy B

If necessary and according to the changing conditions in the hot water, cooling water and chilled water circuits, it is possible to combine the strategies described above, for example, when the temperature of the hot water at the generator inlet is not sufficient to satisfy the thermal demand, the cooling temperature supplied to the absorption machine could be reduced. It is also possible to combine these techniques with the objective of optimizing electrical consumption and the operation of the system itself.

9. Operation control strategies

This section, on the one hand, describes basic control strategies for hot water energized absorption machines, proposed by manufacturers, and on the other, provides an overview of the latest research carried out on control strategies for solar-driven absorption systems.

Control strategies proposed by manufacturers

Manufacturers such as Carrier, Trane and Yazaki propose in their user and installation manuals, various typical piping connection configurations for operating their respective equipment, which are illustrated and described below.

Figure 16, Figure 17 and Figure 18 show typical connection diagrams between the hot water supply circuit and the generator of the absorption machine.

In the arrangement of the schematic diagram in Figure 16, a constant flow is maintained in the hot water supply circuit and a three-way control valve is used for varying the quantity of the flow rate supplied to the chiller. This configuration is implemented when the temperature of the hot water circuit driven the chiller remains within the allowed operating limits.

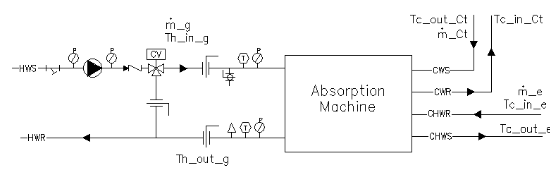

Figure 16: Typical hot water circuit piping connection diagram–Configuration A

The configuration presented in Figure 17 is a proposed alternative by the manufacturers when the working temperatures of the hot water supply circuit are higher than the defined boundary conditions for the chiller.

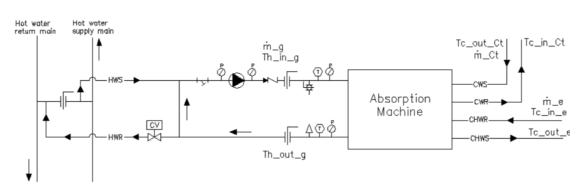

Figure 17: Typical hot water circuit piping connection diagram–Configuration B

In this arrangement, as can be seen, a circulation pump and a header installed between the hot-water supply and return mains are incorporated. The hot water to be supplied to the absorption machine must be taken from the aforementioned header.

The flow of hot water supplied to the absorption machine is held constant, and its temperature is adjusted to meet the required load. This temperature adjustment is achieved by modulating the amount of hot water that enters to the circulation loop, using a two-way modulating valve installed at the outlet of the loop. This valve is controlled based on the chilled water outlet temperature.

The configuration of the connection scheme in Figure 18 is implemented when the flow of hot water through the absorption machine is variable, for which a two-way modulating control valve is used.

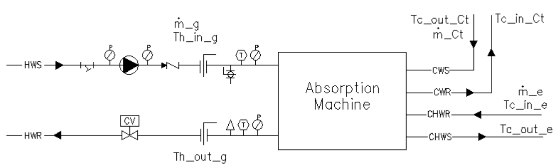

Figure 18: Typical hot water circuit piping connection diagram–Configuration C

Some typical connection diagrams between the cooling water circuit and the absorption machine are presented in Figure 19, Figure 20 and Figure 21.

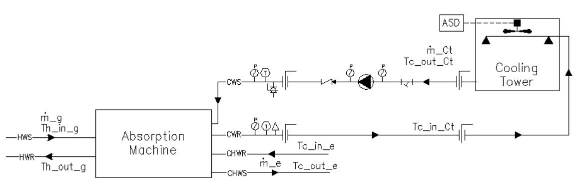

Figure 19: Typical cooling water circuit piping connection diagram–Configuration A

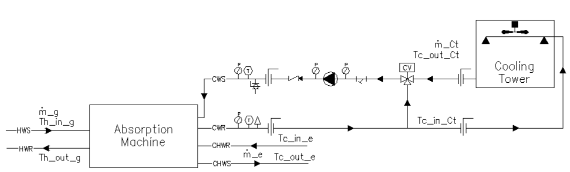

Figure 20: Typical cooling water circuit piping connection diagram–Configuration B

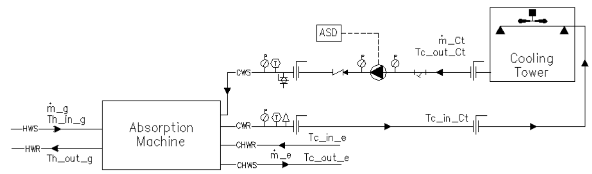

Figure 21: Typical cooling water circuit piping connection diagram–Configuration C

In the arrangement of the schematic diagram in Figure 19, a constant flow is held in the cooling water circuit, and the temperature of the cooling water entering the absorption machine is controlled by varying the speed of the cooling tower fan. The fan speed is adjusted in accordance with the measured temperature of the water in the inlet line to the absorption machine.

