Chapter 5 Approach to the optimization of parameters of a truncated cone solar concentrator using the Excel Solver tool

Capítulo 5 Acercamiento a la optimización de parámetros de un concentrador solar troncocónico, utilizando la herramienta Solver de Excel

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Abstract

This chapter deals with the optimization of the design parameters of a truncated cone type concentrator to capture, transfer and diffuse sunlight, so that the light reflections are concentrated and multiplied on the walls of the cone and then inside the tube to project them to the interior of any building. As an initial parameter, the length of the zenithal opening of an active Ciralight dome with a square section through which the sun's rays enter vertically was considered. Considering the aperture length as the largest diameter (b) and a concentration factor (CF) of 2.46, an Excel Solver tool was used to calculate the optimal fundamental dimensions: angle of the generatrix (α), cone height (h) and smallest diameter (a), for which a desired concentration is achieved. In addition, a truncated cone concentrator was calculated and designed graphically in Mechanical Desktop 6 Power Pack, starting from a unit cone according to the active dome previously mentioned. Finally, a 1:100 scale model was built to measure the illuminance under open sky and controlled conditions, using temperature sensor and photo detectors with ranges of $0 - 130\,Klx$, finding a FC of 1,78 under open sky and 1,89 with a halogen lamp under controlled conditions.

Sunlight, Concentrator, Dome, Illuminance, Optimization

Resumen

El presente capítulo se trata sobre la optimización de los parámetros de diseño de un concentrador tipo troncocónico para captar, transferir y difundir luz solar, de tal forma que los reflejos de la luz se concentren y multipliquen en las paredes del cono y posteriormente dentro del tubo para proyectarlos al interior de cualquier construcción. Como parámetro inicial se consideró la longitud de la apertura cenital de un domo activo de la marca Ciralight de sección cuadrada por el cual entran los rayos solares de forma vertical. Considerando la longitud de apertura como diámetro mayor (b) y un factor de concentración (FC) de 2,46, se empleó herramienta Solver de Excel para calcular las dimensiones fundamentales óptimas: ángulo de la generatriz (α), altura del cono (h) y diámetro menor (a), para los cuales se logra una concentración deseada. Además, se calculó y diseñó concentrador troncocónico gráficamente en Mechanical Desktop 6 Power Pack, a partir de un cono unitario acorde a domo activo anteriormente señalado. Finalmente, se construyó modelo a escala 1:100 para medir la iluminancia bajo condiciones de cielo abierto y controladas, empleando sensor de temperatura y foto detectores con rangos de $0 - 130\,Klx$, encontrándose un FC de 1,78 a cielo abierto y de 1,89 con una lámpara de halógeno en condiciones controladas.

Luz solar, Concentrador, Domo, Iluminancia, Optimización

5.1 Introduction

Most human and biological activities on earth are governed and powered by the sun, as the sun has been a source of illumination throughout human history. The development and use of efficient artificial lights has led humans to separate themselves from the healthiest and best source of illumination: natural light. Studies have shown the benefits in health, safety and labor productivity when buildings are naturally illuminated (Roche, 2000). In addition to the quality of natural light, another reason to use it is its compatibility with lighting control systems to achieve a reduction in the use and cost of conventional energy, thus achieving a sustainable system.

Undoubtedly, sunlight is beneficial inside facilities that house living beings (air quality, non-toxic materials and occupant health) (Gissen, 2002), but the use of artificial light during daylight hours is paradoxical, since there is an abundance of natural light for illumination (Muhs, 2000). Consequently, although artificial light provides sufficient levels of illumination, it cannot provide physiological and psychological comfort (Brainard & Glickman, 2003) (Jenkins & Munner, 2003:2004), benefits of natural light. However, transporting natural light into the facility is sometimes not possible with simple windows and/or domes. Solar concentrators coupled with light pipes are passive systems and represent a simple solution to the problem of natural light deficiency.

In order to transport natural light from the exterior to the interior of a physical space, lumiducts, which are simple structures that allow the transmission of natural light, are being used; there is currently a considerable increase in the use of this technology, with an estimated three million ducts installed worldwide (CIBSE, 2003). Generally, they consist of a collector (usually a hemispherical polycarbonate dome), the duct itself and an emitter. The design of lumiducts has different geometries and improvements and updates are constantly being made, Carter (2002) and Jenkins (2003:2004), used aluminum coated ducts (96% reflection), to such a degree, the light is transmitted in a specular (transparent) way. There are reflective films developed by 3M with a reflection index between 98 and 99%, so that the light is totally transmitted towards the interior. Each innovation made to lumiducts increases their efficiency, but it is important to verify the reliability of this efficiency and its pertinent technological application, hence the importance of corroborating and generating methodologies to quantify the illumination levels achieved (Mohammed & Carter, 2006). Callow (2003), pointed out the benefits of the use of natural light, both for the health of human beings and the world, as well as the reduction in the use of fossil fuels and greenhouse gases. Goulding, Lewis and Steemers (1994), focus their attention on the costs associated with the use of natural lighting inside buildings, as well as the fact of increasing its use.

There is work on the coupling of concentrators with optical fibers (Jutta Schade, 2002) (Hansen, Sato, Ruedy, Lo, Lea, & Medina-Elizalde, 2006), but they have disadvantages due to their high cost and low performance in light transport. On the other hand, commercially and physically, lumiducts are of considerable dimensions, which can hardly be adapted to small spaces and section changes (Jenkins & Munner, 2003:2004).

5.2 Benefits of daylight in buildings

It is a fact that, when it comes to illuminating a visual task, human beings prefer natural light to artificial light or electric light. Light coming from the sun has a perfect color rendering and brings very proactive elements in people's behavior. In addition lower electricity bills and healthier working conditions could be achieved by making better use of daylight. "Numerous studies show that living and working for long periods in areas that receive low levels of daylight disrupts a number of biological cycles" (NewScientist, 2008). Daylight falls broadly into the category of energy efficiency, as it does not generate energy, but reduces the demand for it. The amount of energy demand generated by the use of electric lights is considerable and gives the possibility of significant daylight savings. Peak demand for electric lighting occurs at the same time as low daylight availability.

