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Energy Procedia 30 (2012) 704 – 714

Energy

Procedia

SHC 2012

Experimentation and simulation of a small-scale adsorption cooling system in temperate climate

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Abstract

This paper focuses on the analysis of the operation of a solar cooling system based upon an adsorption chiller. The air-conditioned building studied is a laboratory located in a temperate climate region (Belgium). The monitoring reveals thermal and electrical coefficient of performance (COP) of the cooling system for different time scale (10s to 1 month). The whole system including solar collectors, adsorption machine, recooling unit and hot storage is simulated. The models are then confronted to the measurements. Measurement period is shared between 2011 and 2012. Enhancements have been achieved during winter 2011 to have a more efficient system operation. The aim of this experimental work is to describe, for both measurement periods, the influence of operating conditions on the energy efficiency (thermal behavior and electrical consumption). On the simulation point of view, the main objective is to find accurate models for all the components. The adsorption chiller model is not yet precise enough to evaluate the performance of solar cooling in other conditions.

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Selection and/or peer-review under responsibility of PSE AG

Keywords: Adsorption; solar cooling; solar air-conditioning;

1. Introduction

A small-scale adsorption chiller has been recently installed in the laboratory building of the BEMS research team at University of Liège. This building was previously equipped with a fully monitored heat

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and cold production and distribution system. Besides, a solar collector field is used for building heating and domestic hot water production. Both economical and architectural limits made difficult to enlarge the existing solar collector field. This paper deals consequently with the experimentation and simulation of a solar cooling system plugged into an existing solar system. Previous study [1] on cooling load and available heat for this typical building led to the choice of one of the smallest market available adsorption chillers [2]. The scheme of the installed system is displayed on figure 1.

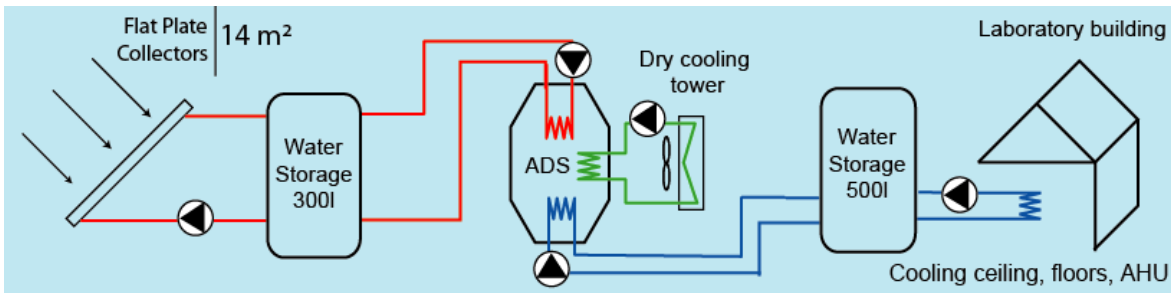


Fig. 1. Monitored solar air conditioning system at University of Liège

By operating and measuring the solar cooling system in real scale conditions (Belgian Climate), it is proposed to assess its thermal and electrical performance. The main components dedicated to solar air-conditioning are listed below (from left to right on figure 1):

- The hot water loop containing flat plate solar collectors (14m²) and hot water storage (300l with 7.2kW electrical heater),
- The adsorption chiller (ADS) containing two reactors with total cooling nominal power 9 kW,
- The recooling loop and its dry cooling tower (with spraying water since 2012),
- The cold water loop including the cold water storage (500l) ,
- Cold emission devices for cooling the laboratory building: cooling floor, cooling ceiling, Air Handling Unit.

The pumps driving water to the adsorption chiller as well as the cooling tower fans are internally controlled by the adsorption chiller itself. The computer controls the other part of the systems (cold water temperature, adsorption chiller start-up...). The installed system pictures take place on figure 2. The hydraulics module contains the three pumps driving water into the chiller.



Fig. 2. Solar air-conditioning system pictures; (a) adsorption machine, hydraulics module and hot storage tank; (b) dry cooling tower.

