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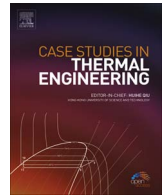


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Case study for experimental validation of a new presizing tool for solar heating, cooling and domestic hot water closed systems

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ABSTRACT

This paper presents a case study experimental validation of PISTACHE which is a new presizing tool intended for designers and planners. It facilitates pre-design and allows the evaluation of annual performance and the integration potential of solar heating, cooling and domestic hot water closed systems. This new tool has been performed in order to standardize the sizing methodology and the comparison of the SHC & DHW closed systems. The comparison framework used in PISTACHE has been performed using seasonal performance indicators that were issued and gathered from experimental data provided by several operating plants. Thus, PISTACHE is an easy graphical user interface and free downloadable tool. In order to check the reliability of the new developed tool, two configuration modes are investigated in this experimental study: a simple cooling mode (RAFSOL plant) and a double cooling and heating mode (SONNENKRAFT installation). The whole validation process is performed using the GenOpt optimization program to determine the optimum set of internal parameters for PISTACHE tool.

1. Introduction

Demand for air conditioning is higher than it has ever been, especially in commercial and residential buildings [1]. Different technologies are used to meet this increasing demand. First, we can distinguish the widespread conventional electric systems. It should be noted that these systems have two major drawbacks: they create a high demand for electricity which places undue pressure on the electrical grid with the risk of blackouts [2] and they release heat, causing the “urban heat island” phenomenon which decreases the efficiency of such systems [3]. More of that, the majority of these systems use hydro-fluorocarbon (HFC) refrigerants which contribute to global warming [4]. Moreover, as 68% of worldwide electricity is produced from fossil fuels [5], conventional air conditioning systems contribute to the emission of greenhouse gas, global warming and climate change.

Faced with the scarcity of fossil fuels, the increased demand for electricity (particularly from air conditioning) and the awareness about global warming; the development of energetic systems in these past few decades has been focused on waste heat recovery and the use of renewable sources like solar energy. In fact, the development of air conditioning systems has been focused on heat-powered chillers, particularly solar thermal cooling systems. Furthermore, solar cooling has the ability to synchronize cooling needs with solar availability especially during summer period when cooling demand is higher. Generally, solar thermal cooling uses sorption

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Nomenclature			
η_{Carnot}	Carnot efficiency [-]	K_{Pstart}	Maximized heating capacity coefficient of the sorption chiller (starting phase) [-]
η_{COLL}	Solar collector efficiency [-]	P_n	Thermal cold nominal capacity of the sorption chiller [kW]
η_0	Solar collector optical efficiency [-]	$Q1$	Solar energy supplied to the hot storage [kWh]
a_1	First order solar collector efficiency parameter [W/m ² °C]	$Q3$	Heating energy supplied to the heating distribution loop [kWh]
a_2	Second order solar collector efficiency parameter [W/m ² °C ²]	$Q6$	Solar energy supplied to the sorption chiller [kWh]
$a_{\text{CR}_{\text{cst}}}$, $b_{\text{CR}_{\text{cst}}}$	Cold storage tank heat loss time constant coefficient [-]	$Q7$	Cold production of the sorption chiller [kWh]
$a_{\text{CR}_{\text{hst}}}$, $b_{\text{CR}_{\text{hst}}}$	Hot storage tank heat loss time constant coefficient [-]	$Q10$	Thermal cold energy supplied to the building [kWh]
A_{coll}	Collector aperture area [m ²]	Q_{hst}	Thermal energy stored in the hot tank [kWh]
B_{clim}	Hourly building cooling demand [kWh]	Q_{lossst}	Thermal energy losses of a storage tank [kWh]
B_{chauf}	Hourly building heating demand [kWh]	Q_{sol}	Solar energy received by the collector area [kWh]
B_{ecs}	Hourly DHW demand [kWh]	$T_{\text{AC,in}}$	Inlet temperature on the heat rejection side (absorber + condenser) of a sorption chiller [°C]
COP_0	Nominal thermal coefficient of performance of the sorption chiller [-]	T_{air}	Outdoor air temperature [°C]
COP_{th}	Thermal coefficient of performance of the sorption chiller [-]	T_{amb}	Indoor ambient temperature [°C]
C_r	Heat loss time constant [kWh/L °C.24 h]	T_{coll}	Collector average temperature of the fluid [°C]
$C_{\text{st,max}}$	Maximal storage capacity [kWh]	T_{DHW}	Set temperature of the DHW production
$C_{\text{st,min,cool}}$	Minimum energy storage capacity in the cooling mode [kWh]	$T_{\text{E,in}}$	Inlet temperature on the cold side (evaporator) of a sorption chiller [°C]
E_i	Electricity consumption of the auxiliaries [kWh]	$T_{\text{G,in}}$	Inlet temperature on the hot side (generator) of a sorption chiller [°C]
G_{HZ}	Global solar irradiation on horizontal surface [W/m ²]	$T_{\text{G,min}}$	Minimum inlet temperature on the hot side (generator) allowed by a sorption chiller [°C]
G_{SL}	Global solar irradiation on slope surface [W/m ²]	$T_{\text{R COOL}}$	Return temperature of the distribution cooling loop [°C]
HR	Relative humidity [%]	$T_{\text{R HEAT}}$	Return temperature of the distribution heating loop [°C]
K_{Pmax}	Maximized heating capacity coefficient of the sorption chiller (operating phase) [-]	T_{st}	Storage tank average temperature [°C]
K_{Pmin}	Minimized heating capacity coefficient of the sorption chiller (operating phase) [-]	$T_{\text{st,max}}$	Maximal storage tank temperature [°C]
		V_{st}	Volume of a storage tank [liter]

technology which can be broken down into open sorption systems and closed sorption systems [6]. The first category is either a liquid or a solid desiccant system using liquid (Lithium Bromide) and solid (silica gel) desiccant materials. The second category is either an absorption process using fluid pairs water/Lithium Bromide or ammonia/water; or an adsorption process that utilizes in turn water/silica gel or water/zeolite. It should be emphasized that sorption is an environmentally friendly solution without any greenhouse gas emissions.

