A closed parabolic trough solar collector

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30th October 2007

Parabolic trough[1] is the most mature technology for large scale exploitation of solar energy. Several power plants based on this technology have been operational for years, and more are being built. However, the current technology suffers from a too high installation cost. This high cost makes it very hard to compete economically with fossil energy without government subsidies, compromising the perspective of using this technology to solve the problem of CO_2 emissions.

In this article, we study a design of closed-box parabolic trough concentrated solar collector. By accepting an optical loss of a few percentages due to reflections by the cover, this design offers several advantages over the current open model, in particular a potential of significant cost reduction.

In Section 1, we first make a rapid study of the actually dominant open parabolic trough design, to locate its main sources of cost, the problems facing it, and the potential of improvement.

The basic design of the closed collector is given in Section 2. It is a hermetic box with a transparent cover and the parabolic reflector forming the back. And the tracking of the sun is done by rotating (swinging) the box around the receiver tube which is fixed with respect to the ground. The advantages include a geometrically rigid structure leading to a considerable simplification of the construction (hence a reduced cost), and the protection of almost all optic surfaces, in particular the reflecting mirror (hence a lower mirror cost without durability problems).

Moreover, we can now adopt a tilted installation that reduces the seasonal variation of the output and improves the capacity factor of the whole system.

The closed-box model and the subsequent size reduction bring about several technical issues that must be dealt with. The most important one is the receiver tube that absorbs the solar energy and transforms it to heat to be carried out by a fluid. The current permanently sealed Dewar construction is not suitable for the smaller collectors, due to probable high price and high thermal losses that

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might counterbalance most of the advantages. To solve this problem, we propose in Section 3 a non-permanently sealed partially evacuated tube that is filled by a low-conductivity gas. While reducing the cost, this design also brings a solution to the problem of hydrogen and helium permeations.

Various other technical points as well as methods to determine concrete design parameters are given in Section 4. Some minor and obvious points are left over, and we have decided not to include the data for a concrete design in this paper, because the large number of parameter choices and their explanations exceed the scope of the paper which is first of all a study of the design principle. Interested readers can ask the author for more details.

An economic comparison with the current open parabolic troughs is made in the last section. It reveals an important advantage of the closed design, with the potential of dividing the levelized electricity cost by 2.

The design of a low cost thermal storage will be studied in another occasion.

No patent application will be filed by the author for the ideas described in the present document.

The author is grateful to NREL for the publication of many precious technical data concerning the current parabolic trough design, without which the present study would be impossible.

1   Cost analysis of current collectors

The currently dominant design of parabolic trough for solar power plants is the one developed by the now defunct Luz during 1980s. The common feature of the several versions of this design is a long parabolic cylinder of $5m$ wide or more, composed of large pieces of curved glass mirrors. The cylinder is constantly oriented towards the sun by an electronic tracking system, so that the solar radiations are reflected by the mirrors to a receiver tube located on the focal line. The tube carries a fluid that is heated by the concentrated radiations, and the hot fluid is used to generate steam and drive a Rankine engine.

The initial installation cost of these parabolic trough solar collectors constitutes the main ingredient in the final cost of electricity produced by the power plant. And the main sources of cost (over 80%) of the collectors are the following: the metal support structure, the parabolic mirror, the receiver (heat collector element, HCE), and the tracking system[3, page 4-10].

Metal support structure (29%)

This is the structure, usually composed of steel beams and rods, that gives and maintains the parabolic form of the mirrors.

Because the mirror itself is not geometrically rigid, the rigidity of the parabolic form wholy relies on the support structure. The technical difficulty is important due to the requirements on optical precision and wind resistance.

Despite the heavy structure (up to $20kg$ per m^2 of opening), material is only a very small fraction of the total cost. This structure needs careful design, and has to be assembled, installed and aligned on the field. All these explain the high labour cost.

The potential for cost reduction, under the current basic design, appears to be quite limited [3]. We just remark that increasing the trough width will probably increase the technical difficulty and the cost of the structure. Decreasing the width decreases the material cost, but before the width is small enough to allow the assembly and alignment to be carried out in a factory, labour cost will probably increase first.

Mirror (19%)

The parabolic mirror is pieced up from several curved glass mirrors fixed on the support structure.