The solar cooling system was installed during spring 2011; 51 days were recorded (between May 12th and July 4th 2011). This is a sunny period representative of summer in Belgium. 2011 measurements revealed some system limitations decreasing its efficiency. The following enhancements were achieved during winter 2011-2012:

- Increase hot loop mass flow to the chiller by replacing the pipe network and the hot water storage tank,
- Installing a spraying kit under the cooling tower to lower the fans electrical consumption during very hot days,
- Make possible some tests throughout the summer by mounting an additional electrical resistance in the hot water storage

Those modifications let us to measure the system operation with the nominal mass flow values (those values are recommended by the manufacturer). Moreover it allows running the system without sunny conditions which permits to gather more data about adsorption chiller behavior. Thus, year 2012 tests consist of two measurement periods. The first one (28 days from April 17th to May 29th) deals with back-up heating to drive the sorption chiller. It allows running the adsorption chiller for long periods with various hot water driving temperature. The second one (13 days from May 30th to June 13th June) is solely solar air-conditioning (without back-up). An additional period copes with emulated solar collector but is not discussed in this article. The measurement aspects are described in next paragraph. The analysis of the two years measurements is also achieved as well as the choice of component models for simulation. The tuned models are simulated using TRNSYS simulation software [3].

2. Solar air-conditioning system monitoring

Within IEA-SHC Task 38 a monitoring procedure for solar heating and cooling systems was developed [4] [5]. This methodology includes measurements of all relevant energy flows (heat, cold, electricity) to be able to derive key figures such as Primary Energy Ratio (PER), thermal COP, Electrical COP, energy savings for cooling. The measurements picked up every 10 seconds in the installed solar air-conditioning system enable the computation of those indexes. The graphical user interface developed to monitor the system is displayed on figure 3. The probes can be split into two groups: thermal and electrical measurements. The computed values are displayed using italics. All figures are real time measurements but thermal and electrical COPs are previous hour mean values.

2.1. Thermal measurements

The thermal measurements consist in temperature, radiation and mass flow sensors. They are mainly used to evaluate the chiller, solar collector and dry cooler thermal behavior. The most important measurements and computed variables are described in table 1. The cold emission and distribution part is also monitored but not used in this work. The cold water storage tank temperature is controlled to maintain 18°C (if possible) as inlet chiller temperature.

Deduced accuracy mentioned in table 1 is based on the probes and mass flow meter specifications. The heat flow balance ($Q_{rej} - Q_{heat} - Q_{cold} = 0$) is nearly met on a daily basis. The heat flow and thermal COPs error listed in table 1 are consequently a little bit pessimistic.