It has been observed that the performance of each solar cooling technology varies with climate [7]. The performance generally focuses on the thermal COP assessed using numerical methods such as physical models [8–11] or artificial neural networks [12]. Thus, to size solar cooling installations and plan their performance, designers should take into account parameters like climate (solar irradiation, outdoor temperature, building loads). Therefore, designers will need a platform based on a holistic approach that compares numerous solar cooling technologies operating under the same conditions where criteria like water consumption, congestion, thermal and overall performance are considered. This platform would allow the designers to objectively analyze the performance of each system and to select the most suitable technology for a specific application. Unfortunately, such platform doesn't exist. For this reason, Pons et al. [7] proposed the first comparison framework wherein several key seasonal indicators of performance are pointed out. This framework is based on experimental data gathered from desiccant, thermochemical, adsorption and absorption cycles properties. In this context, we propose a quick pre-sizing tool "PISTACHE" for a closed sorption system allowing prediction of both design and performance of Solar Heating, Cooling and Domestic Hot Water (SHC & DHW) systems.

The PISTACHE tool has been developed by drawing on the comparison framework established by Pons [7]. This framework aims to provide a new useful method and try to standardize the comparison protocol of several SHC & DHW closed systems. Moreover, the developed tools offer an interesting database of sorption chillers where we can found construction parameters such as: the brand, the nominal power and the nominal COP ... etc. The mentioned list gathers around fifty models for a nominal power ranging from 10 to about 200 kW. The second data base includes a solar panel list which comprises around two hundred models. Both lists enable engineers and planners to have a quick access to relevant information required for selection and design tasks without dealing with the tedious manufacturers data sheet. The PISTACHE tool uses hourly calculations resulting in monthly and annual energy balances [13–15]. Annual performance indicators such as *thermal efficiency*, *solar and global performance indicators*, *water consumption*. etc. are then estimated. In this paper, we are focusing on a case study of the experimental validation of two PISTACHE operating

configurations: a simple cooling mode and a double cooling & heating mode corresponding to RAFSOL [16] and SONNENKRAFT installations.

First, we give a brief description of PISTACHE and its interfaces, as well as RAFSOL and SONNENKRAFT, then we outline the optimization process using GenOpt and performed in two separate phases: identification and validation. The identification phase detects the optimal set of internal parameters minimizing simulated PISTACHE results and the *first season's* experimental data expressed by the proposed objective function for each plant. The validation phase uses the previous set of parameters to compare PISTACHE's simulated results with *second season's* experimental data. Then, relative errors are estimated for both RAFSOL and SONNEKRAFT installations. Finally, the results obtained are analyzed and conclusions are drawn some perspectives are addressed.

2. PISTACHE description

PISTACHE (Pre-sizing Tool for SolArCooling and Heating systEms) software has been developed to help designers, planners and HVAC professionals to quickly assess SHC & DHW plant performances using sorption chillers. In this way, our tool performs quick and easy calculations for solar installation cooling, heating and DHW production. It helps the user to pre-size the installation and provides both energy balances and annual performance indicators. The tool is composed of a user interface to upload meteorological data and building loads, to enter parameters and to choose the main component characteristics. It also includes a commercial list of sorption chillers and solar collectors available in the market and a step by step help file as described in previous works [13,15,17]. The tool is available for free, in French and English [18].

As the simulation of solar cooling and air-conditioning can be performed at different levels such as: material level, component level, process quality level...etc, the development of the PISTACHE tool has been rather based on the *system simulation for planning support* [19] which the main objective is to pre-size the most suitable SHC & DHW systems. In this context, several simulation tools have been used to assist planners in their sizing tasks as seen in Table 1. It can be noticed that EASYCOOL [19] and TDC tools [20] are no longer distributed. Other simulation tools like Energy Plus [9], Spark [21] and TRNSYS [22], initially designed for dynamic simulation in building and air conditioning systems, are not specifically designed for simulation of solar cooling systems. These tools involve time-consuming modeling adaptations and require a good command of the software that make their use for pre-sizing simulations irrelevant. Recent software specifically developed for the solar cooling concern tools like: INSEL [23], Polysun [24], TRANSOL [25], ODIRSOL [26] and PISTACHE. It should be highlighted that PISTACHE tool is the only software which is free, easy to use, with a large database of commercial components and validated with experimental data unlike ODIRSOL.

2.1. The user interface

The user interface [13] consists of four pages which have to be completed in an appropriate order:

- page 1: General information, application selection
- page 2: System configuration selection
- page 3: Component parameters
- page 4: Results and output

The tool is based on a one hour time step energy balance approach. It uses an input file composed of hourly meteorological data (ambient dry bulb temperature (T_{air}), relative humidity (HR), global horizontal irradiation (G_{HZ}) and the corresponding building loads: heating (B_{chauf}), cooling (B_{clim}) and DHW (B_{ecs}) demands). The file is a tab text format with 8760 lines registered with specific extension (*.mnp).