Again, it is the production cost that largely dominates, with the obvious technical difficulty of forming the curved glass with precision. This part should be mostly independent to the size of the trough. However, bigger mirrors are harder to get precise. From many parabolic trough photos, one can easily distinguish the extent of the imperfection of the mirrors ([1]: look at the irregularity of the reflected light in the image). This inevitably limits the concentration ratio and the efficiency of the collector.

For various attempts of alternative mirror designs, a frequent problem is the durability of the reflectivity under the hostile environment with all possible weather conditions.

HCE (20%)

The receiver collects the solar radiations reflected by the mirror, and transforms the energy into the heat conveyed out by the heat transfer fluid (HTF) that flows in the inner tube. There is an outer glass tube and an evacuated annular space between the two, for the purpose of thermal isolation.

It is the most sensitive part of the trough, with two main difficulties: the selective coating with maximal absorptivity and minimal emissivity, and the metal to glass hermetic sealing to maintain the vacuum between the two tubes.

The HCE is also a huge maintenance problem, with its high rate of failures, leaks and breaks.

The cost of the selective coating, as well as radiative heat loss, should be independent to the size of the trough. On the other hand, the cost of the sealing will clearly increase if the size of the trough is decreased. Conductive heat loss will also increase with decreasing size (see the section on the receiver).

Tracking system (controler and drive, 13%)

It is the mechanism to constantly maintain the orientation of the mirros towards the moving sun.

This part clearly has a huge cost reduction potential. The electronics of the controler is probably of old design; a new design based on recent microcontrolers, together with some reprogrammation, may cut the controler cost to near 0.

For the mechanical driver, it suffers from the design choice that made the rotation axis at a long distance of the center of gravity of the rotating object.

This item is often cited as the main obstacle to the size reduction of the trough. This might be true at the early days, but with a proper microcontroler design, this should no longer be the case.

Discussions

There are some other shortcomings, such as a weak wind resistance, an important seasonal variation of the output, etc.

The possibilities of local improvements of the basic design of open parabolic troughs have been studied by many people, and the potential appears limited due to heavy technical difficulties.

However, for the parabolic trough solution to become economically competitive, important cost reduction beyond that of local improvements must be realized. Only a fundamental redesign of the system has a chance to achieve this level of cost cut.

The method of linear fresnel reflectors claims a better cost level[24], but several problems of the parabolic trough are inherited, such as the seasonal variation and the troubles of HCE (with the added difficulty for its access within a big field).

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The optic precision and the concentration ratio are harder to improve, and mirror-to-mirror shading is quite serious despite the ingenious interleaving method. The problem of visual pollution due to the intrusive height of the tube must be dealt with for any installation near human activities. These factors limit the potential of this method.

2   The basic design

Now we give our proposition of a closed concentrated solar collector using parabolic cylinder mirror, our main objective being to achieve a significant cost reduction with respect to the above design.

Our starting point (Figure 1) is to add a cover (1) on the top of the parabolic cylinder (2). This reduces the optical efficiency due to surface reflections, but we will see that the advantages are much more important.

In order to put the receiver tube (4) under the cover, the rim angle[2, 8.2.1] of the parabola must be slightly more than $90°$, so that the width-to-depth ratio of the parabola is close to but less than 4.

And we can recover end losses with two reflecting sides (3). Now the parabolic cylinder, the cover and the two sides can be sealed together to form a hermetic box (hermetic except for the entrances of the receiver tube) as in Figure 2.
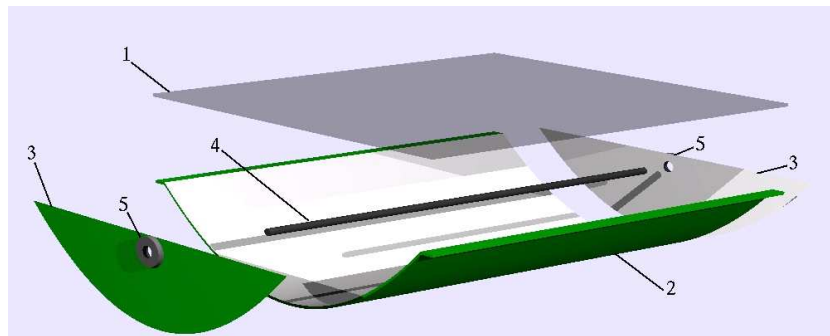