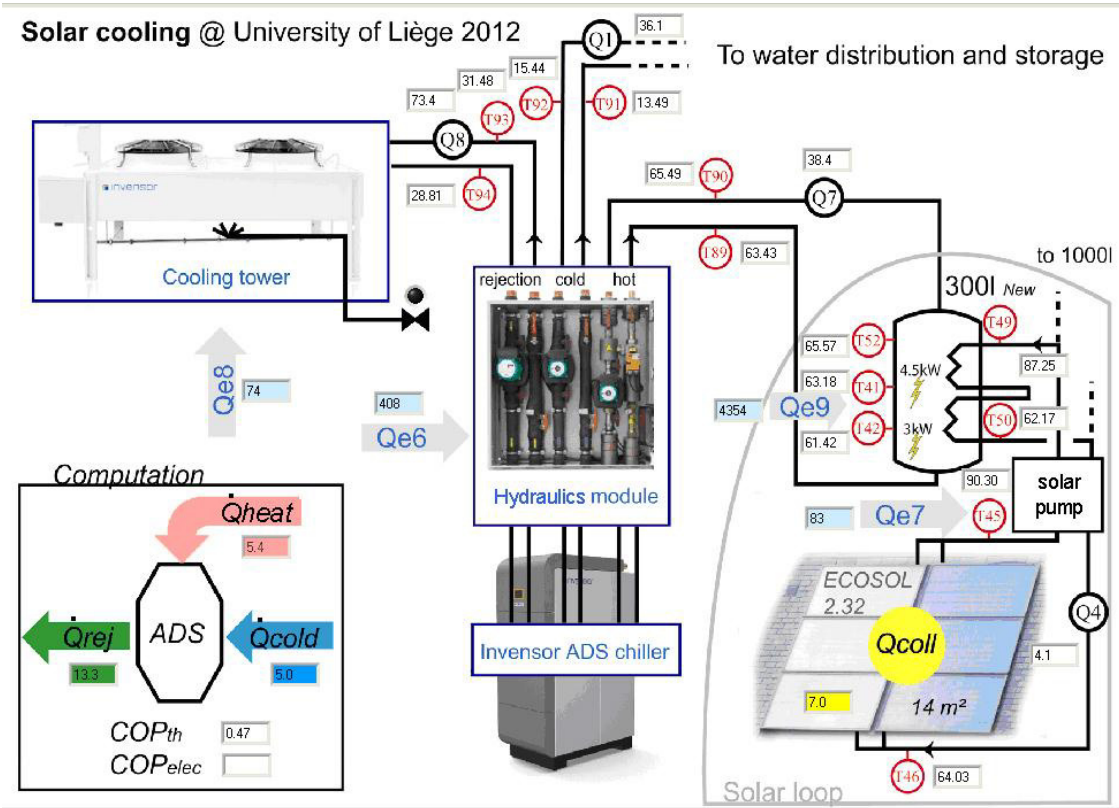


Fig. 3. Solar air-conditioning system monitoring screen

Table 1. Thermal measurements and computed values

Measurement	Probe #	Unit	Probe accuracy	
Water temperature supply/return for each chiller water flow (hot, rejection, cold)	T89-T94	[°C]	+/- 0.2 [°C]	
Solar collector supply/return temperature	T45-T46	[°C]	+/- 0.2 [°C]	
Solar heat exchanger supply/return temperature	T49-T50	[°C]	+/- 0.2 [°C]	
Storage tank temperature	T41-T42-T52	[°C]	+/- 0.2 [°C]	
Mass flow for each chiller mass flow	Q1-Q7-Q8	[l/min]	2%	
Solar loop mass flow	Q4	[l/min]	2%	
Computations (based on measurements above)	Variable name	Unit	Deduced accuracy	
Chiller heat consumption	\dot{Q}_{heat}	[kW]	9%	+/- 1.08 [kW]
Chiller heat rejected	\dot{Q}_{rej}	[kW]	12%	+/- 2.13 [kW]
Chiller cold produced	\dot{Q}_{cold}	[kW]	13.5%	+/- 1.02 [kW]
Solar collector field heat produced	\dot{Q}_{coll}	[kW]	6%	+/- 127 [W]
Hourly thermal COP = $\dot{Q}_{cold} / \dot{Q}_{heat}$	COP_{th}	[-]	22.5%	

To analyze the electrical behavior of the system, it is useful to measure the consumption of each device. Measurements concern only components dedicated to solar air-conditioning. The electrical consumptions due to the emission devices for example are not included as they would be present whatever the air-conditioning system installed. The electrical measurements are shown in table 2. The power range illustrates the minimum and maximum power. The solar drain back system includes a solar pump which has a constant electrical consumption of 83W. The electrical COP computation does not take the auxiliary heater into account. The results mention whether the auxiliary heating is switched on or off.

Table 2. Electrical measurements and computed values

Measurement	Probe #	Unit	Range	Accuracy
Hydraulics module (including three pumps) and chiller consumption	Qe6	[W]	18-450	1%
Solar loop pump power	Qe7	[W]	0-83	10%
Cooling tower consumption	Qe8	[W]	0-1100	0.6%
Hot water tank electrical heating	Qe9	[W]	0-7234	5%
Computation	Variable name	Unit	Deduced accuracy	
Hourly electrical COP = $\dot{Q}_{cold} / (Qe6+Qe7+Qe8)$	COP_{elec}	[-]	16%	

3. Monitoring results

3.1. Long periods results

Three successive measurement periods are recorded (see §1), they are respectively called *2011_Solar*, *2012_Elec+Solar*, and *2012_Solar*. The first and third one are dealing with solar energy as heat source while the second one uses solar energy and electrical heater in order to gather more data about adsorption chiller operation. The following performance indicators (with confidence intervals) for the three separated periods are displayed on figure 4:

- COP_{th} : Thermal COP (defined in table 1),
- COP_{elec} : Electrical COP (defined in table 2),
- $Coll\ yield$: Collector yield is the collector heat divided by available incident solar radiation,
- PER : Primary Energy Ratio is the quantity of cold energy produced divided by the primary energy consumption [4],
- f_{save} : Fraction of energy savings compared to a conventional vapor compression chiller (EER = 2.8) [4],
- Q_{cold} : Mean cold energy produced per day,
- Q_{coll} : Mean collector heat per day.