PISTACHE proposes two layouts as defined by Nowag et al. [14]: one for small scale systems adapted from the solar combisystem concept including a cooling function (also called SSC+ or Solar Combi+) and another one for large scale systems which make up the majority of the current market.

Table 1
Characteristics of simulation software.

Software	Available right now	Specific for solar cooling	Free	Suitable for design offices	Predefined configurations	Hourly time step	External weather file	External building loads	Component library	Validated with experimental data
TDC Tool		X			X	X	X	X		
EASY COOL		X				X	X	X		
ODIRSOL	X	X	X	X	X	X	X	X	X	
EnergyPlus / SPARK	X			X		X			X	X
TRNSYS	X			X	X	X	X	X		
INSEL	X		X	X	X	X				
PolySun	X		X			X		X		
TRANSOL	X			X	X		X		X	
PISTACHE	X	X	X	X	X	X	X	X	X	X

The configuration parameters are the functions provided by the system (solar installations are usually used for cooling, but can also be used for heating and/or DHW production), the solar system priority (if heating and DHW preparation functions are selected, the user must indicate the demand that solar energy has to feed first) and the backup systems (solar energy can be sustained by a cold back-up for cooling and a hot backup for heating). The cooling period is fixed by the user or defined automatically according to the cooling demand.

For each component of the plant i.e. sorption chiller, solar collectors, heat rejection system, buffer and storage tank and back-up systems, the user specifies the main sizing characteristics. To allow this, several automatic functions have been programmed in order to assist the user to pre-size the components. The automatic pre-sizing functions are fully described by Le Denn et al. [17] and cover the sorption chiller nominal capacity, the solar thermal collector area, the hot and cold storage volumes and their heat loss time constants (C_r).

Two chiller technologies are available: absorption and adsorption. After choosing, the user selects an existing chiller from a list established by Boudéhen et al. [27]. A generic chiller with a defined nominal cooling capacity and thermal coefficient of performance (COP_{th}) can also be used. After selecting the solar collector technology (flat plate or vacuum tubes), the user selects a model from the database or a generic one as defined in task 32 of IEA SHC report [28]. The storage volumes and the corresponding storage heat loss time constants are defined by the user or by using an automatic function [17]. Four heat rejection technologies are available: wet cooling tower, drycooler, adiabatic drycooler and geothermal probes. Each system is automatically sized to evacuate the totality of the heat rejection energy required by the sorption chillers operation. If geothermal probes are selected, it is necessary to enter the average depth of the probes and the thermal characteristics of the ground (thermal conductivity, specific thermal capacity and density). The hot and cold backup systems are selected from a list of conventional existing equipment. Their efficiencies are defined according to French building thermal standards [29]. If their auxiliary electrical power consumptions are unknown, 2% of the supplied energy will be considered as auxiliary electrical consumption, according to Sparber et al. [30]. The cooling, heating and DHW required temperatures on the distribution loop (respectively $T_{R\ COOL}$, $T_{R\ HEAT}$, T_{DHW}) at the building side and the ambient temperature of the technical room or substation have default values or can be specified by the user.

2.2. The calculating process common to all operating modes

When all the parameters are defined, the calculation can be processed. Because most SHC plants have very short term storage (a few minutes to a few hours), the calculation is done with an hourly time step. This allows to the load to be compared with the potential solar production at a daily step, throughout the year and thus helps the user to decide if the solar plant is properly sized. Indeed, unlike the classic method used to size electrical or fossil fuel cooling, heating and DHW production systems; the sizing of a solar installation is done for a minimum value, to cover the load all year long and to avoid over-production. For this reason, a one day simulation is not appropriate, as are ratio-based methodologies.

At each time step, the tool calculates energy balance and thermal energy flux $Q1(t)$ to $Q10(t)$ according to the configuration defined by the user. The solar energy in collectors $Q1(t)$ is calculated in Eq. (1) as a function of solar energy $Q_{sol}(t)$ which is in turn calculated in Eq. (2) with solar irradiation $G_{SL}(t)$ in the sloped collector field area (A_{coll}); and collector efficiency $\eta_{coll}(t)$ calculated using the well-known EN 12975 equation, as a function of collector performance coefficients (η_0 , a_1 , a_2), collector average temperature (T_{coll}), solar irradiation $G_{SL}(t)$ and ambient temperature $T_{air}(t)$ expressed in Eq. (3).

$$Q1(t) = Q_{sol}(t) \cdot \eta_{coll}(t) \quad (1)$$

$$Q_{sol}(t) = A_{coll} \cdot G_{SL}(t) \quad (2)$$

$$\eta_{coll}(t) = \eta_0 - a_1 \cdot \frac{T_{coll} - T_{air}(t)}{G_{SL}(t)} - a_2 \cdot \frac{(T_{coll} - T_{air}(t))^2}{G_{SL}(t)} \quad (3)$$

For storage, the output energy values are calculated as a function of the storage tank capacity (in kWh) and heat loss. For each tank and each operating mode (heating, cooling or DHW production), heat loss ($Q_{loss_{st}}$) is a constant, a function of the heat loss time constant, the volume of the tank (V_{st}) and the temperature difference between the tank (T_{st}) and the ambience (T_{amb}), as defined in Eq. (4) for hot storage:

$$Q_{loss_{st}} = \frac{V_{st} \cdot Cr \cdot (T_{st} - T_{amb})}{24 \cdot 1000} \quad (4)$$

