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Energy Procedia 57 (2014) 2636 – 2645
Energy Procedia

2013 ISES Solar World Congress

Sensitivity analysis to optimize a solar absorption cooling system

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Abstract

In the last two decades, the prospect of a free cooling technologies possibilities led to several experimental and theoretical investigations by researchers. Nowadays, low temperature solar thermal systems coupled with sorption machines are the most commercialized solution available to face the cooling demand. Solar heating and cooling systems are currently available on the market and there are a hundred installations worldwide. The next challenge for this technology is to guarantee the performance of any solar cooling plant in the future. This paper aims at presenting the results of the optimisation of a solar cooling plant. This work is part of the French National Research Agency project (MEGAPICS n°ANR-09-HABISOL-007). Parameters, which have a significant effect on power production, are identified. Then simulations are carried out to evaluate the power increase according to an optimised configuration.

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Keywords: solar cooling, sensitivity analysis, optimization ;

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1. Introduction

Building remains at the present time the most electricity-consuming sector. Under our latitudes, one of the most important demands for electricity relates to building air-conditioning during summer (active period of November 1 to April 30), which approximately represents 50% of the total energy consumption, [1]. Solar energy is in abundance in the island (insulation > 5 kWh/m²/day) that's why the development of solar thermal system has increased very quickly since the 90's, see figure 1. At present, solar water heating is the most important application with 20,000 new installations per year for 800,000 inhabitants. Solar cooling plants are very limited (2 industrial plants and 1 experimental pilot at university which cools 4 classrooms).

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doi:10.1016/j.egypro.2014.10.275

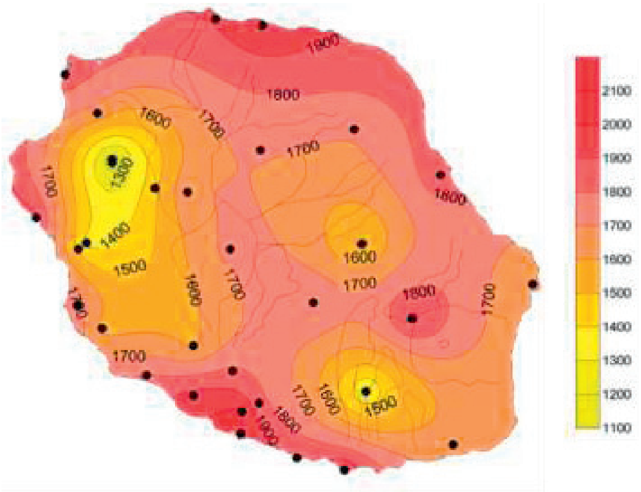

Fig. 1. Global solar radiation (kWh/m^2) distribution

Commercial applications of solar energy for air conditioning systems are fairly recent. Florides [2] and Ziegler [3] give an overview of the latest developments and available technologies. Solar cooling systems can basically be classified in three categories, as described by X.Q Zhai [4], namely: solar sorption cooling, solar-mechanical systems and solar-related systems. Clito [5] offered another classification based on the final energy used to operate the system: (i) Electrically operated, (ii) Thermally operated, (iii) Hybrid. In Reunion, since 2003, a solar absorption cooling system has been studied, [6], [7]. The present work is a part of the MEGAPICS project, which focuses on the definition of a methodology for performance guarantees of a SAC system. In order to ensure performances of solar cooling facilities, a study has been carried out on the prediction models, which have been previously developed at the PIMENT laboratory. This study is a sensitivity analysis enabling to ascertain how these models depend on their input factors. Thus, parameters that have a significant influence on the performance of the different components of the surveyed facility could be determined.

The first part of the paper presents the RAFSOL plant used to undertake the sensitivity analysis. Next, the second part introduces the sensitivity analysis method and its implementation. Then, in a third part, an example of numerical enhancement is illustrated and discussed. This enhancement is presently the first steps of optimization of our pilot plant.

2. RAFSOL solar absorption cooling plant

A sensitivity analysis has been carried out on mathematical models developed under PIMENT laboratory. Details of the mathematical model are presented in previous work, [6]. The experimental SAC plant under consideration is an absorption plant located at the University. It was installed in 2007 and supplied cooling for classrooms of the Civil Engineering Department. The experimental setup is one of the international plants retained in “Task 38 – Solar Cooling and Refrigeration” supported by the International Energy Agency (IEA).