An additional savings associated with daylighting is a reduction in the cooling load for air-conditioned buildings. Because the luminous efficacy (number of lumens per watt) of natural daylight is higher than most artificial light sources, few radiant watts of energy are required for a given level of illumination. In an office building with artificial lights on, it generates a considerable percentage of the heat that needs to be removed and the overall savings with daylighting are significant (Bodart & De Herde, 2002). Although it has been proven many times that the use of daylight reduces electricity consumption, and automated controls are available for the transition from artificial to daylight, it still generates distrust among users. This is because a gradual changeover between the two sources by means of dimmers is necessary.

A form of artificial energy saving, which is taking a lot of strength to optimize the use of energy in artificial sources is intelligent lighting, which provides quality lighting in a very efficient way, helps reduce the price in bills and maintenance costs, in addition to helping to care for the environment and provides a more comfortable life and generates a quiet environment, but even so natural lighting could never be replaced.

An efficient lighting system is one that satisfies visual needs, generates healthy, comfortable and safe environments, makes adequate use of technological resources such as luminaires, optical systems, to mention a few, and makes rational use of energy, which helps to minimize the ecological and environmental impact. Facing the challenge of sustainable development, where non-renewable resources are diminishing rapidly, a fundamental change is needed in the way we use them. It is necessary to act and promote the use of alternative energies in our modern life to reduce the consumption of fossil fuels and therefore to slow down or stop global warming.

Finding a sustainable balance of world life is a challenge today, with a great decrease of resources, this is a primordial call for a change of idea and the conservation of these resources.

5.3 Natural light in agricultural engineering

In agricultural constructions such as greenhouses, Figure 5.1, light is a determining factor for production. However, there is great confusion about the terminology of the radiation factor, since in practice, the application of this knowledge has not been explored, so it is an area of knowledge that presents many opportunities.

It is therefore necessary to consider the implementation of technological strategies to maintain the amount of light at levels not lower than 200 Wm^{-2}, since the average amount of light required by crops ranges between 120-180 Wm^{-2}.

Figure 5.1 Natural light inside a greenhouse

Source: (Melgarejo Moreno, Navarro Quercop, Legua Murcia, & Lidón Noguera, 2002)

Each type of plant requires a different light intensity. The intensity (or quality) of light is difficult to measure without a lux meter, which measures in units of lux. A value of 100 lux or less is usually considered "low intensity" or "indirect" light. A bright office has an illumination of approximately 400 lux. On the other hand, a value of 1,000 lux or more is considered "high density" lighting. Direct sunlight outdoors is on the order of 32,000 to 100,000 lux.

5.4 Quality of light

A balance of light in the entire PAR (photosynthetically active radiation) range shows us the range visible to the human eye, which is the one we are interested in studying in this work, as shown in Figure 5.2.

Numerous researches in the area of light modify the spectrum to improve plant growth. Diffuse light is better than direct light, as it is able to reach the lower parts of the canopy (less shading), and will not cause sunburn. Regardless of whether the light is direct or diffused, it should be of sufficient intensity (lux). The selected coating material can also be used to increase the amount of diffused light. A texture to the glass surface, for example, can increase the proportion of diffuse light, without much reduction in the level of transmitted light. On a cloudy day, most of the light is diffused.

In plant growth control or photomorphogenesis, there are 5 concepts related to ambient radiation:

1) Quantity of radiation.

2) Quality of radiation.

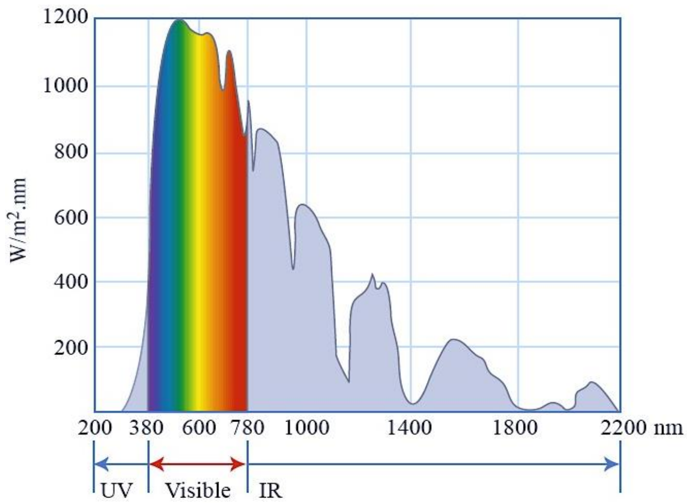
3) Direction of radiation.

4) Duration (time and transition of light and dark).

5) Polarization (arrays of different photoreceptors).

Of these only 1 and 4 are used for design and management decisions.

Figure 5.2 Light spectrum in the PAR (photosynthetically active) range



Source: (Comisión internacional de la iluminación , 1993)

5.5 Intensity of the light

Plants have an optimum light intensity. This is the point at which the process of photosynthesis is at its maximum and plant growth is at its highest. If the light level is lower, growth is reduced. In chrysanthemums, a light level of 4 000 lux is sufficient to equalize the rate of photosynthesis and the rate of respiration. This is known as one-point compensation light. At this point, there is no growth, but the plant can survive.

The point at which an increase in light intensity does not increase photosynthesis any further is called saturation light. In many crops, a top leaf saturates around 32 000 lux. However, due to shading on lower leaves, light levels of around 100 000 lux may be needed throughout the plant to become saturated light. In a greenhouse, light intensity can range from 130 000 lux on a clear summer day to less than 3 000 lux on cloudy days.