As an alternative to the variable frequency drive, the fan could operate at two speeds with a simpler controller, which would be activated according to the temperature requirements at the chiller inlet. The disadvantages of this option are the high electricity consumption of the fans and the continuous changes in the cooling water temperature affecting the chiller performance.

In the configuration presented in Figure 20, the cooling water flow and the cooling tower fan speed are held constant. The temperature of the cooling water is adjusted through a three-way control valve, mixing the return flow of the cooling circuit at the chiller outlet with the cold flow from the cooling tower, according to the measurement of the temperature of the cooling water at the entrance of the chiller.

In the schematic diagram of the Figure 21, the speed of the cooling tower fan is held constant and a pump with a frequency drive is used to vary the flow of water in the cooling circuit. The temperature of the cooling water entering the absorption machine is controlled through the variation of the supplied flow rate.

The supplied cooling water flow rate to the chiller is adjusted by the variable speed pump according to the water temperature measured at the chiller inlet. As the speed of the pump increases, the temperature difference between the warm and cold flow decreases

The chilled water piping connection proposed by the manufacturers and illustrated in Figure 22, can be used for constant or variable flow rate (according to the type of the installed pump) depending on the control strategy to be finally defined by the user.

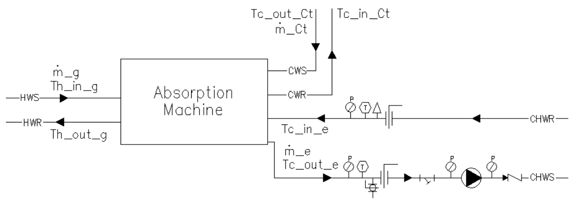

Figure 22: Typical chilled water circuit piping connection diagram

Control strategies proposed in research works

In recent years, the number of investigations regarding the control of solar thermal cooling systems has increased, focused on optimizing the specific functioning of any of its components and/or the global operation of the system.

However, despite the increase in the number of solar absorption installations recently commissioned and the progress in the capabilities of simulation software for this type of system, research in the field of control (for finding and/or defining regulation strategies that optimize its operation) has been limited by the scarce existence of solar absorption facilities suitable for experimental tests, and the absence of realistic simulation models of some components of the solar cooling system, such as absorption chillers, concentrating solar collectors, etc.

Some literature references are discussed below with the aim of providing an overview of the topics recently studied regarding the control and regulation strategies for solar absorption systems, and the current trends in this field.

Dalibard *et al.* [30] studied the optimization of control for chiller driven by solar energy. The work focused solely on analyzing control strategies applied to the cooling circuit for the modulation of the cooling capacity of the absorption machine according to the demand of the building, in order to optimize the operation of the chiller and reduce the electrical consumption of the system (mainly the consumption of the cooling circuit).

The main purpose of the study was to develop an efficient control method for the regulation of chillers driven by solar thermal energy, based on the simultaneous adjustment of the temperature and the flow rate of the cooling water.

Three different strategies were implemented and analyzed to control the cooling circuit of the solar absorption system. The first strategy consisted of keeping the cooling water flow rate constant and adjusting its temperature by varying the speed of the cooling tower fan. In the second, the capacity of the absorption machine was controlled by varying the flow rate of the cooling circuit through a pump with a variable speed drive, maintaining constant the temperature of the cooling water and the speed of the cooling tower fan.

The last strategy consisted of simultaneously varying the temperature and flow rate of the cooling water to adjust the capacity of the absorption machine in accordance with the cooling demand of the building. In each of the strategies described above, the water flow rates in the hot and cold-water circuits were kept constant.

The experimentation was carried out using a system composed of a diffusion ammonia/water absorption chiller with a cooling capacity of 3,8 kW, an open wet cooling tower with a heat rejection capacity of 40 kW, a circulation pump of water in the cooling circuit and two electrical heaters to simulate the solar system and the demand of the building with maximum electrical power of 24 kW and 6 kW respectively. These heaters use internal PI controllers to adjust their respective temperature set-points.

Through the implementation of optimization algorithms and the developed control approach in which the temperature and the flow rate of cooling water are simultaneously controlled, it was possible to achieve significant savings in electricity consumption (20-60 %) and adjust the cooling capacity of the chillers according to the cooling demand of the building.

Kühn *et al.* [31] studied the development of a control strategy for solar cooling systems based on the regulation of the cooling water temperature, using the method of the characteristic equation which describes a linear relationship between driving, cooling and chilled water temperature and cooling capacity.

The study consisted in the comparison of two control strategies for the regulation of solar thermal cooling systems: a conventional and a proposed new strategy. In the conventional strategy, the variation of the hot water temperature supplied to the generator is used as a control variable through a three-way valve, and in the proposed new strategy, the temperature of the cooling water supplied to the absorption machine is varied to optimize the operation of the chiller and reduce the general consumption of the system.

The strategies described above were implemented and simulated with the TRNSYS software, considering the climatic and solar radiation conditions of the cities of Berlin and Iraq. The modeled solar absorption system was composed of 34 m^2 of flat plate collectors directly coupled to a single effect $LiBr-H_2O$ absorption machine with 10 kW of cooling capacity and a tailor-made wet cooling tower.