Where the heat loss time constants for hot and cold storage are defined respectively by Eqs. (5) and (6):

$$Cr_{hst} = aCr_{hst} \cdot V_{hst}^{bCr_{hst}} \quad (5)$$

$$Cr_{cst} = aCr_{cst} \cdot V_{cst}^{bCr_{cst}} \quad (6)$$

As PISTACHE uses a load file for the building, the installation performances are limited at each time step by the specific building needs (DHW/heating and cooling) and by the hot, cold and DHW storage capacities. The maximum storage capacity ($C_{st,max}$) is calculated as a function of the storage volume (V_{st}), the maximal available temperature of the storage ($T_{st,max}$) and the ambient temperature (T_{amb}). It is expressed in Eq. (7) for hot storage:

$$C_{st, \max} = \frac{1.163 \cdot V_{st} \cdot (T_{st, \max} - T_{amb})}{1000} \quad (7)$$

The chiller thermal coefficient of performance $COP_{th}(t)$ is calculated using Eq. (8) as a function of the Carnot efficiency (η_{Carnot}) according to [13]. The Carnot efficiency is the maximal thermal efficiency of the chiller; it can be calculated as a function of the inlet temperatures for an absorption chiller using Eq. (9).

$$COP_{th}(t) = b_1 \cdot \exp \left[\frac{-\eta_{Carnot}(t)}{c_1} \right] + b_2 \cdot \exp \left[\frac{-\eta_{Carnot}(t)}{c_2} \right] + COP_0 \quad (8)$$

$$\eta_{Carnot}(t) = \frac{T_{G,in}(t) - T_{AC,in}(t)}{T_{AC,in}(t) - T_{E,in}(t)} \cdot \frac{T_{E,in}(t)}{T_{G,in}(t)} \quad (9)$$

b_1 , c_1 , b_2 , c_2 coefficients are obtained with experimental values measured by CEA-INES during single effect absorption chillers characterization on a test bench, as described in Fig. 1. The COP_0 coefficient can be considered as the nominal thermal COP of the considered chiller.

At the end of the hourly calculation process, monthly and annual energy balances are established. The user is given the incident solar energy (Q_{sol}), the various system thermal energy values (Q_i) as well as the various auxiliary electrical consumption (E_i) and the water consumption of the heat rejection system (V_1) (see Fig. 2). The performance indicators are calculated with annual values according to [13,14]. In order to help the user to size the system, target values are defined for performance indicators consisting of minimum or maximum limits. The calculation method is also presented by Nowag et al. [14]. The tool immediately compares each indicator to its associated target values and specifies the variance in percent. In case of oversizing, automatic warning messages are displayed.

2.2.1. The calculating process of the cooling mode

As the calculating process is similar for each PISTACHE operating mode, only the “cooling mode” is considered to check the required conditions which will be mentioned later. The calculating process for the step time (t) can be performed only after verification of different conditions for the previous step time ($t-1$). These conditions (starting and functioning tests) simulate the regulation and the functioning of sorption solar installation as depicted in Fig. 3.

2.2.1.1. The starting test. To start the sorption machine, the thermal energy available in the hot buffer tank should be higher than a minimum value determined from the energy demand on the hot side of the sorption chiller (nominal capacity (P_n) divided by the nominal thermal COP (COP_0)) and a maximized heating capacity coefficient (K_{Pstart}). This former coefficient K_{Pstart} represents the required peak power for the starting of the machines. The starting condition in this case can then be expressed as:

$$Q_1(t) + Q_{hst}(t) - C_{st, \min, cool} \geq K_{Pstart} \cdot \frac{P_n}{COP_n} \quad (10)$$

The maximized heating capacity coefficient (K_{Pstart}) is higher than 1.

Where the storage minimal capacity for the cooling operating mode is defined using the minimum temperature required by the chiller ($T_{G, \min}$ —data provided by the manufacturer of the sorption chiller) as follows:

$$C_{st, \min, cool} = \frac{1.163 \cdot V_{hst} \cdot (T_{G, \min} - T_{amb})}{1000} \quad (11)$$

2.2.1.2. The functioning test. At each time step (t), if the chiller was previously ($t-1$) in operation, a “functioning test” determines if it will still be in operation. This test compares the available thermal energy stored in the hot tank to a minimum energy required by the chiller. This minimum value is calculated with the sorption chiller nominal capacity (P_n), the nominal coefficient of performance (COP_0) and a coefficient (K_{Pmin}).

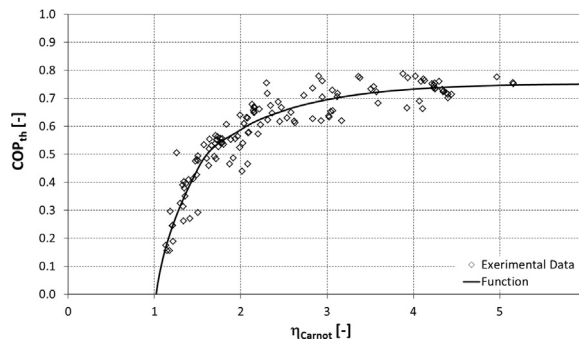


Fig. 1. COP_{th} as a function of Carnot efficiency.

