SURVEY OF CONTROL AND CONFIGURATION OF SOLAR HEAT DRIVEN CHILLER SYSTEMS

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Abstract

Installed solar heat driven chiller (SHDC) cooling systems show a wide variety in both their configurations and control strategies, a variety beyond simple differences in applications and climates. Given the number of possible hydraulic circuit configurations, components, control strategies, and objectives, there are a large number of possible solutions in designing a solar heat driven cooling system. The design and operation of SHDC systems is further complicated by their interdependent and dynamic nature.

This paper presents an overview of SHDC systems with an emphasis on system control, drawn from an analysis of the configuration and control of 11 SHDC systems installed in Europe within Task 38 “Solar Air-Conditioning and Refrigeration” of the International Energy Agency Solar Heating & Cooling Programme [1]. The rated chiller capacity of the surveyed systems ranges from 7.5 to 300 kW chilled water with variations in application, auxiliary heating and cooling, storage strategies and control.

In terms of the secondary circuit control strategy (the driving heat circuit supplying the generator), most systems surveyed control the chilled water temperature by regulation of the driving hot water temperature from a hot water storage tank. Meanwhile, emerging literature and field experience are demonstrating that efficient system performance can be obtained by regulating the cooling water temperature by means of a variable speed drive on the cooling tower fan. This may represent a shift in the way these systems are designed and operated. Such control aspects and their interaction with system configuration will be discussed.

1 Introduction

A recent survey of world-wide solar cooling systems listed only 66 installed solar heat driven chiller (SHDC) based systems, demonstrating that field experience with these systems is relatively limited [2]. The variety of installed SHDC systems reflects designer’s exploration of the different ideas in the field of solar cooling. Within Task 38 “Solar Air-Conditioning and Refrigeration” of the International Energy Agency Solar Heating & Cooling Programme, an overview of solar air-conditioning systems was undertaken. The purpose of this activity (subtask B2 of Task 38), was to collect experiences and analyze both configuration and control of these systems. Results of this activity include contribution to the upcoming next edition of the Solar-Assisted Air-Conditioning in Buildings - A Handbook for Planners [3], as well as a final subtask report.

2 Control of Solar Cooling Systems

2.1 General control objectives

The control of solar cooling systems plays an important part in an overall facility energy management strategy, in order to minimize energy use and cost while maintaining internal comfort requirements. The control of a solar cooling installation is largely dependent on its configuration and application. The design of a solar cooling system, like the design of any HVAC system, is a trade-off between owning costs (primarily the initial capital expenditure), operating costs (maintenance and energy costs), and occupant comfort. The control of a solar cooling system largely influences operating costs and comfort levels. In general, the objectives of control include;

- Autonomous operation of the system
- Minimum cost of energy
- Maximum occupant comfort
- Safety
- Fault detection and correction

HVAC systems in buildings are typically controlled using a two-level control structure. The more general supervisory control level specifies set points and time dependent modes of operation for the lower local-loop control level, which attempts to meet the set points using the control actuators. The following discussion focuses on supervisory control strategies. The main goals of solar cooling control strategies are to;

- Avoid malfunctioning of both the overall system and the several technical components and as well to ensure a trouble-free operation
- Meet the cooling loads (i.e., guarantee certain indoor thermal comfort conditions in terms of relative humidity and temperature of indoor air)
- Minimize the primary energy usage per kilowatt produced chilled water or per cubic meter conditioned air

That means driving the implemented energy consumers (pumps, ventilators, solar collector, chiller etc.) of the overall system in its minimal energy consuming operation point and benefiting from maximal use of solar heat by using it as the major driving energy source for the thermally driven system.