Figure 1: Pieces of the box

The tracking of the sun can be done by rotating the box around the receiver tube, the latter being fixed with respect to the ground. Bearings (5) are prepared for the rotation. A microcontroler module can be mounted on one of the two sup-
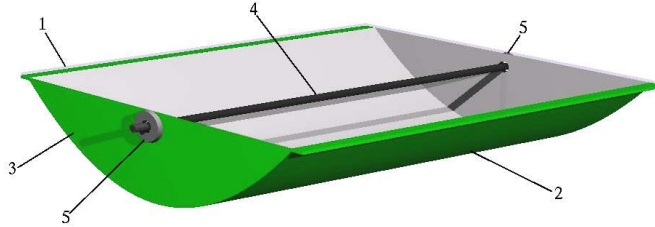
Figure 2: The assembled box

ports of the box, using signals given by two photocells in the box for the relative position of the sun.

The receiver tube (4) may or may not have a glass insulating tube around it.

This new design allows a significant reduction of the size of the trough without running into most of the problems facing the open trough if a similar size reduction is applied. The actual size of the box should be optimised according to the application's context (see Section 4). As a general rule, the optimal width of the box is between $0.6m$ and $2m$, with smaller width best suited for smaller installations and for lower operating temperatures. The length of the box is generally between 1 and 2 times of the width (or longer with a careful study of the strength and deformations), depending on the materials used and the requirements on the precision.

In order to minimize ground work, several boxes can be mounted on a metallic chassis to form a collector block, as indicated by Figure 3.

Advantages

The main advantages of this design are listed below. A detailed economic comparison is postponed to the last section.

1. The sealed box forms a geometric entity that is very resistant to various deformations. That allows the use of lighter materials, and can achieve a better optic precision.

2. The interior of the box is now a protected environment, that can be filled with either dry dust-free air or pure nitrogen to protect the internal optic surfaces. No dust, no corrosion, no cleaning, no scratching. This prolongs
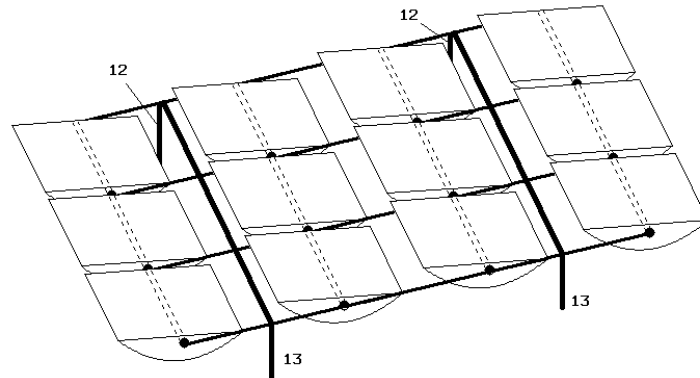
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Figure 3: The chassis

the life of these surfaces, and allows the use of high-performance and low-cost but vulnerable coating technologies. (See Section 4 for some details.)

3. The reduced and variable size of the box makes it suitable for a wide variety of applications, ranging from household water heater ($80°C$ with no need of insulating glass tube around the receiver), to small residential electricity and heat cogeneration stations ($250°C$ to $350°C$, with 20 to 2000 m^2 of collectors), and to large scale solar power stations with an operating temperature up to $400°C$. In all these applications, our configuration seems to have a comfortable economic advantage compared to existing solutions.

4. The reduced and configurable length of the rows of the box allows a north-south tilted installation where the north end (12) is higher than the south end (13) (Figure 3). When the tilting degree is equal or close to the latitude of the site, the incident angle of the sun is reduced to the minimum for all seasons. This represents a gain around 40% of productivity for unit area of collectors compared to the current long parabolic troughs, for installations with latitude between $30°$ and $40°$, which is the case of most current solar power plants [5, Fig. 5].
Moreover, the tilted installation considerably alleviates the severe seasonal variation of the output of the current long troughs oriented north-south, whose winter daily output usually drops to around 20% of that of the summer, while the demand on energy is often maximal[14]. For an optimally

tilted installation, the seasonal variation can be contained within the range of $\pm 15\%$. This also contributes to the cost reduction of the power block, via a significantly higher capacity factor.

