Diseño y Dimensionamiento del Actuador de un Sistema de Seguimiento Solar de un Colector Cilindro-Parabólico para una Planta Solar de Aire Acondicionado Utilizando Herramientas de Simulación por Software

Design and power calculation of the Sun Tracking System Actuator of a Parabolic Trough Collector for an Air-Conditioning Solar Plant Using Software Simulation Tools

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PALABRAS CLAVE:

planta solar, CCP colector cilindro-parabólico, sistemas solares de aire acondicionado.

RESUMEN

Este artículo presenta el diseño y dimensionamiento del actuador necesario para el sistema de seguimiento solar de una planta de acondicionamiento de aire solar basada en la tecnología de colectores cilindro-parabólico. El correcto diseño y dimensionamiento del actuador es una etapa de diseño realizada en una primera fase y juega un papel muy importante en el desempeño del sistema completo de control ya que el sistema de aire acondicionado tiene restricciones de diseño y de operación. El problema es resuelto utilizando: (i) un algoritmo de posición solar bien definido, (ii) una herramienta de simulación numérica para el cálculo de los ángulos oblicuos necesarios para el esquema de seguimiento solar de un solo eje con orientación norte-sur y este-oeste y (iii) un software de diseño CAD en 3D para el correcto dimensionamiento del actuador. El diseño propuesto es una solución hecha a la medida para cumplir los requerimientos de diseño y operación del sistema de aire acondicionado.

KEYWORDS:

solar plant, PTC parabolic trough collector, solar air conditioning systems

ABSTRACT

This paper presents the concept design and dimensioning of a solar actuator. This device is needed for the sun tracking system into a solar plant based in parabolic trough collector technology for air-conditioning purposes. The correct design and dimensioning of the actuator is a first approximation design for a very important role in the performance of the whole automatic control system because the proposed air-conditioning system imposes restrictive design and operating requirements. The problem is tackled using: (i) a well-defined sun position algorithm, (ii) a numeric software simulation tool for the calculus of the oblique angle needed for a north-south and east-west single axis tracking orientation scheme and (iii) a 3D CAD software tool to realize the actuator geometric dimensioning. The proposed design scheme achieves a tailored solution that meets the restrictive air-conditioning system requirements and operating conditions.

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1 INTRODUCCIÓN

Since the last century, solar energy has been exploited mainly by means of photovoltaic technology or low, medium or high-temperature thermal technologies to counteract the environment degradation. Nowadays, a wide variety of solar energy applications exists: electrical and mechanical energy production, water pumping and desalination, solar cooking and solar refrigeration, among others.

Solar refrigeration technology engages a system where solar power is used for cooling or air-conditioning purposes. This systems are very suitable for both purposes because solar radiation availability usually coincides with geographic and seasonal requirements [1]. Cooling can be achieved through four basic methods: solar photo-voltaic cooling, solar thermoelectrical cooling, solar thermo-mechanical cooling, and solar thermal cooling [2]. Solar thermal cooling systems are based in a solar thermal plant where solar energy is collected, then concentrated, and transferred to a thermal fluid and stored in a thermal storage tank TST [3]. The system is completed with an air-conditioning unit that is run by the hot refrigerant coming from the storage tank, and the refrigerant circulates through the entire system [2]. There are basically two types of solar thermal cooling systems: open and closed sorption systems. In the case of closed sorption systems in turn they can classify in: (i) absorption cooling systems where the thermal energy is used to separate a refrigerant from a refrigerant/absorbent mixture, and (ii) adsorption cooling systems where molecules are adsorbed on to a solid porous surface by means of an interaction between the surface and molecules when a vapor molecule contacts the surface.

Solar thermal cooling systems have been studied since the 70's with successfully theoretical and experimental results. Since then, the most common used systems are those based in closed sorption cycles, especially LiBr-H2O single effect absorption chillers feeded by flat-plate FPC and/or evacuated tube collectors ETC [1]. The use of solar cooling systems with parabolic trough concentrators dates back from 1957 and since the beginning of the new century several experimental and test facilities have appeared in the literature. The principal advantages of PTC's in comparison with the FPC and ETC are higher efficiency, as a higher working temperature is reached, and lower thermal losses. The principal disadvantages are: higher installation and maintenance costs, the fact that they can only work with direct solar radiation and with moderate wind speeds, and the necessity of a sun tracking system.