2.2 Survey of scientific literature

Taking a broader perspective of the control issues, two strategies meeting two different objectives of control can be identified; a solar-guided strategy, and a cold-guided strategy [3]. The solar-guided strategy is characterized by a high chilled water demand such that the chiller operates whenever driving heat is available, maximizing the cold production at the cost of a variable chilled water temperature. The cold-guided strategy alternatively represents an active attempt by the controller to reach a chilled water temperature set-point, at the cost of reducing the chilling capacity. Regulation of the chilled water temperature by control of the cooling water circuit is an active area of research. Advantages of this strategy include reducing cooling tower electricity consumption, a major factor in determining system efficiency, and also water consumption [4]. A comparison of driving heat circuit and cooling circuit control is elaborated in [6].

2.3 Survey of systems

Within Subtask B of IEA Task 38, a survey was sent to experts responsible for designing and operating solar cooling installations. The survey contained 3 levels of contribution, from basic information, to more advanced details of, and experiences with, the control strategies employed. Table 1 lists the 11 SHDC systems whose designers and operators contributed an advanced level of detail in their experiences in design and control. Contributions varied in scope and detail of information, but the survey methodology included sections on general information, hydraulic scheme, control strategy, as well as general recommendations. These systems are a subset of a larger and more general survey within IEA Task 38 [7]. General conclusions are drawn in the areas of capacities and sizing, specific components chosen, and control strategies employed. Table 1 lists these systems, their locations, and their applications and chiller capacities.

Table 1 - Systems surveyed for control and configuration

City	Country	Lat	Long	Application	Application	Chiller Capacity
		-	-	-	-	kW
Perpignon[1]	France	42°42 N	2°53' E	Offices	Fan-coils	7.5
Rimsting[2]	Germany	47°53 N	12°20 E	Research		15
Rohrbach	Austria	48°34 N	13°59 E	Offices	Fan-coils	30
La Reunion	France	21°20 S	55°28 E	School	Fan-coils	30
Valladolid	Spain	41°32 N	4°45 W	Offices	Radiant floor	35
Gleisdorf[3]	Austria	47°06 N	15°42 E	Offices	Fan-coils	35
Sophia-Antipolis	France	43°37 N	7°33 E	Offices		35
Karlsbad	Germany	48°54 N	8°30 E	Offices	Fan-coils	54
Oberhausen	Germany	51°31 N	6°51 E	Offices	Fan-coils	58
Antalya	Turkey	36°53 N	30°42 E	Supermarket	Fan-coils	233
Bolzano	Italy	46°30 N	11°20 E	Offices		300

Notes

1 - Adsorption chiller
2 - Many various configurations possible
3 - Dual SDEC / SHDC installation

3 Results

Based on the completed survey contributions from the systems in Table 1, many various configurations were observed. Table 2 below summarizes the main aspects of configuration for these 11 systems based on the submitted hydraulic schemes and descriptions.

Table 2 - Survey of system configuration

City	Solar Field		Aux. Heating		Heat store	Aux. Cooling		Cold store	Heat Rejection
	m^2	Type	kW	Type	m^3	kW	Type	m^3	-
Perpignon	25	FP			0.3			0.3	Closed
Rimsting	71	ETC / FP		Gas	2.0			1	Open / Closed
Rohrbach	120	FP	220	HP / Gas	8.0	100	VC	0.5	Open
La Reunion	90	FP2			1.5			1	Open
Valladolid	77.5	ETC / FP	235	Gas	8.0			1	Closed
Gleisdorf	302	FP			4.6		DEC	1	Open
Sophia-Antipolis	90	CPC / ETC	50	HP	0.3	50	HP	0.5	Open
Karlsbad	196	CPC			2.0			2	Closed
Oberhausen	108	ETC			6.7		VC	1.5	Open
Antalya	432	CPC			8.0		VC		Open
Bolzano	424	ETC	1031	Gas / Cogen	10.0	632	VC	5	Open

A description of the above configurations follows.