It should be noted that it is harder to tilt a long trough, even if the field has a good slope. A $30°$ slope of the field induces $300m$ of altitude variation for a trough of $600m$ long, which generates an over-pressure of HTF over 20 bars at the lowest point of the circuit. This over-pressure requires stronger tubes and joints, generating extra cost.

5. Field alignment is no longer necessary. And as long as the chassis has a reasonable size, it can be assembled and tested in a workshop, reducing labour cost and the hardness of the work.

6. As the receiver tube is now fixed, the tracking of the individual boxes is totally independent, with no possible interference between adjacent boxes in a same row (distortion of the tube due to unequal tracking angles). Thus the tracking control is greatly simplified.

7. The solid structure and low profile offer a much better resistance to wind.

Inconveniences

It has also some inconveniences.

1. The cover brings about some loss of incoming radiations, reducing the optical efficiency. The loss is mainly due to reflection by the two surfaces of the cover, which amounts to 8% if the surfaces are not treated anti-reflection. Moreoever, this reflection loss will worsen when the incident angle (the angle of the sun with respect to the normal plane of the axis of rotation of the box) is greater than $40°$ [2, Fig. 8.29]. This wll be avoided by mounting the boxes in the south-north direction, with a tilting angle close to the latitude of the site.

2. The reduced size of the box multiplies the number of some parts whose cost may be multiplied. While the cost of the tracking system is not really a problem, the multiplication of the receiver tubes, with more sealings and more evacuations, risks to compensate all the advantages, even if the sealings are now easier.

   Another problem is the conductive thermal loss that do exist with evacuated

HCEs after a few months' service [6]. The reduction of the trough's width, with a proportional reduction of the HCE diameter, proportionally increases the thermal loss which will quickly become too important.

We will study the problem of the receiver in the next section.

3. The smaller primary HTF circuits need more interconnecting circuits to collect the fluid, increasing the circuit cost. But this part of the cost is marginal.

4. The solar radiations towards the space between two adjacent boxes is lost, representing a $5\% - 10\%$ loss of land use.

5. The much shorter rows of the collectors, required in particular by a tilted installation, need much more header piping to connect adjacent rows. This leads to some cost and pressure loss of the HTF. But this inconvenience is widely overweighed by the advantages of the tilted installation.

3   The receiver tube and the HTF circuit

In this section, we discuss an alternative solution to the use of totally evacuated HCE tubes. It only concerns high-temperature applications ($200°C$ or up). Water heaters don't need insulation at all, as the heat loss is very limited[1].

We extend the double concentric tube (pipe-in-pipe) configuration to the whole interconnecting circuit of the HTF, with a steel inner tube conducting the HTF, and an outer tube for air tightness. The outer tube can be plastic (except in the collector box), similar to the household water evacuation tubes. They are tightly connected to the outer glass tubes of the receivers. The sealing between the glass tube and the outer tube of the circuit is outside the heating area, so the temperature is sufficiently low to allow an organic air-tight sealing (e.g. caoutchouc).

Inside the collector box, the outer tube is transparent (usually borosilicate glass), with possibly coated surfaces. In particular, the possibility of coating the inner surface of the glass tube to reflect far infrared can be considered. This may help to contain the loss by emissions.

The annular space between the two tubes then forms a connected circuit that can be evacuated by a central vacuum pump constantly installed in the field. The basic idea is to install one vacuum pump for every one or two hectares of collectors.

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[1]The convective heat loss of the uninsulated tube is estimated to be around $30W/m^2$, which is equivalent to or less than the optic loss brought by an uncoated insulating glass tube.

The outer surface of the inner tube and the inner surface of the outer tube can be coated with a highly reflective material, to reduce the radiative heat loss within the circuit.

The cost of the vacuum pump, as well as its energy consumption, are negligible for any subfield of more than $1000 m^2$ of collectors, but a vacuum circuit length up to $100 m$ makes it impractical to expect a vacuum depth below $10 Pa$ (or $0.1 Torr$). This is not enough to suppress molecular heat conductivity of the remaining air in the annular space. In fact, at this level of vacuum the heat loss by conductivity just started to drop [6, Fig. 2], and a vacuum depth below $0.1 Pa$ ($10^{-3} Torr$) is required to totally eliminate this heat loss.