The solar cooling plant, which has been set up, consists in six major components, see figure 2:

- 90 m2 of double-glazed flat-plate collectors, arranged in 3 series of 10 units and a series of 6 units.
- 30 kW LiBr/H_2O single effect absorption chiller (EAW LB30), which has a nominal operating temperature that ranges from 70 to 95 °C.
- 80 kW cooling tower.
- 1500 L hot water storage tank to ensure a stable supply of hot water.
- 1000 L cold water storage buffer.
- 13 fans coil units mounted in the classrooms (room. 1 & 2: 4 fans - room. 3: 3 fans – room. 4 : 2 fans)

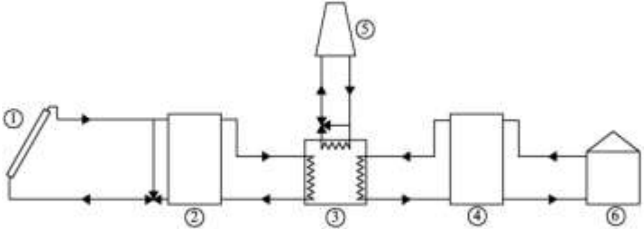

Figure 2a Scheme of the plant: 1: Solar collector field; 2: Hot tank; 3: Absorption chiller; 4: Cold tank; 5: Cooling tower; 6: Building

Figure 2b Photographs of the solar absorption cooling system : 1 - Solar collector field ; 2 - Cooling tower; 3 - Absorption chiller ; 4 - Hot water storage tank; 5 - Cold water storage tank

3. Sensitivity analysis

As defined by Saltelli [10], the objective of the sensitivity analysis (SA) of model is to ascertain how a given model (numerical or otherwise) depends on its input factors. It is also possible to determine if the model does not exhibit unexpectedly strong dependencies upon non-influential parameters.

This analysis is an important step in the verification and validation of models. Thus, SA helps to understand the fundamental mechanisms underlying the behaviour of the model and interactions between the different factors. There are indeed different types of SA, and numerous techniques have been developed. In the present work, the strategy employed is based on two consecutive techniques:

- A screening test proposed by Morris [11], which allows identifying qualitatively, the relative influence of factors.
- FAST method (acronym of Fourier Amplitude Sensitivity Test) to determine the influence of factor and its nature, [12].

In this paper, we will present the results of the second step, i.e. the spectral analysis by FAST.

3.1. The FAST Method

The Fourier Amplitude Sensitivity Test (FAST) method is a variance-based method. It allows quantifying the contribution of each input factor to the variance of the output.

Considering a numerical model with a single output Y and k different input parameters regroup in the X array such as X={X_1, X_2,…,X_k} and Y=f(X_1, X_2,…, X_k). Each factor of the model is associated with a different integer frequency (ω_1, ω_2,…, ω_k).The principle is to vary each input parameters following periodical functions and to determine the effect of these variations on the variance of the output Y. Thus, distinct frequencies are respectively assigned to all input factors allowing their sampling using the following equation:

$$X_i = G_i\left(\sin(\omega_i s)\right), \qquad \forall i = 1,2,..k \quad (1)$$

The functions G_i are chosen according to the probability density of X_i, to give a good representation of the wide range of the factors. Mara has proposed a sampling method of the factors in 2002 [13]:

$$G_i(x) = X_i^* + \frac{\delta_i}{\pi}\arcsin(x) \qquad (2)$$

N and represent the simulation number, N is the total number of simulations. X_i^* is the basis value of the parameter X_i and δ_i is defined as $X_i \in \left[X_i^* - \delta_i, X_i^* + \delta_i\right]$. The Shannon criterion defines the minimum number of simulation as equal to $N = 2\times\omega_k + 1$.

Thus the expectation of Y can be approximated by :

$$E(Y) = \frac{1}{2\pi}\int_{-\pi}^{\pi} f(s)\,ds \text{, where } f(s) = f\left(G_1(\sin(\omega_1 s)),...,G_k(\sin(\omega_k s))\right) \qquad (3)$$

Further, considering the properties of Fourier series, [14] an approximation of the variance of Y is given by :

$$Var(Y) = \frac{1}{2\pi}\int_{-\pi}^{\pi} f^2(s)\,ds - [E(Y)]^2 \approx 2\sum_{j=1}^{\infty}\left(A_j^2 + B_j^2\right) \qquad (4)$$

where A_j and B_j are the Fourier coefficients.

The Fourier transform of the output Y of the model is computed and the spectrum is plotted at the frequency 1 and its higher harmonics.