5.6 Light level in livestock activity

Among the biological activities that living beings perform throughout their lives, those that occupy most of it, not only in time but also in space, are work, production, rest, among others. In this sense, these activities, in order to be developed in an effective way, require that light (environmental characteristic) and vision (personal characteristic) complement each other, since it is considered that 50% of the sensory information received by animals is visual, that is, it has light as its primary origin, and in the case of plants it is required to carry out the photosynthesis process. The integration of these aspects will result in greater productivity, comfort and safety in an efficient and effective manner.

The light intensity experienced by animals housed close to the source can differ markedly from that experienced by others farther away, because intensity is inversely proportional to the square of the distance from the light source.

There are few studies on the effect of light quality or light spectrum on animals. It has been found that the lighting in rooms where animals are housed should have as much as possible the characteristics of sunlight.

Photoperiod is a set of processes that allows plants to regulate their biological functions by using the number of hours of light throughout the year. Photoperiod influences seasonal changes, the breeding season of various species, bird migration, plumage coloration of some birds and the fur of some mammals. It is probably the characteristic of light that most influences animals, in humans, being exposed to very abrupt changes of light, in terms of intensity and wavelengths, this photoperiod has been losing strength, even when working in natural light, generates more visual comfort and improves their quality of life.

It has an influence on circadian rhythms found in biochemical, physiological, and behavioral aspects in animal models stimulated and synchronized through the neuroendocrine pathway. The circadian cycle may affect the animal's response to drugs or its resistance to inoculated infectious organisms (Mcsheehy, 1983). The light/dark relationship may affect reproductive performance and sexual maturity. It is believed that if a change occurs in an animal's photoperiod, experiments should not be performed on it for at least one week (Davis, 1978). If the light period is interrupted by darkness, there are few important effects; conversely, if the reverse occurs, endogenous rhythms may be significantly affected.

Table 5.1 Specific environmental lighting considerations *

Species	Illuminance [Lx]
Cattle	215 - 538
Rams	538
Pigs	500-1000
Horses	200-800
Poultry	10-35

Source: Canadian Council for Animal Welfare (CCPA)

5.7 Light transport systems

Basically, there are two main groups of innovative devices for transporting natural light: Light Conductor Systems and Light Transporter Systems. The former, although very efficient in redirecting sunlight over considerable distances into the interior of spaces, hardly reach more than 10 m, so for longer distances it is necessary to use systems that transport the light to the heart of the buildings.

Providing natural lighting to all interior spaces is not always possible with traditional strategies (side windows) and therefore new natural lighting strategies have been incorporated, such as lumiducts.

Lumiducts are reflective internal wall ducts that, through successive reflections, transmit light to the interior of homes and buildings that normally require artificial lighting during the daytime period. Although the reflective materials convert part of the visible radiation into heat, the high luminous efficacy of the solar radiation allows high luminous fluxes to be obtained at the exit of the ducts.

These systems for transporting natural light through ducts with a reflective internal surface are used when a room has no possibility of receiving natural light because it has no wall exposed to the outside or because the natural light that enters is considered insufficient.

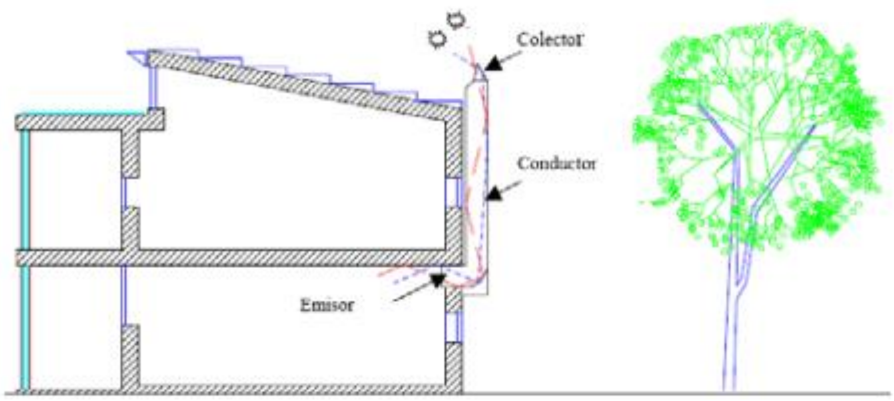
The main function of light transport systems is to transfer the external light resource to an internal emitter. The transport system can be divided into different types, the most basic form being a simple empty cylinder along which a collimated light beam can travel. Mirrored ducts, for example, are a system where the light is guided using the reflectance of the mirror surface to reflect and diffract the light to a required distance, likewise the surface can be another reflective material. As mentioned above, this system consists of three main components, as shown in Figure 5.3:

1. Collector, which can be a concentrator, heliostat, mirror or transparent dome.

2. Duct, the light transport system,

3. Emitter, an element for diffusion or distribution of light into the interior spaces.

Figure 5.3 Design of lumiduct (with indication of its components)



Source: (Melgarejo Moreno, Navarro Quercop, Legua Murcia, & Lidón Noguera, 2002)

5.8 Optical geometry

Considering a typical optical system with input aperture A_1 and output aperture A_2, light enters the system within a cone defined by $\pm\theta_1$ and output within $\pm\theta_2$ measured with respect to the optical axis (Figure 8.1). The radiance of light, L, is the flux per unit solid angle Ω, per unit projected (Welford and Winston, 1989; Sizmann and et. a 1990; Siegel and Howell, 1981). The incident flux over the top of a Lambertian surface is given by the area integral of the radiance and the projection of the solid angle.