It should however be noted[6] that a totally evacuated HCE suffers from helium and hydrogen infiltration to the evacuated space with age. After a few months to a few years of use under high temperature, the conductive thermal loss grows to a level as high as $1/3$ to $1/2$ of that of a partially evacuated tube at best (when only helium infiltration occurs), but may grow up to much worse than a non-evacuated tube (when there is sufficient hydrogen permeation). According to [6, Fig. 2], we give the estimation of the conductive thermal loss of an aged HCE to be in the range of $17W$ to $35W$ per m^2 of collector, for a parabolic trough of $5.77m$ wide.

Now the conductive heat transfer in a concentric annular space is given by the formula

$$k = \frac{2\pi}{\ln(D/d)} k_m \; , \tag{1}$$

where d and D are the diameters of respectively the inner and the outer boundaries of the annular space, and k_m is the thermal conductivity of the material filling the space. In particular, the conductive thermal loss remains constant when both d and D change proportionally. Therefore for example by decreasing the width of the trough to $1.4m$ while keeping all the dimensional proportions including an aged HCE, the conductive thermal loss would grow to $70W/m^2 - 140W/m^2$, which would be too much.

To address this problem, there are several cost effective methods to reduce the conductive thermal loss for a partially evacuated tube.

1. Increase the width of the annular space. This will decrease k, but a too big value of D/d is not interesting due to the logarithmic function. Values of D/d from 2 to 4 can usually be considered.

2. Fill the residual pressure by a gas with low thermal conductivity. Some possible choices are listed in the following table. The value of k_m is for

$T = 250°C$, and k is computed for $D/d = 3$. both k and k_m are in $mW/m \cdot K$, and the cost is in euros per m^3 under atmospheric pressure.

Gas	k_m	k	Cost	Reference
air	42	240	0	[7, 8]
CO_2	34	194	0.2	[9]
argon Ar	27	157	0.5	[10]
krypton Kr	14	82	200	[11, 12]
xenon Xe	9	50	1000	[11]
iodine I_2	5	36	150	Rough estimation

I_2 has a very low conductivity and a sufficiently high vapor pressure above $30°C$, but its corrosivity must be checked. A lower cost of Kr than in [12] is put into the table, because here it is bulk low-quality Kr. It is also reported that the price of Kr is going down due to increasing demand (window filling).

Many other heavy gases may be interesting for this purpose, such as PF_5, $R227$, $R1216$, SbH_3, SeF_6, TeH_2, WF_6. But we have no data concerning them, especially the chemical stability.

3. For circuits outside the optical focus, partially fill the annular space by a porous insulating material, such as glasswool or perlite, as shown by Figure 4. Here 15 and 16 are respectively the inner and the outer tubes, and 17 is
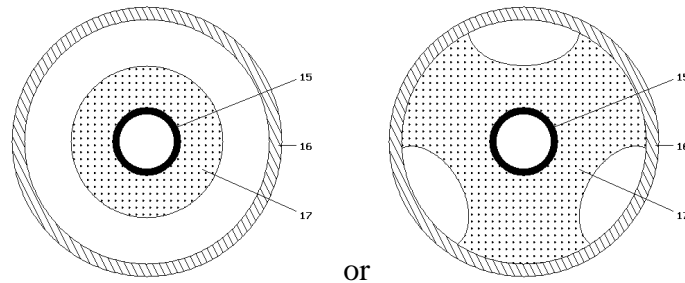

or

Figure 4: Glasswool insulation

the insulating material.

The glasswool offers a thermal conductivity $k_m \leq 5mW/m \cdot K$ under a partial vacuum of $30Pa$ or less [13, Fig. 4]. If Kr is used as filler gas, $50Pa$ should be enough.

Having the annular space filled by a gas with a residual pressure has an important advantage with respect to a totally evacuated space. That is, the low conductivity gas can "absorb" limited leaks and infiltrations into the insulating space without significant increase in thermal loss. It is easily estimated that impurities up to, say, 3% has only a marginal effect on the conductivity. The high molecular conductivity of helium or hydrogen will be blocked by the overwhelming big gas molecules. As the infiltrations are generally quite slow, a periodic refreshment of the annular space is enough to keep a constantly good insulation.