Solar field type

FP	Flat-plate solar thermal collector, single or double glazing
ETC	Evacuated tube collector
CPC	Concentrating parabolic collector

Auxiliary heating types

Gas	Natural gas boiler
HP	Heat pump
Cogen	Waste heat from electricity cogeneration unit

Auxilliary cooling types

VC	Vapor compression chiller
DEC	Solar desiccant cooling system
HP	Heat pump

Heat rejection types

Open	Open wet cooling tower
Closed	Closed wet cooling tower

In order to compare the systems, metrics based on the collector area and storage volumes, each divided by the chilled water capacity, can be employed. Therefore, the collector-capacity ratio is defined as the collector area divided by the chiller capacity. The collector-capacity ratio varied between 1 and 9 m^2/kW_{cold}. At the high capacity end, (> 200 kW cooling), the two systems show a relatively low ratio, near 2. All small systems vary across the entire range. However, the different collector field types must be considered in this metric, where a concentrating or evacuated tube collector will have an increased performance compared to a flat-plate collector. Similarly, the heat storage ratio and cold storage ratio vary between 0.01 to 0.25 m^3/kW_{cold} and 0.01 to 0.07 m^3/kW_{cold} respectively. Once again, the large scale systems show similar ratios at the lower range, with the smaller systems showing no trend.

Table 3 summarizes the control aspects related to each of the 11 surveyed systems, with a detailed description of each strategy following.

Table 3 - Survey of system control

City	System design	Solar start	Solar control		Chiller control	
Perpignon	Auton	Radiation, Diff. Temp.	On-Off	Diff. Temp	On-Off	Driving / Cooling temp
Rimsting	Assist		On-Off	Diff. Temp	Cooling fan	Driving / Cooling temp
Rohrbach	Assist	Diff. Temp	On-Off	Diff. Temp	Gen. mix	Driving Temp
La Reunion	Auton	Radiation	On-Off	Diff. Temp	On-Off	Driving Temp
Valladolid	Assist	Radiation	Proportional	Radiation	Gen. mix	Driving Temp
Gleisdorf	Auton		On-Off		Gen. mix	Driving Temp
Sophia-Antipolis	Assist		On-Off	Radiation	On-Off	Driving Temp
Karlsbad	Auton		On-Off		Gen. mix	Driving Temp
Oberhausen	Assist	Radiation	Proportional		Gen. mix	Driving Temp
Antalya	Assist		On-Off		Gen. mix	Driving Temp
Bolzano	Assist	Radiation	On-Off		Gen. mix	Driving Temp

System design

Auton	Autonomous - No back-up for heating or chilling.
Assist	Assisted - No backup present, or back-up present but not

	used or planned on being used.
Solar Start	
Diff. Temp.	The primary solar circuit circulation pump is activated in response to a set differential temperature.
Radiation	The instantaneous radiation on the collector field is measured and used to switch the primary circuit on and off.
Solar control	
On-Off	The simplest method of solar circuit temperature control, measure difference between tank and collector temperatures, and turn on the solar circuit circulation pump in response to a set differential temperature. Hysteresis is used to limit cycling.
Proportional	A more advanced control strategy taking advantage of a variable speed pump. The instantaneous temperature difference between the storage tank and collector field proportionally controls the mass flow rate of the solar heat circuit.
Diff. Temp	A temperature differential between tank and collector field is used to regulate the primary pump.
Radiation	The instantaneous irradiation on the collector field is measured and used to proportionally control the mass flow of the solar circuit. Stable temperature is main advantage. Empirical correlation between irradiation and mass flow is required.
Chiller Control	
On-Off	Simple on or off control of chiller depending on conditions.
Gen mix	Three way valve on generator for driving heat regulation.
Cooling fan	Vary the cooling temperature using the cooling tower fan.
Driving Temp	Control the generator temperature using a mixing valve or pump control.
Cooling temperature	Vary the cooling capacity using a variable speed fan on the cooling tower to control heat rejection temperature.

Solar circuit (primary loop) control was typically on-off with hysteresis. The secondary loop, which provides hot water from the storage tank to the absorption chiller, was controlled most commonly by a three way mixing valve and constant speed pump. Some systems have an on-off control only for regulating the hot water temperature. Two systems have the capability to use the cooling tower fan speed to regulate the cooling water and consequently the chilled water temperature. In the case of the Rimsting installation, a research installation with many possible control modes, a recommendation was made to use cooling tower fan speed regulation to improve system performance.