Since 2016 a cooling system for air-conditioning pilot plant has been designed in CIICAp, Mexico (Galindo, et al., 2017, Jiménez-Ávila, 2017). The designed solar thermal cooling system is an absorption NaOH-H2O cycle type and pretends to be autonomous, in the sense that has only to operate with sun energy, so photovoltaic panels are also included to feed the peripheral equipment. The solar thermal plant is PTC with double TST based and has an energy demand of 6,600 kW/h for the air conditioning of six rooms of a building. The geographical situation of the building is favored by a solar resource of about 5.0 kWh/day-m2. From a control point of view, the proposed air-conditioning system do not pretend to regulate a room temperature at a fixed set point, instead, the goal is to achieve a temperature difference (of about 3ºC) between the inside room temperature from respect to the ambient one. In few words, the goal is to enhance the comfort inside the building during the warmest days of the year.

Prior to the control system design of the solar thermal plant, in this work is presented the design and dimensioning of the actuator system needed for the sun tracking of the PST. A tailored solution for the pilot plant is achieved using two software simulation tools to achieve a correct tracking system design that meets the air-conditioning restrictive system requirements and operating conditions.

The paper is organized as follows: in section 2 a description of the solar thermal plant is presented, in section 3 the sun position algorithm and the calculus of the oblique angle needed for a north-south or east-west tracking orientation is presented. In section 4, simulation results are presented and analyzed for design purposes, and finally conclusions are presented.

2. DESCRIPTION OF THE PLANT

The solar thermal plant of the air-conditioning systems is composed of a collector field, two thermal storage tanks, two pumps and the valves and pipelines that interconnect the system elements (Fig. 1). Meanwhile, the distributed solar collector field (Table 1) is composed of 15 units of parabolic mirrors (Figure 2) with a total mirror surface of 40.05 m2. The field can be east-west (3 rows of 5 collector units) or north-south (5 rows of 3 collector units) aligned with single axis tracking control. The Heat Transfer Fluid (HTF) of the solar collector is a mixture 50-50% of water and ethylene glycol. The flow is forced with two pumps that delivers a maximum of 36.5 l/min. The solar thermal plant is dimensioned to provide the 6,600 kW-h needed by the thermal load.

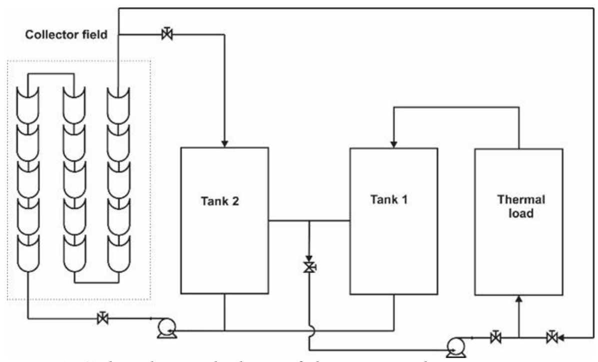


Fig. 1. Solar thermal plant of the air-conditioning system.

From a control point of view, the disturbances of the system are: (i) huge changes of the solar irradiance due to clouds and (ii) the inlet and ambient temperature variations, and the controlled variable is the mean outlet temperature of the HTF. Unlike other common thermal plants where the controlled variable has to be maintained in a fixed desired value in spite of the disturbances [4]–[6], in this plant the controlled variable has to be maintained within a desired range, this means between 85-110 ºC. The minimum temperature warranties: (i) the proper operation of the thermodynamic cycle of the air conditioning system and (ii) the energy required by the thermal load, and the maximum is established for safety considerations (Galindo, et al., 2017, Jiménez-Ávila, 2017).

Fig. 2. Solar collector unit.

2.1 Solar thermal plant restrictions and operating conditions

The solar plant presents some important restrictions to be taken in to account since the design stage: (R1) the pilot plant has to be designed with the lowest price elements, (R2) the total useful area for the thermal and photovoltaic collector field must be restricted to the one of the building roof: 75 m2, (R3) for security reasons, the total weight of the equipment must be beneath 2 ton, and (R4) all the peripheral electric-electronic equipment must operate with the 1,300 W (or 108.3 A with 12V CD) generated by the photovoltaic field, without electrical storage as a design requirement.