This spectrum allows the determination of the most important factors by identifying the frequency of each peak of the graph. The Shannon criterion used for the FAST method, which defines the number of simulations to run, has been insufficient for almost all the models (solar loop, solar collector field, entire plant). Indeed, when the criterion is respected, a spectrum-folding phenomenon is observed. This folding affects the spectrum by shifting all peaks corresponding to all influential parameters. Thus, results obtained by using the sensitivity analysis are inconsistent. The number of simulations has been increased to avoid this phenomenon. This necessity to run additional simulations can be explained by the studied models, indeed they are strongly dynamics and they do not tolerate any combinations of inputs.

4. Results and discussion

The sensitivity analysis has been carried out over all the SAC plant: solar collector field, absorption, and storage tanks. The observed output parameters are the coefficient of performance (COP) defined as follow:

- COP_{th} : thermal COP of the sorption chiller
- COP_{sol} : cooling energy produced from the storage tank divided by solar energy received.
- The thermal COP (COP_{th}): energy produced at the evaporator divided by the energy consumed at the generator;
- The COP_{elec}: energy produced at the evaporator divided by the electrical energy consumed by the chiller.
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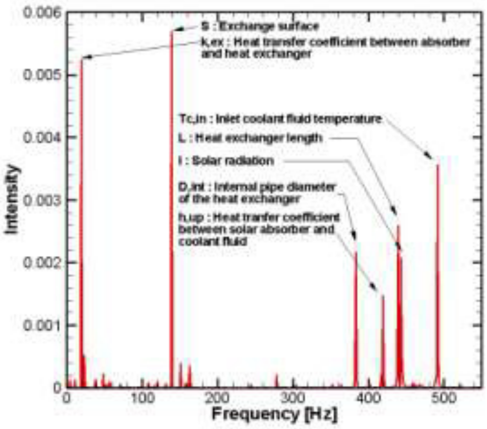
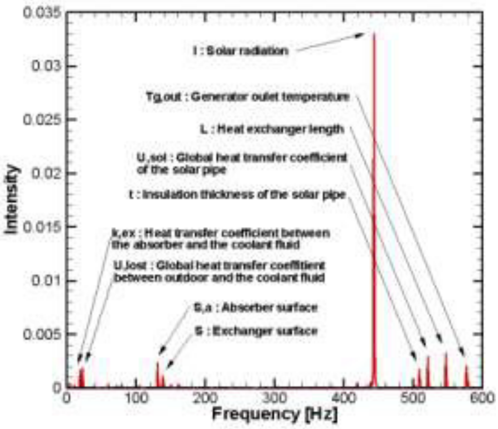
A Detailed definition of theses indicators of performance have presented in a previous work by Nowag,[15].

All parameters have been considered: environmental factors such as air temperature, solar radiation and geometrical/physical properties such as insulation thickness.

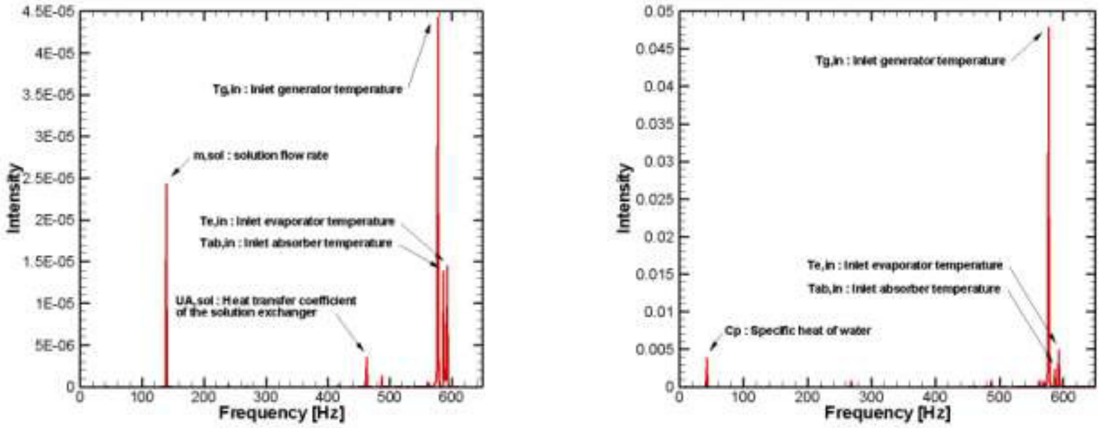
All details used for the parameter in the FAST method (frequency, range of variation, units…) have been indexed in Appendix A. Even if the sensitivity method is global, the ranges of variation of the parameters remain within the limits of actual operating data with physical meaning. In addition, the wide range of variation could lead to instability of numerical models.