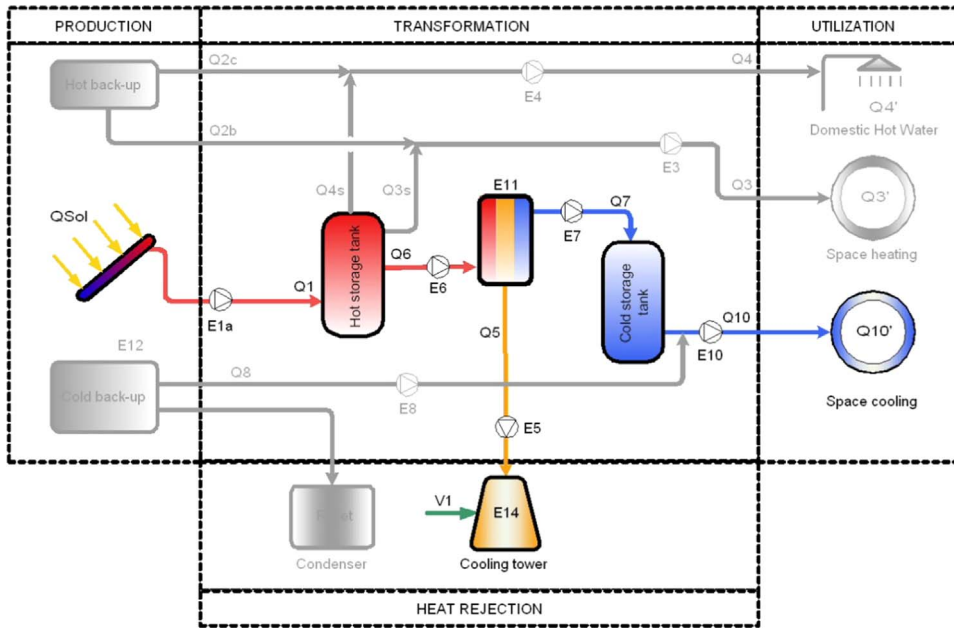


Fig. 2. Equivalent PISTACHE RAFSOL scheme.

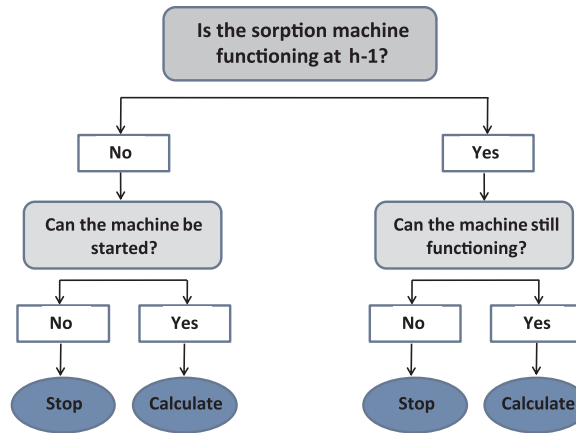


Fig. 3. Calculating algorithm for the cooling operating mode.

This coefficient highlights the fact that sorption machines can operate at low capacity compared to their nominal capacity even with a thermal COP close to the optimum. Thus, the functioning condition can be formulated as:

$$Q1(h) + Qhst(h) - C_{st, \min, cool} \geq K_{P \min} \cdot \frac{P_n}{COP_0} \quad (12)$$

The minimized heating capacity coefficient ($K_{P \min}$) is lower than 1.

While the two previous conditions are fulfilled, the sorption chiller can be said to produce the cooling effect. Subsequently, the thermal heat energy supplied to sorption machine ($Q6$) and the thermal cooling energy ($Q7$) are estimated respectively by Eqs. (13) and (14):

$$Q6(t) = \min \left[Q1(t) + Qhst(t) - C_{st, \min, cool}; K_{P \max} \cdot \frac{P_n}{COP_{th}(t)} \right] \quad (13)$$

$$Q7(t) = COP_{th}(t) \cdot Q6 \quad (14)$$

With $K_{P \max}$ a maximized heating capacity coefficient (higher than 1) expressing the ability of the sorption chiller to produce cold with a higher capacity than its nominal value.

3. The PISTACHE validation process

3.1. Description of the installation used for the validation

3.1.1. “RAFSOL” solar cooling installation

The “RAFSOL” solar cooling installation was built in March 2008 to cool university classrooms under a tropical climate without any backup systems (hot or cold). The thermal comfort inside the building is achieved with a self-stabilizing operating system that maintains the indoor temperature 6 °C below the outdoor temperature. It should be noted that the purpose of this installation is only to cool the building, so it works six months per year (no heating mode or hot water system). We can see the PISTACHE equivalent scheme of the installation on Fig. 2.

This solar cooling system has five main components: a 90 m² solar collector field, 2 buffer tanks of 1500 L and 1000 L for hot and cold water respectively, a 30 kW LiBr/H₂O single-effect absorption chiller, a 80 kW cooling tower and 13 fan coil units. The double-glazed flat-plate solar collector field converts incident solar irradiation into thermal energy and transfers it to the working fluid i.e. water. The hot water is stored in a hot buffer tank and then is used to warm the absorption chiller which produces chilled water. The chilled water is stored in a cold buffer tank and then distributed to fan coil units. The cooling tower rejects the medium temperature heat produced in the absorber and the condenser of the absorption chiller.

During some critical periods of the year, when the outdoor temperature is very high and the solar cooling system can not provide enough refrigeration, indoor thermal comfort is achieved using ceiling fans.

3.1.2. “SONNENKRAFT” solar cooling and heating installation

As shown by the equivalent PISTACHE SONNENKRAFT scheme (Fig. 4), the “SONNENKRAFT” installation was designed for the cooling and heating of 1200 m² of office rooms. Solar energy is recovered by a 116 m² solar field fixed to the roof of the building and constituted of 2 types of collectors. The thermal energy is stored in two separate 2000 L buffer tanks. During the winter, heating is guaranteed by a heat pump. The solar collectors are used if enough irradiation is available. In summer, the solar collectors feed a single-effect absorption chiller (LiBr/H₂O) of 17.5 kW nominal cooling capacity, whereby the heat rejection is performed by a dry cooler system. Heat and cold are distributed to the different parts of the building by a subfloor heating-cooling system and fan coils.