There are also two operating conditions of the air-conditioning system to be considered. These conditions are closely related to the principal goal of the system (to enhance the comfort inside the building) and are: (i) the system must operate in the warmest months of the year, this means from the first of April to the end of July and (ii) the system must operate in the warmest hours of the day, that is to say from 10:00 to 17:00 hours.

parameter	value	units
focal lenght	0.26	m
collector aperture	1.05	m
collector lenght	2.55	m
collector area	2.67	m^2
concentration ratio	13.3	/
total collection area	40.05	m^2

Table 1. Solar collector field parameters

The described plant restrictions and operating conditions has restrictions in the control system as weight and current consumption limits that had to be complimented in the design stage.

3. SUN POSITION ALGORITHM

The most commonly used configurations for sun-tracking systems are azimuth-elevation and tilt-roll tracking systems [7], being more popular the first one since it is inspired by an ordinary optical mirror mount. By this fact many sun position (azimuth-elevation) algorithms have been reported in the last twenty years [8] varying from simplest to complex ones and with different accuracies, up to a very complex algorithm, the NREL Solar Position Algorithm, with an uncertainty of ±0.0003º [9]. Nevertheless, all the reported algorithms are suitable only for two axis tracking. One axis tracking has been commonly tackled with: (i) closed-loop algorithms using a light sensor to generate the feedback signal of the loop, without needing the calculus of a desired angle, or (ii) using one axis tilted by the angle of the latitude of the location, and the rotation of tracking determined by the hour angle [10]. However, this last approach cannot be applied for systems where the tracking axis is perpendicular to the horizontal plane, as is the case. To solve this problem, in this work is proposed the calculus of the desired tracking angles for one axis tracking in east-west or north-south alignments draw from the azimuth and elevation angles. For that, first is necessary to establish the sun angles and sun vector.

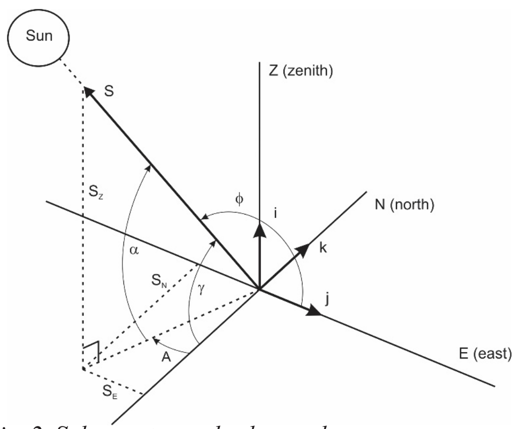


Fig. 2. Solar vector and solar angles.

3.1 Sun vector and sun angles

The sun vector S is the one formed between a point in the surface of the earth and the centre of the sun (Fig. 2). Is commonly defined by means of azimuth A and elevation α sun angles. Azimuth angle is the one formed between the horizontal plane measured from the true south (or north) to the horizontal projection of the sun rays. Elevation angle (also called altitude angle) is the one formed between the horizontal plane and a line that connects a point in the surface of the earth and the sun. The sun vector can be defined by terms of the i,j,k components, this means the zenith S_Z, east S_E, and north S_N components respectively (Fig. 2). This cartesian components can be defined in terms of the azimuth and elevation angles (1)

$$S_Z = \sin(\alpha) \quad \ldots(1a)$$

$$S_E = \cos(\alpha)\sin(A) \quad \ldots(1b)$$

$$S_N = \cos(\alpha)\cos(A) \quad \ldots(1c)$$

For one axis tracking, azimuth and elevation angles are meaningfulness. The useful angles are: (i) ϕ the angle formed between the horizontal plane and the projection of the solar vector in the zenith-east vertical plane for north-south one axis tracking, and (ii) γ the angle formed between the horizontal plane and the projection of the solar vector in the zenith-north vertical plane for east-west one axis tracking. Both angles can be expressed in terms of solar vector cartesian components and therefore in terms of solar angles (2-3).

$$\tan(\phi) = \frac{S_Z}{S_E} = \frac{\tan(\alpha)}{\sin(A)} \quad \ldots(2)$$

$$\tan(\gamma) = \frac{S_Z}{S_N} = \frac{\tan(\alpha)}{\cos(A)} \quad \ldots(3)$$

With definitions (2) and (3) any azimuth-elevation algorithm can be used to calculate the desired oblique angles (ϕ,γ) for north-south or east-west one axis tracking respectively. In this work the selected algorithm is the well know one presented in (Grena, et. al., 2008) a medium-complex algorithm with an accuracy of ±0.027º.