Now we make a simulation of a concrete situation, based on the following hypotheses. The box will be $1.5m$ wide, with a inner receiver tube of outer diameter $1.6cm$. The glass tube will be of $4.8/5.4cm$. And the annular space is filled by Kr with a pressure of $50Pa$. The operating temperature is $300 - 400°C$.

The concentration ratio is 94 times. Assuming a temperature difference of $250°C$ ($350 - 100°C$), the conductive thermal loss is $20.5W$ per meter of tube, or $14W$ per m^2 of collector surface. This is below that of an totally evacuated but aged HCE. And under the hypothesis of a heat flux of $600W/m^2$, the loss represents merely 2%.

Outside the boxes, there may be up to $0.6m$ of HTF circuit for each m^2 of collector. For this circuit, the conductivity is limited to $10W/m$ due to the isolating effect of the glasswool. So up to 1% should be added to the loss, making a total of 3%.

To estimate the cost of Kr, there is less than $2L$ of annular space per m^2 of collector. We need $1mL$ of Kr under atmospheric pressure to fill this space to $50Pa$, with probably another $1mL$ or so to chase out the remaining air in the space for a first time fillup. So the cost amounts to $0.02c/m^2$ per refill.

If there is a daily refreshment and if the Kr coming out of the vacuum pump is not recovered, the total cost of Kr during 1 year of operation grows up to $7c/m^2$, contributing to about $0.01c/kWh$ of O&M cost.

The real refreshment rate of Kr should be determined according to the leak rate in the space. For this, remark that helium permeation will never reach the 3% level, because its natural pressure is only $0.5Pa$. Data for hydrogen permeation rate are missing, although the fact that a small getter in the current HCE can last several years suggests that hydrogen buildup needs at least a few hours to affect the thermal loss.

It remains the leak of air from outer tube sealings. Tolerance for air can grow to 10% in the filler gas, or $5Pa$. This corresponds to one leak of $10^{-3}Pa \cdot L/s$ in every $15m$ of circuit, which is rather enormous. Therefore air leak is not a big problem.

On the other hand, if the vacuum circuit length is limited to $100m$, a central vacuum pump needs only less than 10 minutes to pump to the depth of $50Pa$ for all the collector circuits within a subfield covering a few hectares. Thus the frequency of the filler gas refreshment may go up to several times an hour, or even become continuous during production period, should the hydrogen permeation be too fast.

Of course, if the refreshment frequency is more than once a day with Kr or if Xe is used as the filler gas, equipment to recover the precious gas should be installed at the outlet of the vacuum pump. Ar needs no recovery even under continuous refreshment.

And if Xe or I_2 is used as filler gas, the glasswool insulation may become unnecessary. In such a case, a higher residual pressure can be applied for better absorption of leaks.

4   Some technical points

This is a new design, for which many technical aspects should be studied. Here we only include the most important ones; many other details are omitted in order to keep the paper within a reasonable length.

Optimising the size of the box

The basic dimension is the width of the box. Its optimisation is a compromise among conflicting factors.

Factors calling for a smaller width:

1. Material cost: lighter materials can be used to form the box.

2. Transportation cost: wider boxes are deeper, so assembled boxes take more space in the truck when transported.

3. Height of the installation: boxes with small width need less height when rotating. This is particularly important when the collectors are installed on a roof or a wall.

4. Wind resistance.

Factors calling for a bigger width:

1. Manufacturing cost.

2. Cost of accessories (controler, support, valve, chassis).

3. Conductive thermal loss in the tube.

4. Interconnecting circuit cost.

Once the width is fixed, the box can be as long as possible, with a length limit governed by the requirement of strength, wind resistance and geometrical deformations. In particular, most of the deformations grow with the square of the length, so in general it is not very practical to make a box whose length is much more than twice the width.

As a reference value, for household water heaters one may choose width from $0.6m$ to $0.8m$, and length about $1m$.

For large scale high temperature applications, boxes of $1.5m$ wide and $2m$ long are practical.

Many of the above factors are also valid in choosing the size of the chassis.

The concentration ratio

As usual, the concentration ratio r is defined to be the ratio of the width of the box to the diameter of the tube that absorbs the solar radiation.