The first two periods on the graph show solely solar driven cooling. The 2012 period is actually much less sunnier; this implies a lower cold energy produced by the adsorption chiller. The thermal COP of those two periods is quite low due to the low driving temperature (55-65°C) and short operation periods. On the electrical point of view, the electrical COP is slightly higher in 2012 but is still around 2.5 which is very low. The cloudy days encountered during those two periods are really damaging the electrical performance because of stand-by power and hot water storage losses. The PER and f_{save} are directly linked to the electrical COP. The collector yield value around 30% is consistent with common solar system; Available incident radiation incorporates periods where the solar pump is not activated (typically beginning and end of the day)

The third period on the graph copes with auxiliary heating electrical device. It implies continuous operation and higher supply temperature (60-75°C). It involves much higher thermal COP. Moreover, the

electrical COP and PER reach a peak, as they take into account 'free' heat from electrical heater. 'Free' heat means for example a solar thermal flow which has no need of electrical power to be brought to the hot water storage tank. The fraction of energy savings and PER are not displayed for this period because it has no sense, an electrical heater for heating the driving flow should not be installed in common solar air-conditioning systems.

The daily results developed in the next paragraph illustrate increased performance values for typical days.

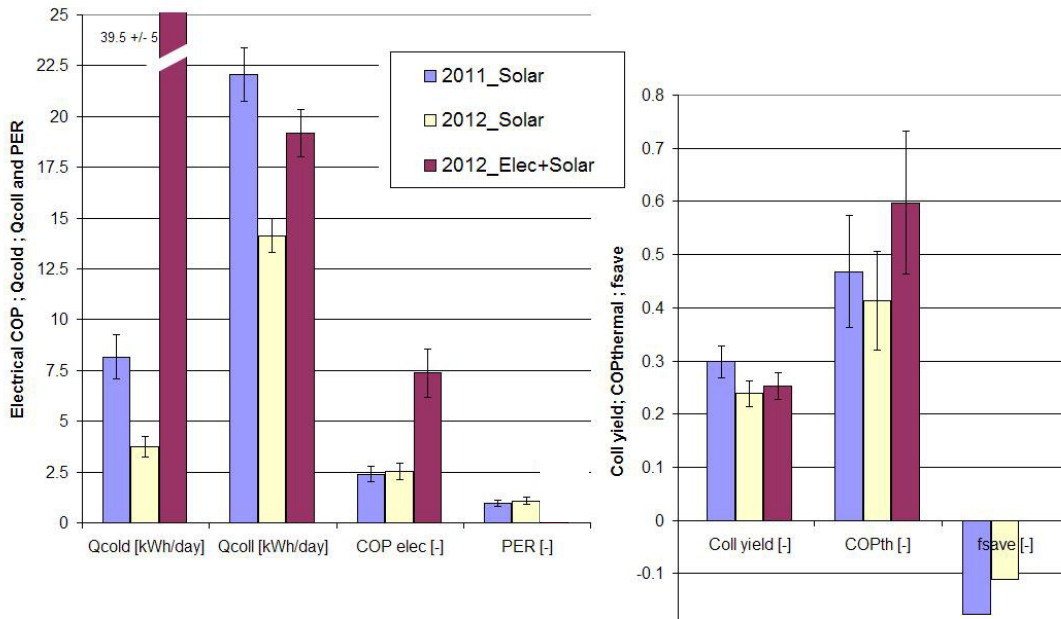


Fig. 4. Mean daily values of long periods results and their confidence intervals

3.2. Daily results

The selected period reveals the solar air-conditioning system behavior during two quite sunny days. These are respectively the two hottest days of the two measurements period in 2012. The first one (May 26th – figure 5) uses solar energy and electrical energy as heat sources. It implies a continuous chiller operation through the day (see Q_{cold} curve). The second one (May 29th – figure 6) uses only solar energy. A discontinuous operation with four chiller starts is encountered. The three chiller inlet temperature, the external temperature and the hourly thermal COP are also displayed. The chiller control requires a hot source temperature at 70°C to start the chiller and stops it as soon as the storage tank temperature drops below 55°C.