4. SOFTWARE SIMULATION RESULTS

Employing the selected sun tracking algorithm the azimuth and elevation angles are calculated in the range dictated by the operating conditions (Figs. 3-4) between day 91 and 211 of the year and from 10:00 to 17:00 hours. Using a structured programming methodology a main code is properly written in a numeric simulation program (MATLAB, Appendix 1), and various functions are programmed and called from the main code, including equation of time, declination angle, hour angle and the solar angles (Appendix 2). With this data, and the equations (2-3) the oblique angles (ϕ,γ) are also calculated (Figs. 5-6). With the use of a MATLAB code the maximum and minimum values of each solar and oblique angles are also calculated (Table 2).

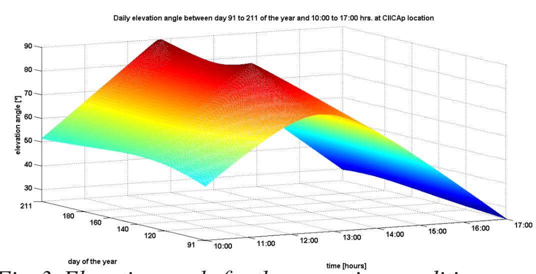


Fig. 3. Elevation angle for the operating conditions.

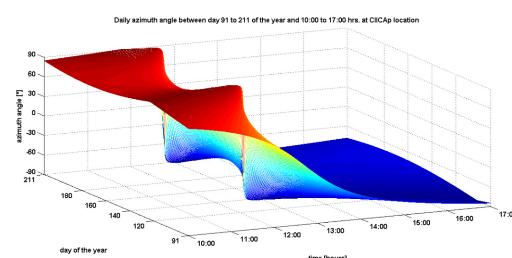


Fig. 4. Azimuth angle for the operating conditions.

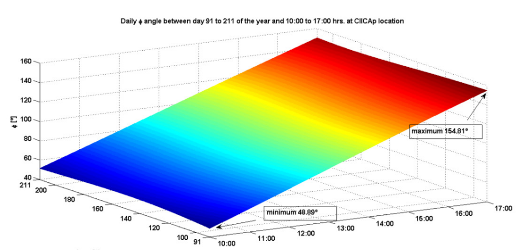


Fig. 5. ϕ angle for the operating conditions.

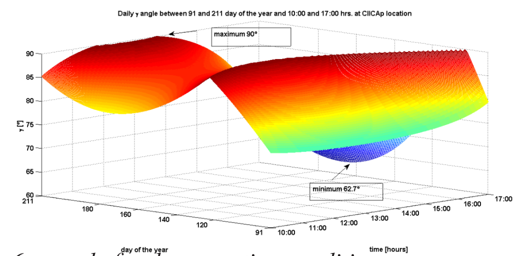


Fig. 6. γ angle for the operating conditions.

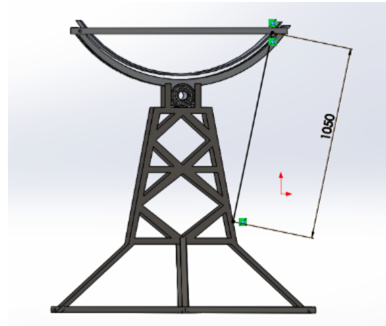
alignment	angle	maximum [°]	minimum [°]	range [°]
east-west	γ	90.00	62.79	27.29
north-south	ϕ	154.81	48.89	105.91
azimutal	A	90.00	-90.00	180.00
elevation	α	89.92	25.10	64.81