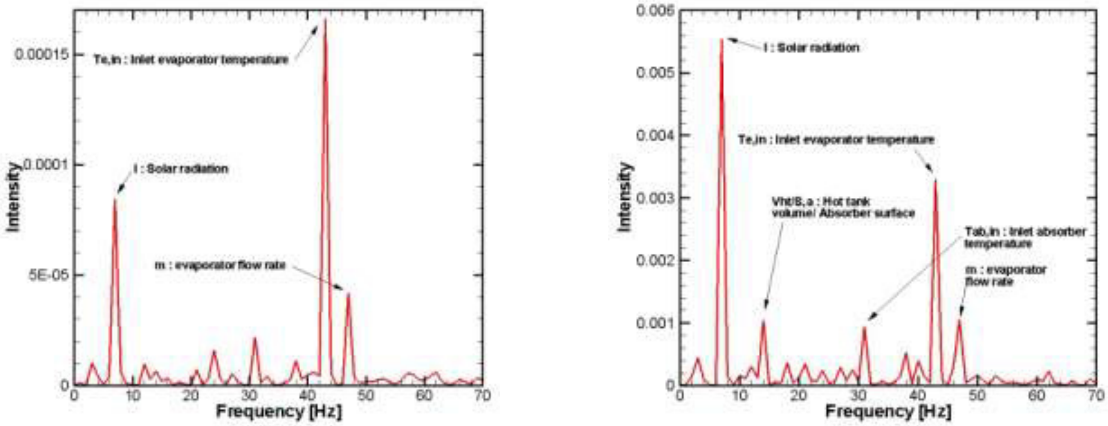
(a) COPsol of the solar collector



(b) COPsol of the solar loop



(c) COPth of the absorption chiller (d) COPelec of the absorption chiller



(e) COPsol of the SAC plant (f) COPth of the SAC plant

Figure 3 – FAST analysis applied to all the components of the SAC plant

As shown in figure 3, the FAST method clearly highlights the parameters, which have a significant influence. The intensity of each peak indicates whether the parameters have a strong influence or not.

Regarding the solar collector and solar loop analysis, the SA shows that parameters linked to dimensioning a significant influence:

- Solar collector (exchanger length, absorber surface…)
- The solar pipe (heat transfer coefficient, insulation thickness)

Figure 4 presents an example of parameters ranked in order of importance.

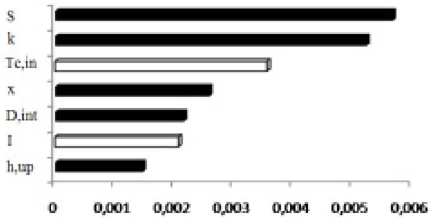


Figure 4 – Most influential parameters of the solar collector

The analysis clearly shows that all inlet temperatures of the absorption chiller are important. Moreover, the variation range of these temperatures is directly linked to their influence. Thus, special attention should be paid to the control strategy of the machine.

The FAST analysis of the entire plant highlights the influence of two parameters. Moreover, these parameters remain the most influential, whatever is the studied output, and correspond to the solar radiation and the inlet evaporator temperature. It is interesting to notice the importance of the inlet evaporator temperature that directly influences the building loads. This indication clearly identifies the importance of performing an accurate sizing of building loads and its dynamical evolution during the day to see if the SAC plant will be able to meet the cooling demand.