The theoretical limit of r is a bit more than 200, as the angular diameter of the sun is a bit less than 0.01 radian [2, Table 2.1], while the maximal optic length of the reflected radiations in the box is half of the width. Such a ratio is unpractical, due to the very high precision requirement and the possibility of radiations hitting the receiver tube at small angles, reducing the absorption rate.

The interest in having an r as high as possible lies principally in the fact that thermal loss by emissions from the receiver tube is inversaly proportional to r. And if the glass insulation tube is not used, losses by conductivity and convection too.

For water heaters where the thermal loss is not an important factor due to the low working temperature, a range of r between 40 and 50 is recommended for a low manufacturing cost and a robust product.

For power plant uses with operating temperature up to $400°C$, we recommend the value of $r = 90$ for a first approach. This is slightly higher than the current open parabolic troughs ($70 - 82$), but the closed model is intrinsically more precise. The corresponding tolerance for the reflector surface is about $\pm 0.15°$ at the most demanding locations near the border.

Choice of material

There is no particular requirements on the material used to form the box, but for the usual qualities on cost, mechanical resistance and durability.

In general, steel or plastic sheets can be used for the back and the sides, and glass or transparent plastics (acrylic, UV-protected polycarbonate, etc.) can be used for the cover.

However, care must be taken for the thermal expansion rates of different materials. In particular, there is a big difference between the thermal expansion rate of the steel/glass and that of plastics, the latter being much more important. If the two are mixed, the box will deform when the environmental temperature changes, causing defocusing and loss of efficiency. So such a mixing has better be avoided when the concentration ratio is high.

A safe choice is steel sheets plus glass.

Geometric deformations

We just give an example to show the usual extent of the deformations. Take a box of $1.5m$ wide and $2m$ long, with glass of $4mm$ as cover and steel sheet of $0.5mm$ as back. We give an estimation of the deformation under a uniform stress of $500N/m^2$ applied to the normal direction of the cover: this is more than the maximal wind resistance level calculated below.

The depth of the box is about $40cm$. A rapid estimation gives a second moment of area of more than $1000cm^4$ of the section of the box in the normal direction of the cover. So with a uniform load of $750N/m$, the maximal deformation is $< 0.1mm$ and the maximal stress for the steel back is $< 15MPa$[22]. These values are negligible.

This load places an important stress on the glue that seals the cover and the back. This must be taken into account while choosing the glue and the sealing method.

The interior environment of the box

The breathing of the box should be prepared, that is, air coming into or out of the box due to thermal expansion or pressure variation of the environment. Air coming into the box must have dust control, in order to avoid accumulation of dust on the optic surfaces. And humidity in the box should also be controled to avoid condensation and subsequent damage to the optic surfaces, in particular the reflecting mirror.

For low-end uses such as household water heater, a rechargeable dessicant cartridge incorporating a filtered air passage (hole) will be enough. On the other hand, large-scale installations may consider controled filling of the collector boxes.

That is, the interior of the boxes can be filled to a slight overpressure ($50Pa$ or so), with air or gas supplied by a central equipment. The filling air may enter the box via the bearing around the entrance of the receiver tube, using the internal space of the rectangular beams forming the chassis as the distribution circuit, at no extra cost.

In general, dust-filtered, dehumidified and depolluted air will be enough. Active carbon can be used to remove most of the gaseous pollutants, and the flow rate is so small that one HEPA filter of $0.6m$ can meet the need of a field of 1 square kilometer.

Dust control is an important matter, because the box cannot be opened for cleaning. So we make a computation here of the dust accumulation to see what efficiency is required for the air filter.

For a box of width $1.5m$, the average depth is $27cm$, so there are $270L/m^2$ of air in it. Assuming an average daily peak-to-peak temperature variation of $15°C$, the daily air circulation is $13L/m^2$, or $5m^3$ per year per m^2 of collector surface. The accumulation for a life time of 20 years is $100m^3$.

The particulate quantity in air is around $25\mu g/m^3$ in the city and less than $10\mu g/m^3$ in the countryside[15]. So the volume of dust is about $10^{-11}m^3/m^3$, or $10^{-9}m^3$ in $100m^3$ of air, making an average thickness of $1nm$ when deposited on $1m^2$ of surface.