Table 2. Comparison of the angle displacement with different alignments

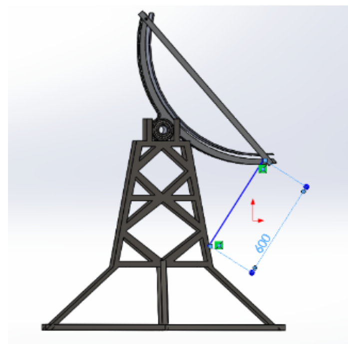
The comparison between the range needed wit north-south and east-west alignments in CIICAp location (18.98231º latitude, 99.234096º longitude) and operating conditions shows some differences (Table 2). This information is very pertinent to select an appropriate actuator between different options (Table 3) available in the market. The cost information of Table 3 was obtained in the month of July of 2017, the torque of the linear actuator was obtained multiplying the maximum push load force with the lever arm (5) that is the distance between the edge of the collector and the rotational axis.

$$\text{torque} = (\text{Force})(\text{lever arm}) = (1500\text{N})(0.68\text{m}) = 1020\ \text{Nm} \quad \ldots(5)$$

An analysis of Table 3 data allows calculate that linear actuator presents the less weight and price per Nm and a middle current consumption in comparison with the other actuator types, thus being the best option to meet (R1) and (R3) and an intermediate option for (R4) design restrictions. Taking in to account that the approximated angular range achieved with a linear actuator depends on: (i) the geometry of the collector, (ii) the selected attachment points of the actuator edges, and (iii) the maximum length of the actuator, a geometric dimensioning is done to determine the angle range that can be obtained with different standard commercial [11] (1500 N) linear actuators (Table 4). Selecting the largest actuator with a stroke of 18” and drawing the collector unit in a 3D CAD design software (SolidWorks 2016) it can be estimated the difference between maximum extension (1050 mm) at 90º and minimum one (600 mm) at 44º (Fig. 7a,b) yielding a range of 46º, surpassed for the east-west alignment angle displacement range of 27.29º (Table 2).



a. maximum extension of linear actuator yielding an angle of 90º



b. minimum extension of linear actuator yielding an angle of 44º

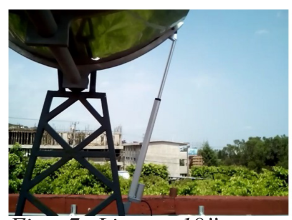


Fig. 7 Linear 18” actuator at maximum and minimum extensions in 3D CAD draws (a,b) and actual pictures (c,d).

actuator	type	Angle range [°]	Price [$USD/Nm]	Weight [kg/Nm]	Current consumption [mA/Nm]
Slew drive	rotational	360	0.57	0.042	6.00
CD motor coupled with reductor	rotational	360	2.19	0.091	0.88
CD motor coupled with bands-sprokets	rotational	360	6.45	0.160	0.86
Linear actuator	longitudinal	~90	0.05	0.002	3.00

Table 3. Comparison of different actuators

The previous analysis defines that the linear actuator with east-west alignment is preferred. It is important to emphasise that the simulated 3D CAD design angles matches perfectly to the actual angles (Fig. 7c,d). Moreover, this selection reduces the cost of the control system because with east-west alignment only three linear actuators are needed (one per row) instead of the five needed if north-south alignment is used.

Even though it has been reported that in summer north-south alignment provides more energy to the system (Kalogirou, 2014) the four design restrictions (R1-4) makes east-west alignment a better option for this particular plant.

Actuator stroke [in]	2	4	6	8	10	12	14	16	18
Retracted length [mm]	115	205	260	320	370	420	470	550	600
Extended length [mm]	205	305	410	520	620	720	820	950	1050

Table 4. Standard 1500N linear actuator dimensions

5. CONCLUSIONS

This paper presents a first approximation design and dimensioning of the actuator system needed for the sun tracking of a parabolic trough collector for air-conditioning purposes that imposes restrictive design and operating requirements. To achieve a correct sun tracking system design the problem was tackled using: (i) a well-defined sun position algorithm, (ii) the use of a software simulation tool to calculate the oblique angles needed for a north-south and east-west tracking orientation scheme, and (iii) the use of 3D CAD software tool to realize a correct geometric dimensioning. The simulation results with the design requirements, operating conditions and geographical position of the plant and the comparison of different actuator options permits to establish a tailored solution in the design stage. The solution establishes that the one axis tracking of the PTC for the air-condition is better achieved in this plant with east-west orientation and a linear actuator even though it has been reported that north-south orientation yields more energy in summer periods of operation.

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