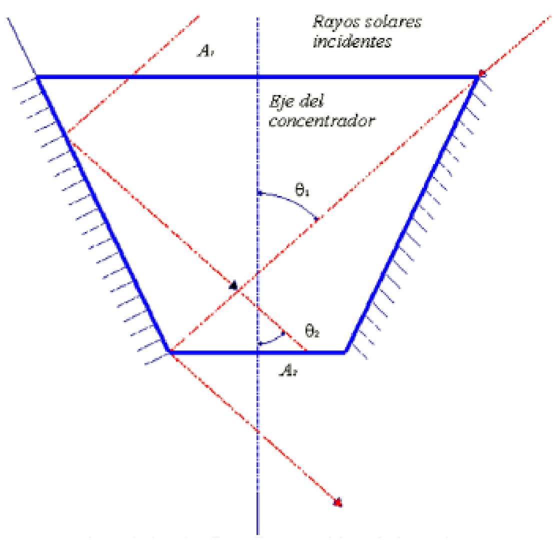
$$\Phi 1 = \int L1A1cos\theta d\Omega \ = \int_0^{\theta_1} 2\pi L1A1sin\theta cos\theta d\theta \ = \ \pi L1A1sin^2\theta 1 \quad (1)$$

A similar expression is obtained for the output aperture with subscript 2, the concentration C is given by the ratio of illumination over the output and input apertures.

$$C \equiv \frac{\frac{\Phi_2}{A_2}}{\frac{\Phi_1}{A_1}} \quad (2)$$

In a geometric system, the concentration is obtained by the conservation of the flow through the system, under the condition of $2 \ = \ L1$. This means that the area decreases, the divergence or angle increases for compensation (Welford and Winston, 1989; Sizmann and et. al. 1990; Siegel and Howell, 1981).

Figure 5.4 (Typical concentrator). Typical configuration of solar concentrators. Light incident on input area A_1 with $\pm\theta_1$ and output area A_2 with $\pm\theta_2$



Source: Author's own

This can be viewed as if the area were exchanged so that the angle determines the concentration. The maximum geometric concentration rate is given by:

$$C \leq \frac{sin^2\theta_2}{sin^2\theta_1} = \frac{1}{sin^2\theta_1} \quad (3)$$

Where the exit angle is normally taken to be 90°. If the concentrator is constructed in a medium with refractive index n, and the output plane is immersed in this medium it is necessary to modify the concentrator equation. The extreme ray Θ_1 is refracted to Θ'_1 in the concentrator, where $sin\,\Theta_1 = n\,sin\,\Theta'_1$, where from Snell's Law. For when the concentrator whose output is immersed in the environment with Θ_2, changes or is not refracted, the concentration is characterized by:

$$C \leq \frac{sin^2\theta_2}{sin^2\theta_1} = \frac{n^2 sin^2\theta_2}{sin^2\theta_1} \quad (4)$$

For convenience, the concentration is defined by a maximum external angle of incidence Θ_1 and a final angle of departure Θ_2 . It follows that for a passive system. This means that the traversal within a medium with high refractive index, the radiation is confined to a small solid angle, and thus we would have the maximum radiance (Seigel and Howel, 1989; Born and Wolf, 1975). For a 2D system, where light is reduced to one direction, the concentration is the square root of the 3D value.

There are many image-forming concentration systems, such as fresnel lenses and parabolic reflectors, whose concentration obeys equation (4.4) for a factor C=4 (Welford and Winston, 1989; Gleckman, et al., 1989). Both are particular cases, since they partially transfer the image of the sun at its exit and the exit angle is less than 90°, thus obtaining the maximum luminous fluxes.

5.9 Method

Among the biological activities that living beings carry out throughout their lives, one of the activities that occupies most of it, not only in time but also in space, is work, production, rest, etc. In this sense, these activities, in order to be carried out efficiently, require that light (environmental characteristic) and vision (personal characteristic) complement each other, since it is considered that 50% of the sensory information received by animals is visual, that is, it has light as its primary origin, and in the case of plants it is required to carry out the photosynthesis process. The integration of these aspects will result in greater productivity, comfort and safety in an efficient and effective manner.

An optimization problem consists of finding those values of certain variables that optimize (i.e., make maximum or minimum, as the case may be) a function of these variables. The best known method to find the optimum of a function is through the analysis of its derivatives. This method has two limitations: the function is not always derivable, and, in addition, the optimum does not always give us a solution that makes sense in practice. The complexity of this method converged in the so-called numerical methods, added to this the programming in different languages made the process simpler, so the tool we will use to achieve this optimization will be Solver, popular because it is in Excel and easy to use.

First the objective function subject to be optimized (angle of the truncated cone generatrix α, see figure 9.1; which contains the parameters or variables to be determined (height of the cone ((h)) and minor diameter of the cone (a) and the constant parameter (major diameter of the cone ($b = 1181{,}1mm$), then it is expressed by:

$$\alpha = tan - 1\,[2h/b - a]$$

Once the objective function is established, it is subject to the following restrictions:

$a > 0\,mm;$

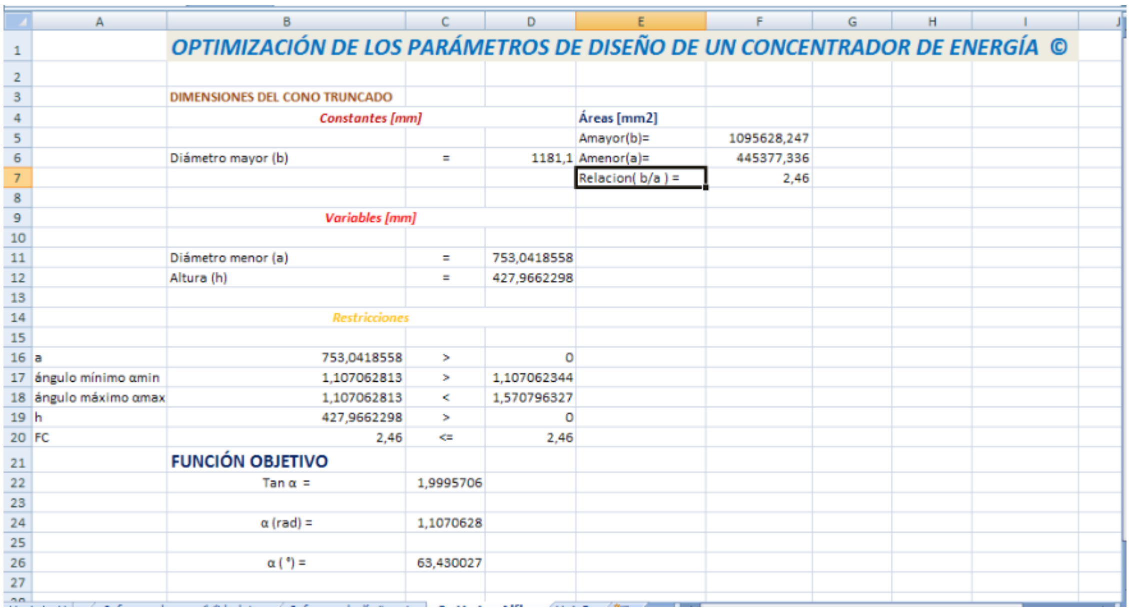
$h > 0\,mm;$

$\alpha min = 1{,}107062344\,rad;$

$amax \ = \ 1,570796327 \, rad \ y$

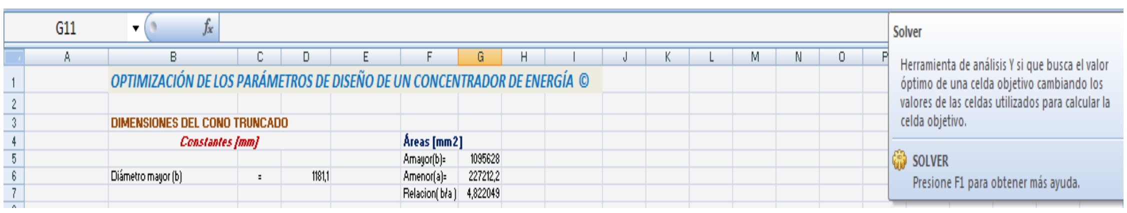
$FC \ = \ 2,46$

Figure 5.5 Definition of initial design parameters for optimization



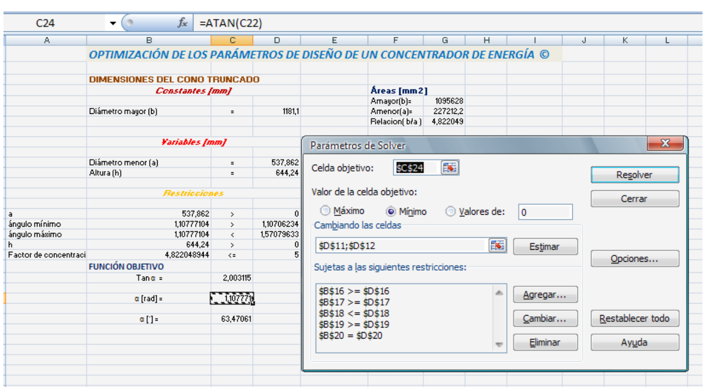
The constraint values of $FC, \alpha max \ y \ \alpha min$ were determined graphically using the geometry of a cone in Mechanical Desktop (Figure 9.1). Once these values have been defined and set, the Solver tool is accessed from the Data menu bar and then Solver, see Figure 5.6.

Figure 5.6 Access to the Solver tool



The following window will appear containing the following characteristics, as shown in Figure 5.7:

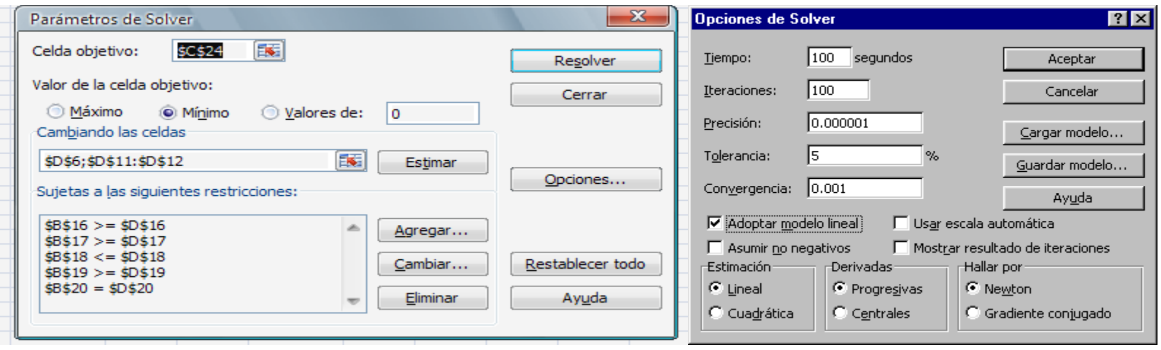
Figure 5.7 Definition of a and minimum h according to restrictions



In the target cell parameter the cell containing the target function $\alpha \ = \ tan - 1 \ [2h/b - a]$, will be entered, valued with proposed constant starting values: $b \ = \ 1181,1$, the constraint of $FC = \ 2,46$ and for the variables a and h possible starting values are assigned. The required function is selected, whether it is the calculation of a maximum or a minimum.