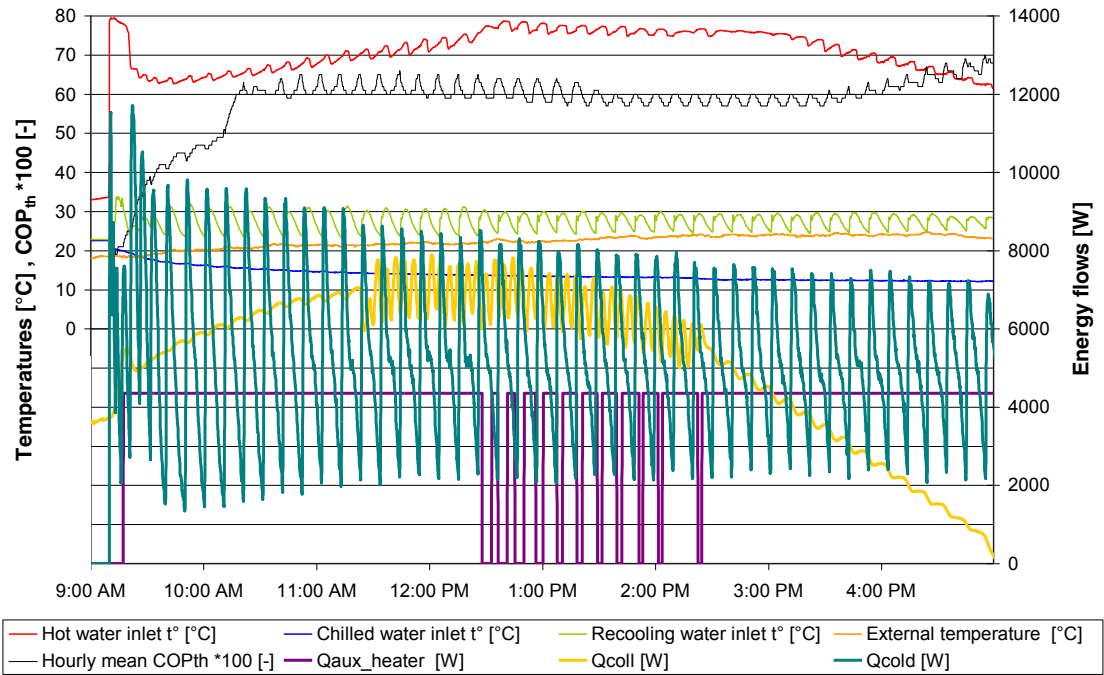


Fig. 5. Daily result for the May 26th 2012 : Solar energy + electrical back-up

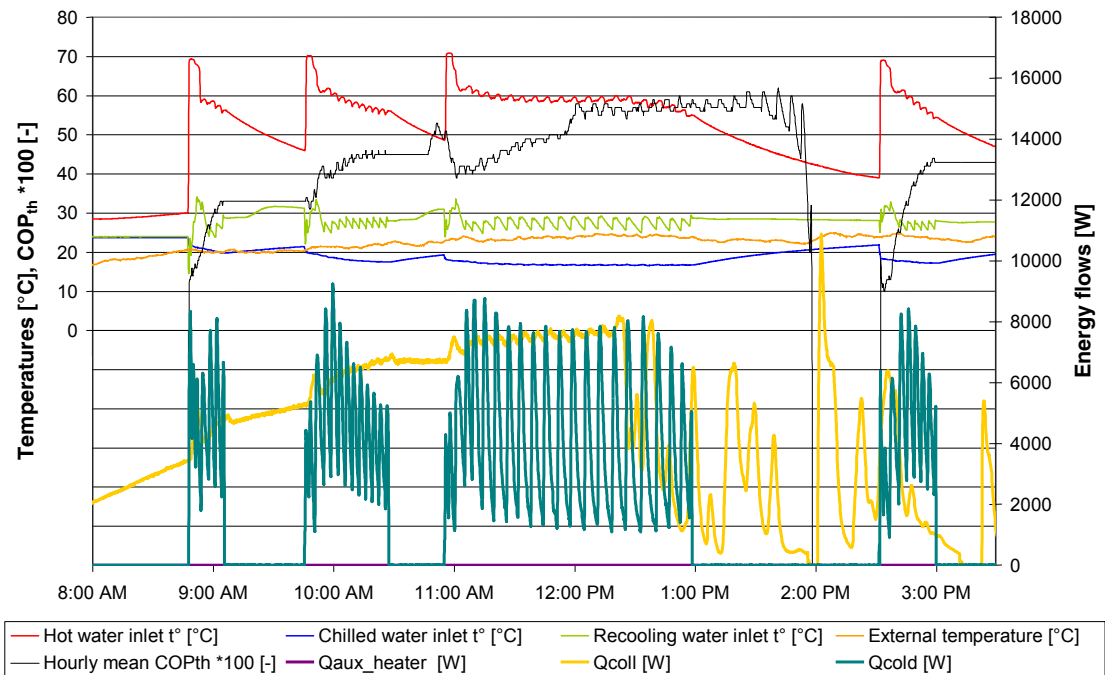


Fig. 6. Daily result for the May 29th 2012 : Solar energy only

By using solar energy and auxiliary heater (figure 5), the hot water supply temperature is higher and more stable. The hourly thermal COP varies through chiller operation. Adsorption machine beginning operation period reduces the thermal COP; this appears only one time the day. Daily thermal COP reaches therefore a high value (0.6). After the beginning period the hourly COP varies between 0.6 and 0.7 which is a good performance figure for an adsorption machine. The collector power is oscillating at midday, it is due to the over heating in collectors. Thus, the solar pump cycles and the collected energy slightly decreases.

The second day (figure 6) shows a lower thermal COP due to the four "start-stop" of the chiller and lower driving temperature. Beginning operation period and low driving temperature illustrates shorter half cycle duration (time between Q_{cold} peaks). Nominal operation half cycles accomplishing good thermal COP last around 10 minutes. This sunny day does not collect enough heat to drive the adsorption in highly efficient conditions. The thermal COP dwindles by around 20% to achieve a daily value of 0.47. The daily performance values of these two days stand on table 3 (last lines).