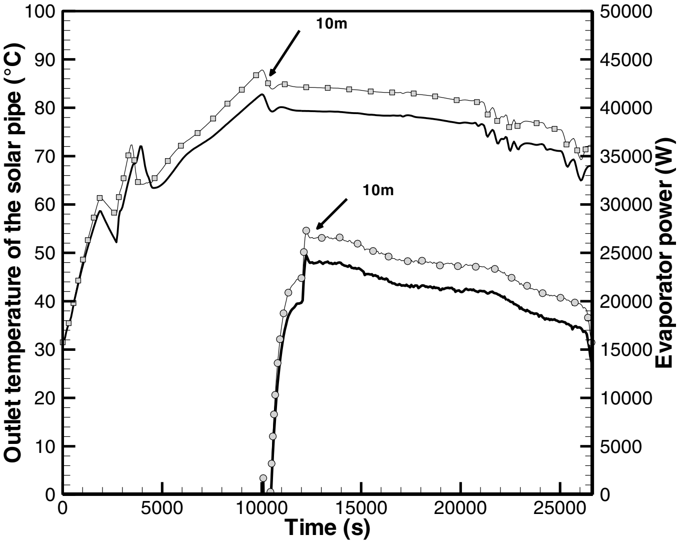


Figure 5 – Improved SAC plant

The FAST analysis applied to all the components shows the importance of heat exchange in solar loop for heat production. Hence, a first optimisation configuration is presented in figure 5. Presently, in our pilot plant, there are 100m between the solar collector field and the hot storage tank in the building service rooms. One future possibility of extension works is to move the service rooms just under the solar collector field. Figure 5 presents a simulation of this optimisation, the distance between collector and hot storage will be 10m instead of 100m. Thus, we can notice 12% increase of the evaporator power, which is clearly significant for the SAC plant.

5. Conclusion

To guarantee the performance of a cooling installation is the challenge of this project ANR. This warranty goes through various points involved at different stages of the project and the completion of an installation project. The models have been tested and validated on experimental databases of RAFSOL facility at the University of Reunion.

Therefore it is important to perform first work on prediction tools. We are especially interested in the different component models of a solar cooling. This approach helped to validate our models and to extract other useful information for installing solar cooling. The FAST analysis enables us to clearly identify parameters, which have significant influence on the performance of the SAC plant. The simulation of a new configuration of RAFSOL has carried out a first step in optimization / enhancement of the plant. Accordingly, it will be particularly useful for planners to be especially heedful to parameters that can be controlled such as flowrate, or to precise sizing of some of the facility components such as exchanger surface.

6. Acknowledgements

This work has been supported by French Research National Agency (ANR) through Habitat intelligent et solaire photovoltaïque program (project MEGAPICS n°ANR-09-HABISOL-007).

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Appendix A. Variation range of parameter values used for the FAST method.

Solar collector

Factor	Definition	Range of variation	Unit	Frequency (Hz)

S	Surface of the interface between solar absorber and heat exchanger	[0.01 - 0.10]	m²	139
K,ex	Heat transfer coefficient between absorber and heat exchanger	[100 - 600]	W/m²/K	19
Tc,in	Inlet collector fluid temperature	[25 - 90]	°C	491
L	Heat exchanger length	[0.5 - 2.5]	m	439
D,int	Internal pipe diameter of the heat exchanger	[0.009 - 0.036]	m	383
I	Solar radiation	[0 - 1100]	W/m²	443
h,up	Heat transfer coefficient between solar absorber and coolant fluid	[200 - 500]	W/m²/K	419

Solar loop

Factor	**Definition**	**Range of variation**	**Unit**	**Frequency (Hz)**
I	Solar radiation	[0 - 1100]	W/m²	443
L	Length of the solar pipe	[5 - 150]	m	547
U,sol	Global heat transfer coefficient of the solar pipe	[0.5 - 7.0]	W/m²/K	521
S,a	Absorber surface	[0.15 - 0.30]	m²	131
Tg,ou	Generator outlet temperature	[50 - 90]	°C	577
U,lost	Global heat transfer coefficient between outdoor and coolant fluid	[0.5 - 5.0]	W/m²/K	23
t	Insulation thickness	[0.054 - 0.150]	m	509
K,ex	Heat transfer coefficient between absorber and coolant fluid	[100 - 600]	W/m²/K	19
S	Surface of the interface between solar absorber and heat exchanger	[0.01 - 0.10]	m²	139

Chiller-COPelec

Factor	**Definition**	**Range of variation**	**Unit**	**Frequency (Hz)**
Tg,in	Generator inlet temperature	[76.5 - 93.5]	°C	577
Te,in	Evaporator inlet temperature	[15.7 - 18.7]	°C	593
Cp	Specific heat of water	[3771 - 4609]	J/kg/K	43
Tab,in	Absorber inlet temperature	[27 - 33]	°C	587

Chiller-COPth

Factor	**Definition**	**Range of variation**	**Unit**	**Frequency (Hz)**
Tg,in	Generator inlet temperature	[76.5 - 93.5]	°C	577
m,sol	Solution flow rate	[0.198 - 0.242]	L/s	139
Te,in	Evaporator inlet temperature	[15.7 - 18.7]	°C	593
Tab,in	Absorber inlet temperature	[27 - 33]	°C	587

UA,sol	Heat transfer coefficient of the solution exchanger	[1440 - 1760]	W/m²/K	463