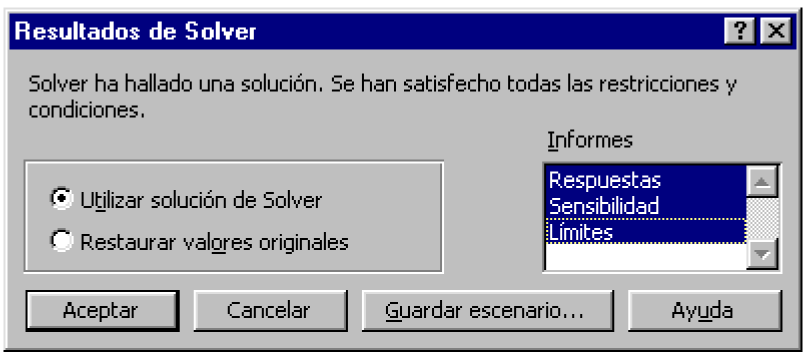
The cells containing the values of the variables to be optimized (a and h) subject to the above-mentioned constraints (Figure 9.3) are entered in the estimation point. In the Add section, the constraints to which they are subject are defined (Figure 5.8).

Figure 5.8 Parameters and Solver options



Once these data are entered, select Solve, and Solver, if everything is OK, will display, the data of the optimal a and h variables and 3 reports, one of Answers, one of Sensitivity and Limits of the solution found that satisfies all the given constraints and conditions (Figure 5.9).

Figure 5.9 Solver results



To determine the permissible angles for all the rays that fall vertically on the truncated cone concentrator to enter it and then the duct that will transfer them to the interior of the physical space to be illuminated, the graphic design method was used, starting from the geometric characteristics of a cone such as: angle of the generatrix, diameter of the base and height, and once this is truncated, the optimal smaller diameter (equal to the diameter of the duct) is obtained, all this supported by the CAD Mechanical Desktop 6 Power Pack software.

Then we proceeded to build a scale model to concentrate and transport light through luminous pipelines with energy concentrator, so the necessary materials are:

- Physical space.
- Portable computer equipment.
- Physical components to generate prototypes: passive and active dome, tube, extractor, aluminum foil light concentrator and accessories.
- DB-526 Multilog datalogger.
- Light sensors range 0-130 klx.
- Temperature sensors range -25 - 110 ºC.
- Software: Solver , Mechanical Desktop.

5.10 Results

The results obtained in the design of the solar concentrator are shown; we take as a starting point the largest diameter (*b* = 1181.1 mm) of the dome to calculate the fundamental dimensions: optimum angle of the generatrix (*α*), cone height (*h*), largest diameter (*b*) and smallest (*a*), for which an optimum concentration is achieved (Figure 5.10).

Using the Solver we have:

Figure 5.10 Report of responses

Celda objetivo (Mínimo)

Celda	Nombre	Valor original	Valor final
$C$24	α (rad) = <=	1,107062813	1,107062813

Celdas cambiantes

Celda	Nombre	Valor original	Valor final
$D$11	=	753,0418558	753,0418558
$D$12	=	427,9662298	427,9662298

Restricciones

Celda	Nombre	Valor de la celda	Fórmula	Estado	Divergencia
$B$16	a Restricciones	753,0418558	$B$16>=$D$16	Opcional	753,0418558
$B$17	ángulo mínimo αmin Restricciones	1,107062813	$B$17>=$D$17	Obligatorio	0
$B$18	ángulo máximo αmax Restricciones	1,107062813	$B$18<=$D$18	Opcional	0,463733513
$B$19	h Restricciones	427,9662298	$B$19>=$D$19	Opcional	427,9662298
$B$20	FC Restricciones	2,46	$B$20=$D$20	Opcional	0

In Figure 5.10, the response report is shown, we have that in Objective Cell appears the cell of the objective function (Figure 5.1) which is in cell C24, the Name, the initial value before optimizing and the optimal value (final value). In Changing Cells appear the cells of the controllable variables, the name, the initial solution or initial values of the variables and the optimal solution (final value), i.e. a in cell D11 with final value of 753.04 mm and *h*=427.96 mm in cell D12.

In Constraints we have: Cell value: it is the value taken by the left side of each constraint in the optimal solution (figure 1). Formula: reminds us of the constraints we have entered, including whether it is ≤, or ≥ . State: tells us whether the constraint is exactly met, with an equality, and there is no margin. In other words, it tells us if the constraint is active. Divergence: is the margin that each constraint has. If the inequality is ≤, then it is the right-hand side of the constraint (the constant) minus the left-hand side. If the inequality is ≥, then it is the left side minus the right side (the constant). If the constraint is active, then of course the margin will be zero.

In the sensitivity report (Figure 5.11) it shows: in the Changing Cells part the Value cell: reminds us of the optimal values of the controllable variables *a* and *h* cells D11and D12 respectively. Reduced Gradient: indicates how much the coefficient of the objective function should change for the variable to take a positive controllable value, in this case it is 0.

Constraints.

Equal value: is the final value taken by the left-hand side of each constraint in the optimal solution of a (cells B16), h (cell B19), FC (cell B20), α_{min} and α_{max} (cells B17 and B18 respectively). The constraints (cells D16-D20), indicate the right-hand sides of the inequalities to which the objective function was conditioned and which are satisfied.

Figure 5.11 Boundaries report

Celda objetivo		
Celda	Nombre	Igual
$C$24	α (rad) = <=	1,107062813

Celdas cambiantes			Límite	Celda	Límite	Celda
Celda	Nombre	Igual	inferior	objetivo	superior	objetivo
$D$11	=	753,0418558	753,0418558	1,107062813	753,0418558	1,107062813
$D$12	=	427,9662298	427,9662298	1,107062813	#N/A	#N/A

Changing cells

Value: reminds us of the optimal values of the controllable variables. Lower bound: is the smallest value that the variable can take (assuming that the others maintain the optimal value found), and satisfy all constraints. Objective cell (cell C24): value of the objective function if the variable takes the value of the lower limit and the others maintain the optimal value found. Upper bound: the largest value that the variables *a* and *h* (cells D11 and D12) can take (assuming that the others maintain the optimal value found) without violating the constraints. Objective cell: value of the objective function if the variable takes the value of the upper limit for variables *a* and *h* and the others maintain the optimal value found. Finally, the drawing of the final plane of the truncated cone concentrator with optimal parameters was made in Mechanical Desktop (Figure 10.3). All sun rays entering at b are concentrated and finally enter at a. The parameters of the truncated cone concentrator are shown in Table 5.2.