The external temperature is not really high for May 26th 2012. It involves a low fan consumption which is not consistent with a hot summer day. Thus, two additional days are mentioned in table 3 to discuss about the auxiliaries electrical consumption. The electricity consumption sharing between the different auxiliaries for various sunny days is described. The electrical consumption per cold energy produced varies quite a lot ($3.12 < \text{electrical COP} < 7.85$); the fan power is strongly linked to the external temperature. For the hottest day in 2011, the fan consumption dramatically reduces the electrical performance. June 27th and July 4th are very similar in terms of solar radiation but the maximum ambient air temperature are respectively 32°C and 26°C. To keep the recooling temperature below 30°C (if possible), the fan power is controlled from nearly 0 to 1200W. The operation during hot periods requires maximum fan power permanently. That's the reason why a spraying kit was installed in 2012. Unfortunately, hot days are not yet recorded in 2012 to analyze the effect of spraying water on the cooling tower. The highest electrical COP is encountered for the day with a certain amount of 'free' heat. The solar loop pump has consequently a lower impact. The standby consumption is measured for fan, chiller and pumps altogether. It is impacting significantly the total energy consumption depending on operation duration through the day (around 10-15% for sunny days). It counts globally for 20% of the total electricity consumption for the testing periods without electrical heat back-up. The adsorption chiller and hydraulics module electrical consumption remains nearly constant whatever the operating conditions (400-420 W). It includes the pumps (constant mass flow), the electronic devices and the valves.