3.2. Description of the methodology used for the validation

The validation phase aims to ascertain input parameters of PISTACHE (storage tank heat time constant and cooling power coefficients) from an initial experimental period named “season 1” and to validate predicted PISTACHE results with a second experimental period named “season 2”. The validation covers two different configurations: cooling mode only and, both heating and cooling modes. Parameters are ascertained using the generic optimization program GenOpt developed by Wetter [31]. It identifies PISTACHE parameters which minimize the associated objective function defined as:

$$F_{obj} = (Q1_{exp} - Q1_{PIST})^2 + (Q6_{exp} - Q6_{PIST})^2 + (Q7_{exp} - Q7_{PIST})^2 + (Q3'_{exp} - Q3'_{PIST})^2 \quad (15)$$

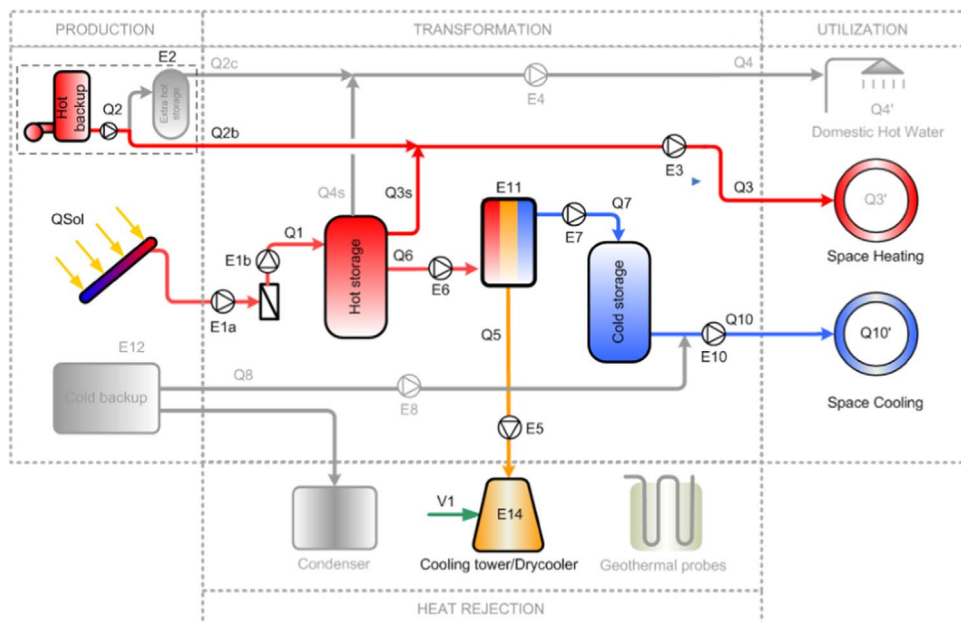


Fig. 4. Equivalent PISTACHE SONNENKRAFT scheme.

To complete the process, PISTACHE and GenOpt should be coupled as depicted in Fig. 5 which was inspired by the GenOpt user manual [31] and previous work carried out by Bigot [32] and Tamasauskas [33].

The GenOpt process firstly involves creating specific files, namely:

- An initialization file that specifies the location of all files required for this optimization,
- A command file that contains optimization settings (selected algorithms, step variations, upper/lower bounds),
- A configuration file that gathers information related to the PISTACHE simulation,
- A simulation input template file.

Next, PISTACHE is launched from the GenOpt interface then the objective function is calculated. After that, the objective function value is saved or recalculated, if necessary, by using a new set of parameters as showed in the above diagram of Fig. 5. Finally, the optimization sequence is stopped when the minimum objective function value is reached and, the parameters are identified.

This study is mainly focused on PISTACHE internal parameters corresponding to the operating modes of both RAFSOL and SONNENKRAFT. These parameters are: starting and functioning coefficients (K_{Pstart} , K_{Pmin} , K_{Pmax}), both cold and hot storage tank heat time constant coefficients ($a_{CR_{cst}}$, $b_{CR_{cst}}$, $a_{CR_{hst}}$, $b_{CR_{hst}}$).

3.3. Results analysis of the validation process

3.3.1. Validation with “RAFSOL” data

The parameter detection process is carried out with the basic assumptions gathered from first and second season RAFSOL experimental data; these assumptions are summarized in the Table 2:

Initially, the temperatures are entered into the PISTACHE user interface. Then, the optimization process is launched from GenOpt. Meteorological and load input files corresponding to the first RAFSOL season are used, allowing a new set of internal parameters to be identified. These are summarized in the Table 3.

Then, the parameters obtained are utilized for the validation phase. In this case, a new simulation is run directly from PISTACHE, without the GenOpt program, whereby RAFSOL second season meteorological and building load input files are used. Next, the energy balance predicted by PISTACHE are compared with the annual experimental data (Fig. 6) by relative errors expressed as:

$$Err(\%) = \frac{|Q_{i_{exp}} - Q_{i_{PIST}}|}{Q_{i_{exp}}} \cdot 100 \quad (16)$$

Fig. 6 denotes relevance accuracy between experimental data and PISTACHE predictions. Solar energy supplied to the hot storage (Q1) has been estimated at 15843 kWh by PISTACHE while the thermal heat energy supplied to the sorption machine (Q6) and the thermal cooling energy supplied by the evaporator (Q7) have been evaluated at 13139 kWh and 7313 kWh respectively. In fact, the relative errors from the parameter identification phase are evaluated at 0.13% for Q1, 0.24% for Q6 and finally 1.98% for Q7.