Table 5.2 Dimensions of the solar energy concentrator

Optimum parameters of the truncated cone concentrator			
b [mm]	a [mm]	h [mm]	α [rad]
1181,1	753,0418558	427,9662298	1,107

With the dimensions obtained, a concentration *FC*= 2.46 is achieved; if a different concentration is required, the values of *a* and *h* can be varied while maintaining the value of α. A 1:100 scale prototype of the concentrator covered with a reflective aluminum foil film (Figure 10.3) was built and placed on a closed cardboard box 300 mm long, 120 mm high and 150 mm wide. The external illuminance (*Ie*) [Klx] unconcentrated light, the internal illuminance (*Ii*) [KLx] concentrated light and the temperature (*T*) [ºC] were measured to determine the gradient inside the prototype.

Figure 5.12 Final design of the truncated cone solar concentrator

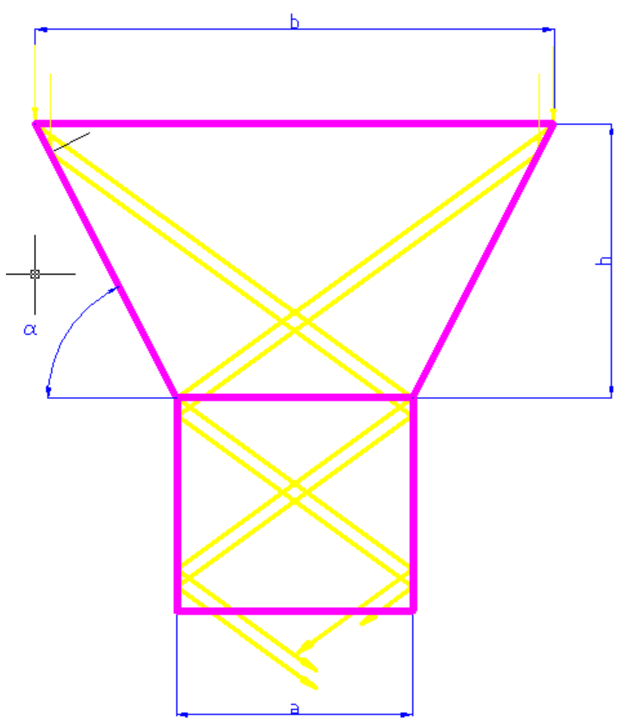


Figure 5.13 Scale model, concentrator and sensors

Figure 5.14 *Ie, Ii and T*, under controlled conditions

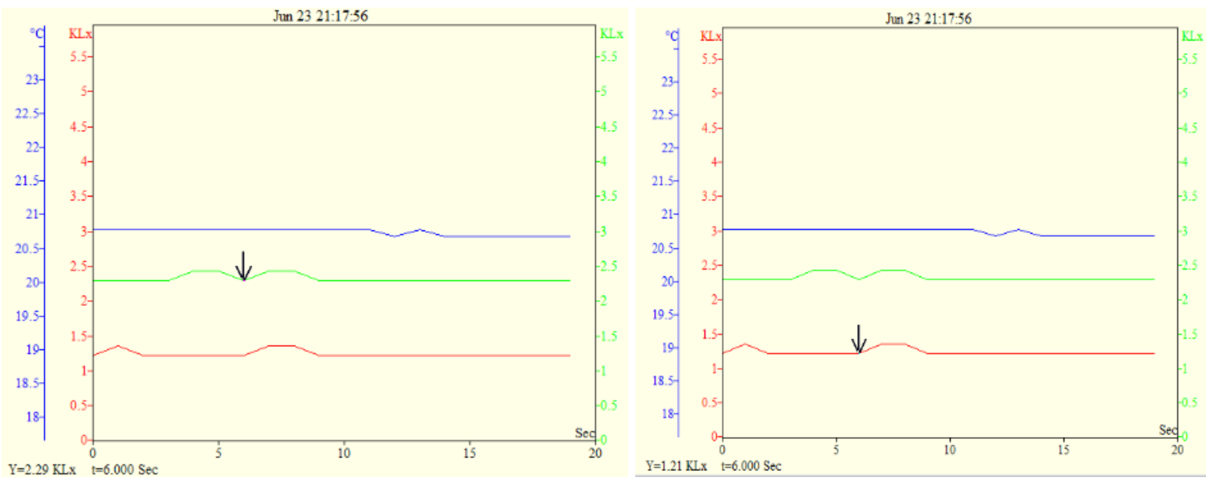


Figure 5.15 *Ie*, *Ii* and *T*, under open sky conditions

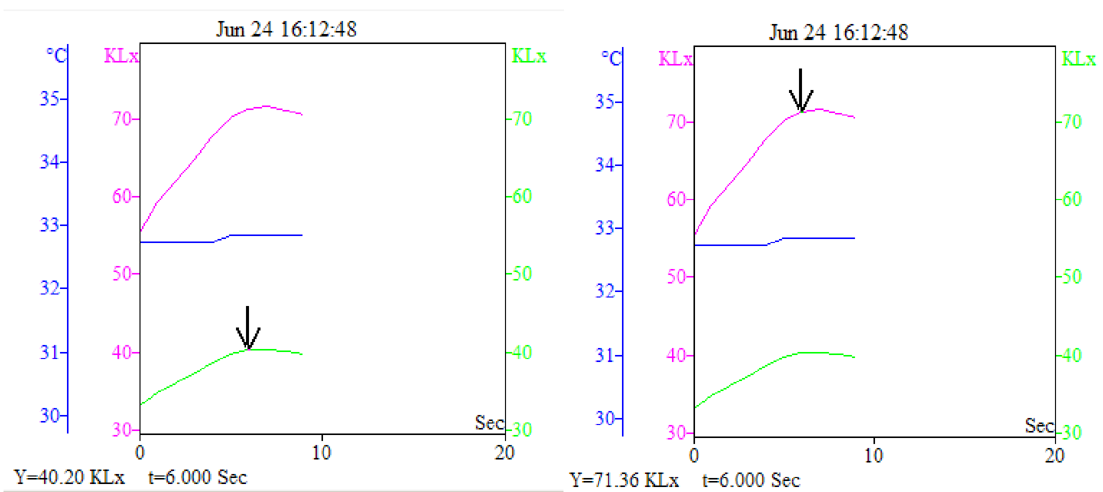
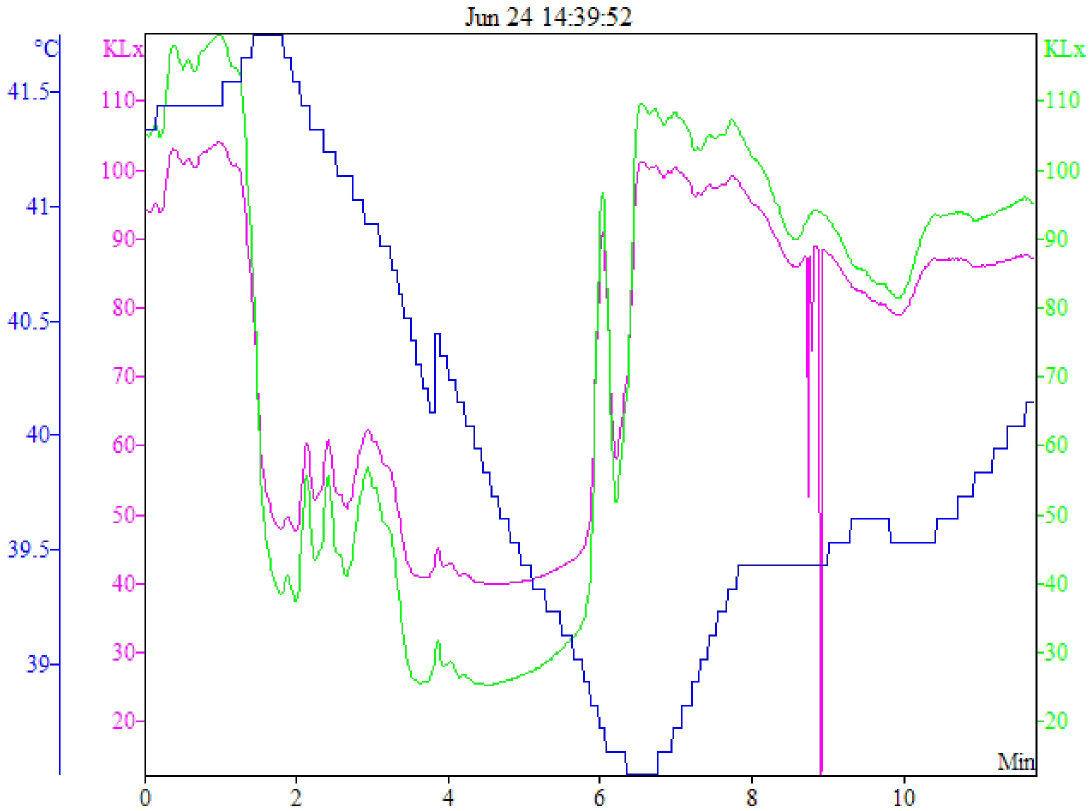


Figure 5.15 shows the behavior of the light under controlled conditions, using a 35 W halogen lamp, 120 V, 29 A and 60 Hz, with which an *FC*= 1.89 was obtained, considering the digital values at the base of the graph and indicated by the arrows inside the graph. The green line shows the value of Ii (concentrated light), Ie (unconcentrated light) in red and T in blue.

Figure 5.16 shows the values of *Ii* (concentrated light) magenta line, in green *Ie* (unconcentrated light), with which *FC* = 1.78 was obtained, as additional data in blue is observed the behavior of the temperature inside the prototype.