The obtained results from the performed simulations determined that the new control strategy based on the adjustment of the cooling water temperature indicated a stable behavior of the generated chilled water temperature by the the absorption machine, and a reduction of the electrical consumption of the system when the solar irradiation was sufficient to satisfy the cooling demand.

Witheephanich *et al.* [32] reviewed in detail some advance control strategies and approaches currently available for the control of solar thermal cooling systems, considering the operational characteristics of a solar absorption system installed at the University of Seville, Spain, composed of 352 m^2 solar field of linear Fresnel collectors directly coupled to a double effect $LiBr-H_2O$ absorption machine with 174 kW of cooling capacity, a direct-fired natural gas burner and a PCM storage tank. This installation uses the water of the Guadalquivir river as a means of heat dissipation.

The advance control strategies and approaches analyzed and considered suitable for the control of solar cooling thermal systems were: model predictive control, fuzzy logic control and neural network. These, were selected according to their virtues regarding the main problem raised in the work, which consisted of maintaining the outlet temperature of the solar circuit at a specific set point.

Ortiz *et al.* [11] investigated the implementation of a split-range control technique on the operation of a linear Fresnel collector in order to improve an absorption plant performance, with the aim of achieving a more adequately manage of the solar irradiance intermittency, increase the use of solar energy in the operation of the absorption system and thereby reduce auxiliary consumption to meet the cooling demand.

The proposed study was carried out by proposing, modeling and analyzing modifications in the control system of the absorption refrigeration system installed at the University of Seville, which consisted on the one hand in using a split-range controller capable of manipulating both flow and defocus of the Fresnel collector, and on the other, replacing the original chiller on-off controller with a PI controller. The analyzed solar cooling thermal installation consists of 352 m^2 solar field of linear Fresnel collectors directly coupled to a $LiBr-H_2O$ double effect absorption machine with 174 kW of cooling capacity, a direct-fired natural gas burner and a PCM storage tank.

The obtained results from using the new proposed control system showed an increase of 66 % in energy generation and 63 % of exergy production.

Meligy *et al.* [33] studied the development of a control system for regulating the operation of a small-scale multi-generation solar power plant driven by linear Fresnel collector, located in SEKEM medical center near Belbis city, Egypt. The proposed control strategy consisted in keeping the outlet temperature of the linear Fresnel collector in a constant value by varying the oil flow pumped through the field, using for this a proportional integral controller (PI-controller) to regulate the speed of the circuit pump.

The solar field of linear Fresnel collectors, which comprises an area of 296 m^2, has been modeled quasi-dynamically with the Conventional and Renewable Energy Optimization Toolbox (CARNOT) software, and subsequently implemented in MATLAB/Simulink together with the rest of the components of the studied system. (storage tank, pipes and a centrifugal pump).

The developed control strategy was implemented and evaluated under nominal conditions, in the presence of disturbances due to variation of ambient temperature, inlet oil temperature and solar radiation, and even modifying the operating conditions of the system.

To continue delving into the field of control strategies for thermal solar cooling systems, it is recommended to consult the varied but not so extensive literature available so far in this area of research, among which [18, 22, 34, 35, 36, 37, 38, 39, 40, 41].

10. Conclusions

The implementation of an inappropriate control strategy would result in an inefficient operation of the installation, regardless of the quality of the components, the correct dimensioning of the installation and/or the implementation of appropriate hydraulic concepts and configurations.

An inadequate operation of a solar cooling system is reflected in the low electrical efficiency of each of its components and in a high consumption of the auxiliary energy used to energize the absorption machine and be able to satisfy the cooling demand.

Control modes without the possibility of modulating the capacity of the absorption machine at partial loads, result in a high consumption of auxiliary energy, due to the generation of unnecessary cooling for which this type of energy supply is required.

The design of control and operating strategies for solar thermal cooling systems is first conditioned by the objectives to be achieved, such as optimization of the electrical consumption of the general system, maximization of the cooling generation or optimization of the available solar and residual energy resources. And second by the characteristics of the installation and the project itself, including: climatic conditions, characteristics of the building, the type and characteristics of the components of the installation itself, the hourly profile of the cooling demand, the presence of usable residual energy, among others.

Considering the above regarding the subjective nature of each solar cooling solution, it seems necessary to model and simulate the solar absorption installations to design, evaluate and select the most appropriate control strategy for the system to be implemented in order to optimize its operation and achieve significant auxiliary energy savings. Evidencing the importance of the development and improvement of realistic simulation tools of this type of thermal systems.

In most of the research carried out to date, control strategies implemented independently in any of the circuits that compose a solar cooling system (hot, cooling and chilled water circuits) have been evaluated and/or studied, and very few works have studied the combined and simultaneous implementation of control strategies in the various circuits. The aforementioned is a field yet to be explored and with significant possibilities, although it would depend on powerful computer programs and control approaches with the capacity to handle this type of interaction, such as machine learning, among others.

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