In the histogram of the validation phase, we note that relative errors are higher than those obtained in the identification phase.

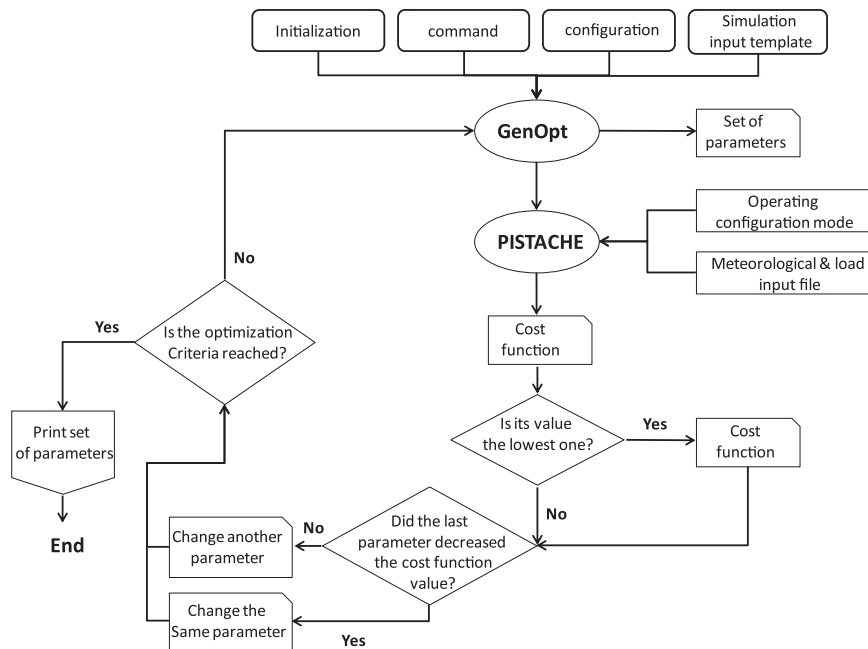


Fig. 5. Schematic representation of the entire PISTACHE validation process.

Table 2

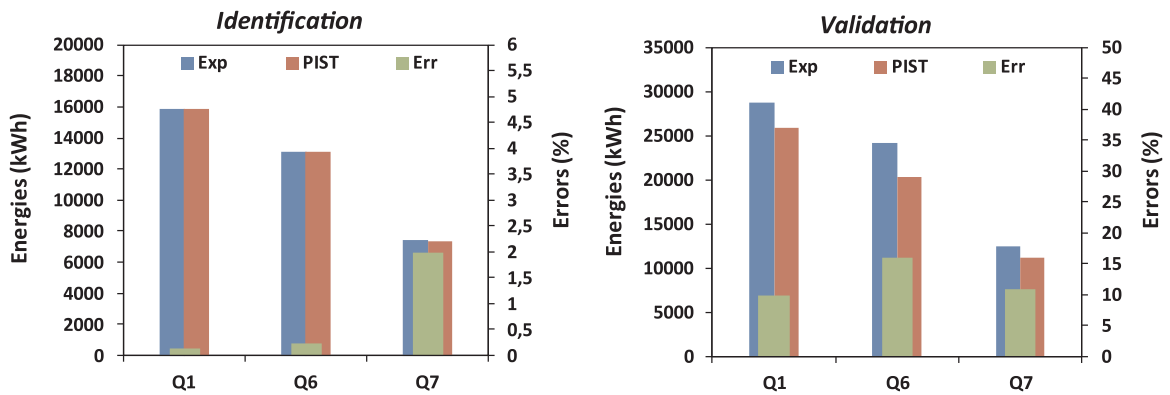
RAFSOL assumptions for identification and validation phases.

	Temperatures [C°]	Annual first season RAFSOL energy values [kWh]	Annual second season's RAFSOL energy values [kWh]
T _{amb}	27	–	–
T _{cool}	12	–	–
T _{Gmin}	65	–	–
T _{STC MAX}	100	–	–
Q1 (Exp)	–	15864	28698
Q6 (Exp)	–	13108	24132
Q7 (Exp)	–	7461	12455

Table 3

Identified set of parameters for the RAFSOL operating mode.

a _{CR_{hst}}	b _{CR_{hst}}	a _{CR_{cst}}	b _{CR_{cst}}	K _{Pstart}	K _{P min}	K _{P max}
6.6719	–0.4141	4.8786	–0.3333	0.9697	0.2941	1.0815

**Fig. 6.** Comparison of RAFSOL experimental data and PISTACHE results for identification and validation phases.

For the second season, PISTACHE predicted captured solar energy to be about 25887 kWh, the absorbed thermal energy of the sorption machine to be about 20268 kWh and a thermal cooling energy of 11108 kWh; leading to relative errors of 9.8%, 16% and 10.8% respectively for the cooling energy. Moreover, for research purposes, the operating scenario during the second season (a much longer operating time with Q1 of about 30000 kWh) was different compared to the first one (Q1 is about 16000 kWh) so, PISTACHE provides relevant predictions with maximum errors close to 16%.

3.3.2. Validation with “SONNENKRAFT” data

Like the previous case study, validation of the PISTACHE tool uses the following assumptions (Table 4):

Both identification and validation phases follow the previous RAFSOL study steps mentioned above, whereas the only requirement for the SONNENKRAFT study is to consider thermal energy supplied for heating (Q3'). Using SONNENKRAFT first season meteorological and building loads inputs, the parameter identification process gives the next set of parameters (Table 5).

The parameters identified are subsequently used to validate PISTACHE using the second season SONNENKRAFT experimental data. The results obtained are compared in Fig. 7.