Figure 5.16 shows the behavior of the light over time, as well as the temperature gradient affected by the solar concentration inside the prototype. 15,000 samples were taken every second in total. A sampling time of 12 minutes is shown under combined sunny and cloudy sky conditions, i.e. direct light and diffuse light, so that for certain values of *Ii* (green line) is lower than *Ie* (magenta line), T (blue line), such situations should be studied in more detail, increasing the sampling time and determine the concentration ratio of the concentrator when there are open sunny-cloudy sky conditions where the values of internal and external illuminance change continuously. Additionally, a direct relationship is observed in the change of temperature (increase of 1 ºC on average) with respect to the increase and decrease of the illuminance values in the presented ranges of *Ie* = 94 - 102 klx and *Ii* = 105 - 130 klx.

Figure 5.16 *Ie*, *Ii* and *T*, under sunny - cloudy open sky conditions



5.11 Conclusions

A truncated cone solar concentrator was designed using computer tools to optimize the sizing, leaving: $b = 1181{,}1\,mm, a = 573{,}04\,mm, h = 427{,}96, FC = 2{,}46\ y\ \alpha = 63{,}43\,°$.

A scale model was built to measure the illuminance at the entrance and exit of the truncated cone concentrator covered with aluminum reflective film, with which it was possible to capture, transfer and diffuse concentrated sunlight at average ratios of 1.78 for open sky, 1.89 with halogen lamp, which are below the *FC* = 2.46, which would be the ideal according to the sizing of the concentrator, This shows that it is possible to achieve higher concentrations depending on the angle of the generator, the height and diameter of the exit section of the cone according to the desired illumination levels inside a building with deficient or no natural lighting.

5.12 References

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