Table 3. Daily results

	Q_{coll}	Q_{cold}	COP_{th}	COP_{elec}	Electricity sharing	Standby consumption	f_{save}	External temp.
Units/ comments	[kWh]	[kWh]	[-]	[-]	Chiller+pumps/fans/solar loop pump [%]	[% of total consumption]	[%]	Daily mean / max [°C]
June 27 th 2011 hottest day	45.8	21.3	0.54	3.21	33/56/11	10	13	24/32
July 4 th 2011 sunny day	44.6	17.9	0.44	5.14	62/15/23	12	45	18/26
May 26 th 2012 Elec+Solar	44.3	47	0.60	7.85	68/20/12	7	-	21/29
May 29 th 2012 Solar only	34.3	15.2	0.47	5.02	59/18/23	20	44	19/25

4. Simulation and outlook

The system described in the previous paragraphs has also been modeled [5] into the TRNSYS simulation software. By modeling the thermal behavior of each part of the solar air-conditioning system the objective is to evaluate the possible energy savings in other conditions than those measured. The system is split into three subsystems that can be tuned separately to monitored data:

- The solar loop and storage tank using Type 1 for collectors, Type 22 for pipes, Type 60 for storage tank and a controller,
- The dry cooling tower using Type 544 and a controller,
- The adsorption chiller using new Type 255 [6] interpolating the manufacturer steady state curves.

The cold storage and the cooling load are not included in the simulation, it is a boundary condition. The three subsystems are to be validated with measurements.

The solar loop simulation with weather data measurement and chiller heat consumption as inputs give an accurate evaluation of its thermal behavior. At the beginning, a 15% error was encountered between measured and simulated solar heat collected. The error is largely due to the temperature measurement in the collector. Aided by the storage temperature, the collector temperature controls the pump start. The model does not include any collector inertia; at the beginning of the day, the simulated collector temperature has a quicker response than the measurement. It is taken into account by modifying the hysteresis dead band of the simulated controller. The solar loop model is now as precise enough (less than 1% error).

The rejected heat and electrical consumption of the cooling tower are evaluated by the model. The simulation takes the water inlet temperature and the external temperature as inputs. The cooling tower water return temperature is controlled to reach a set point (most often 27°C). By modifying the fan controller gain and the integration constant, the measured heat flow can be met. The simulated electrical behavior gathers also the measured values (the fan electrical power depends on the third power of the fan air flow). Precision obtained by the model is higher than the possible error on measurements.

The adsorption chiller is the core of the solar air-conditioning system. The electrical consumption is considered as constant but the thermal behavior is largely influenced by the temperature of the heat sources and sinks. The model has the three flow inlet temperatures as inputs and is based on the steady state manufacturer data curve [2]. As seen on the figures 5 and 6, the beginning period has a low thermal performance. Moreover, the manufacturer data are not provided for a large temperature range. These two reasons lead to large error (20 to 30%) between measured and computed cold energy produced by the adsorption chiller (measurements of the April-May 2012 period). To model accurately the adsorption chiller behavior in a real solar air-conditioning system, the beginning period (around 15 minutes) and a wide range of operating temperature should be considered. This adsorption chiller model establishment is still in progress and will be presented in a future paper.

The complete model is not yet precise enough for the evaluation of a complete solar air-conditioning system in other operating conditions. The focus is now put on the adsorption chiller modeling. It will be than possible to assess the performance of a solar air conditioning system with other components : vacuum tube collector, ground heat exchanger...

5. Conclusions

The measurements of the solar cooling system installed at the University of Liège provide a number of performance indicators for different operating conditions. For the whole measurement periods the solar air-conditioning system with 14 m² collector does not save energy compared to classical air-conditioning due to less sunnier and cloudy days, low driving temperature and the intermittent operation. The enhancements brought to the system after one year operation lead currently to a slight increase in the energy performance (but no hot period has been recorded yet in 2012). Chiller operation with a bigger heat source (electrical resistances and solar energy) implies a higher driving temperature and leads to a higher chiller performance. Thus, next tests are run with the equivalent of 28 m² solar collectors (half real and half emulated with electrical heaters). It is more representative of common design of solar air-conditioning systems that have about 3 m² collectors per kW cold installed power [8].

The electrical performance is also analyzed and provides the main electricity savings fields: standby and fan consumption (for hot days). Sunny days results show better overall efficiency results than long periods measurement. For those sunny days, the solar air-conditioning system can actually save energy (up to 45%) even if low driving temperature and intermittent operation are met.

Acknowledgements

The authors would like to thank the University of Liège, the University of Luxembourg and the company INVENSOR for their support in this project.

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