4 Conclusions

In a previous IEA TASK, IEA SHC Task 25, basic control strategies of SHDC systems were documented and described [3]. Nevertheless, a comprehensive documentation of practical experience and results in the design and operation of SHDC systems with applied control strategies was missing. Thus the activities of TASK 38 aim mainly to;

- Provide a comprehensive overview on applied SHDC system control
- Document and assess the experiences in the different demonstration projects
- Summarize important control issues as a result of this comprehensive work

This paper contains a selection and compilation of 11 case studies of applied control strategies of SHDC systems. Based on the Task 38 experts, practical experience regarding the applied control strategies and some selected general rules are stated which can guide a successful SHDC system design and operation.

Each SHDC system is more or less unique and only a few SHDC system providers offer comprehensive and recommended control strategies. The development of standard control strategies for the wide range of different SHDC system configurations is still a research task by many. Therefore, the effort required in order to develop and to implement a suitable control strategy of a SHDC system can be significant because there is no existing standard practice. Furthermore, it is obvious that the complexity of control strategy depends strongly on the complexity of the hydraulic scheme. Standard SHDC system configurations have been described, but local conditions and restrictions limit their applicability [3]. The control strategy can only be developed if the SHDC system configuration is decided and the comfort and system requirements (boundary conditions) are well determined.

Solar-assisted air-conditioning systems include a variety of components which need to be controlled efficiently in order to cover the comfort requirements and to meet expectations on the overall system efficiency. However, the implementation of control components such as actuators, sensors, and control system, increases the system costs and therefore has a significant influence on the economics of the system. Therefore the control devices should be selected in order to meet the highest possible system efficiency (primary energy saved, electric efficiency, etc.) with the lowest possible control effort (complexity, cost). In order to monitor the energy performance of a SHDC system it is highly recommended to implement the required hardware and software equipment. Normally the sensor equipment and measured data points of the implemented control system do not fulfil the requirement of an appropriate assessment of the energy SHDC system performance. This field equipment should be extended to meet a minimal monitoring level [1].

In existing control systems there are often different options to meet the same control task, but with different impact on the overall system performance. For example, the control options to manage the chilled water temperature strongly depend on the hydraulic system configuration and on the type of distribution system. Moreover, the whole control strategy should be very different if the system is mainly working at part load or full load conditions.

If a SHDC system with a comparatively low nominal COP is employed and a fossil-fuelled heat source is used as the back-up, a high solar fraction is necessary in order to achieve significant primary energy savings. An appropriate design of the solar system, i.e., suitable dimensioning of the solar collector and system-integrated energy storage, is necessary for this purpose. The control strategy should enable to use of solar heat as much as possible. Especially for solar-assisted air-conditioning with additional heat sources like cogeneration units, district heating, and boilers, the control priority should be using solar heat followed by the auxilliary heat sources.

Finally, a key target of the control strategy of a SHDC system is to minimise the primary energy use per produced kW of chilled water or conditioned air. That means driving the implemented energy consumers (pumps, ventilators, solar collector, chiller etc.) of the overall system at its minimal energy consuming operation point. Consequently, the control strategy has to be flexible and adaptable in order to optimise the overall SHDC system. The control system and software should enable easy adaptation of control algorithms, parameters and set values. In many of the above presented case studies, the applied control software and hardware is more or less open source.

Given the above discussion of the complexity of control and configuration based on practical experiences from 11 SHDC systems, it is clear that a comparison between all systems is difficult both in that each system is unique, and that there are not enough systems, or active contributions from experts managing the systems. Therefore, it is difficult to make a statistically important statement about an optimum configuration or control. This conclusion leads to the recommendation to first clearly define boundary conditions and objectives for success in the system design and operation, and to use computer simulation tools and current expert advice to achieve a successful SHDC system.

5 Acknowledgements

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6 References

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