Table 4

SONNENKRAFT assumptions for identification and validation phases.

	Temperatures [C°]	Annual first season SONNENKRAFT energy values [kWh]	Annual second season SONNENKRAFT energy values [kWh]
T _{amb}	20	–	–
T _{cool}	12	–	–
T _{G min}	65	–	–
T _{STC MAX}	100	–	–
Q1 (Exp)	–	37432	39350
Q6 (Exp)	–	11733	11759
Q7 (Exp)	–	6235	6852
Q3 (Exp)	–	53762	45130

Table 5
Identified set of parameters for the SONNENKRAFT operating mode.

$a_{CR_{hst}}$	$b_{CR_{hst}}$	$a_{CR_{cst}}$	$b_{CR_{cst}}$	$k_{P_{start}}$	$k_{P_{min}}$	$k_{P_{max}}$
5.00597	−0.368	5.606	−0.442	1.111	0.264	1.274

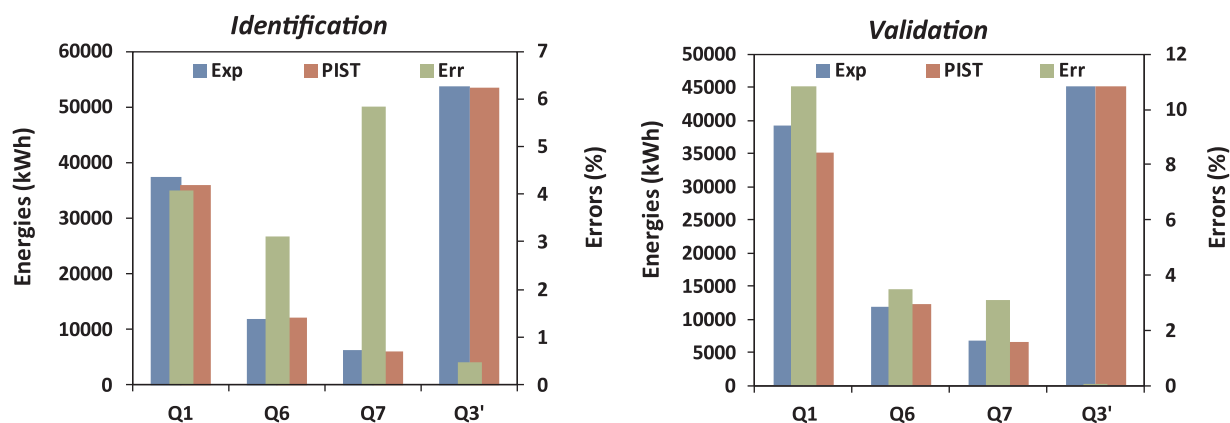


Fig. 7. Comparison of SONNENKRAFT experimental data and PISTACHE results for identification and validation phases.

As confirmed by the results in Fig. 7, the energy values were accurately predicted for the identification inducing low relative errors namely: 4.1% for Q1, 3.1% for Q6, 5.8% for Q7 and only 0.5% for Q3'. The accuracy of PISTACHE's predictions can now be easily checked. Compared to the results identified above, we note two major trends: firstly, relative errors have been increased to 10% and 3.5% for Q1 and Q6 respectively while a decreasing trend was observed for Q7 and Q3' with relative errors of 3.1% and 0.01% respectively. Consequently, the reliability of PISTACHE in heating and cooling modes is quite good with precisions higher than 90%.

4. Conclusions and perspectives

The presented work is a case study experimental validation of the new pre-sizing tool so-called PISTACHE. Two operating modes have been investigated: a simple cooling mode corresponding to the RAFSOL installation and, both cooling and heating modes corresponding to the SONNENKRAFT plant. The validation process presented in this paper completes the previous work done by Le Denn et al. [13].

The first part of the validation consisted of a study to determine parameters. This phase aimed to minimize the objective function in order to superimpose the real experimental data on PISTACHE's predictions for each installation. Utilizing the first season's meteorological and load input files, the identification phase was performed by the GenOpt program wherein a new set of internal parameters were defined for PISTACHE. The estimated energy relative errors used were below 2% for RAFSOL and 5.8% for SONNENKRAFT. The second step was the validation phase. For this purpose, a new PISTACHE simulation was carried out by exploiting the new parameters from the previous identification phase, the second season meteorological and load input files. The results obtained for the validation phase were very satisfactory. The relative errors calculated for the RAFSOL configuration were under 16%. For the SONNENKRAFT configuration the error was less than 10%.

Therefore, we conclude that even with a calculation method based on annual energy balance; the PISTACHE tool is able to provide a relevant prediction for the two operating modes under investigation with an accuracy greater than 84% for the RAFSOL configuration and up to 90% for the SONNENKRAFT. We have also observed the reproducibility of PISTACHE results from one season to the next. Thus, the numerical and experimental result comparison shows that PISTACHE is a suitable tool for prediction of either a simple cooling mode "RAFSOL" or a double cooling and heating mode "SONNENKRAFT".

PISTACHE is an innovative tool based on general holistic approach laying on thermal efficiency, global and solar performance indicators and also ecologic and economic indicators. This tool has been developed to be used by designers and planners to quickly determine annual performances and the best integration potential of a SHC & DHW plant using a sorption chiller. Moreover, PISTACHE should be used to compare the predicted performance at the pre-design phase with the observed performance of newly-built solar cooling installations.

In the future, it would be interesting to extend PISTACHE to other specific solar applications like solar desiccant evaporative cooling, solar heating for swimming pools, industry and district heating.

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