As the average particle size is well over $100nm$, the mirror surface covered by dust after 20 years of service is less than 1%.

With a simple filter that reduces the particulate quantity to $1\mu g/m^3$, the deposit will be less than 0.1%, which is negligible. While the HEPA filter has efficiencies of 99.97% or better.

Reflective coating

One can make a "first surface mirror", with a reflective coating (aluminium, enhanced aluminium or silver) directly applied on the interior surface of the parabolic back and the sides of the box, via vapor deposition or electroplating.

First surface mirrors must be protected against atmospheric corrosion (tarnishing). In our context, this can be done by a simple organic overcoat, such as 1-phenyl-5-mercapto-tetrazole (PMTA), benzotriazole, or a shiny polymer sheet.

Such a protection layer can last quite long without physical forces to scratch it. Together with depolluted filling, the durability of the reflectivity can be assured.

Inorganic (dielectric) protection may also be considered, with the particularity that we don't need a strong anti-scratching feature.

For high end collectors, silver coating is a very interesting choice because of its high reflectivity (more than 97%). The cost of silver is not important, as the thickness of the coating is generally about $100nm$, which takes only $1g$ of silver per m^2 of mirror, costing 0.3 euro at current silver price.

The biggest problem for first surface silver mirrors is tarnishing. The principal reason is the formation of silver sulfide Ag_2S by chemical reaction with molecules in the air containing sulfur, mainly H_2S and SO_2.

No data is found about the relation between the quantity of Ag_2S and the drop of reflectivity. It is a complicated matter depending on many factors. Here we put up a rough critical value of $0.5mg/m^2$ of sulfur, corresponding to a uniform layer of 1 molecule of Ag_2S. The drop of reflectivity is conjectured to be important but tolerable (around 10%).

The main source of sulfur in the air is SO_2 and H_2S. The average content of SO_2 in the air is generally less than $10ppb$ (parts per billion)[15], and still less for H_2S[16]. Taking other sources into account, we can assume that the sulfur content in unfiltered air is less than $20\mu g/m^3$. After an active carbon filter with an efficiency of 99% or more, the total quantity of sulfur that may enter into contact with the silver mirror during its life of service will be less than $20\mu g/m^2$, not enough to tarnish the mirror and reduce the reflectivity.

Of course, a protective layer of the mirror is always needed, if only to offer protection during the transport and the assembly, or to prevent damages due to accidental spikes of sulfur.

And the air distribution circuit must be checked against the possibility of sulfur recontamination.

Tracking

The sun's position with respect to the box can be detected by two photocells in the box, for example as in Figure 5.

Here the photocells (7) use the shades of the receiver tube (4) and a central bar (6) to detect the sun's position.

The signals of the photocells are sent to a controler module mounted on one of the supports of the box. When the box is misoriented, one of the photocells will
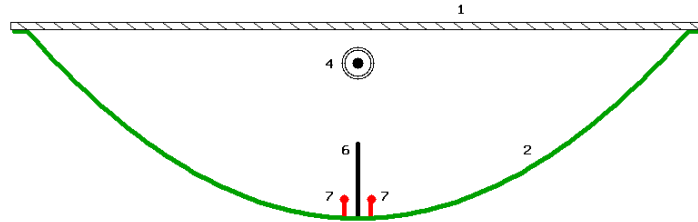
Figure 5: Photocells

receive more light than the other, which allows the controler module to detect the misorientation and rotate the box via a small motor.

The microcontroler in the controler module controls the rotation of the box according to the signals of the photocells and commands from the center.

The driving of the box can be done through an indented semi-wheel fixed on the side of the box. The linear speed can be limited to $1cm/$min, or $0.2mm/s$. And the maximal force is less than $500N$. Therefore the mechanical power is limited to $0.1W$, and a small motor of $1W$ will be more than enough.

Several boxes can share a same controler module, using mechanical links. But doing so will sacrifice some precision and wind resistance, while the cost savings are not obvious due to the low cost of the controler module.

Using a serial communication protocol, one communication line is enough for the communication between controler modules and between a controler module and the center. The communication lines of the controler modules can be connected in series, with each module relaying the communication to the next one.

In this way, electric cables linking the controler modules need only two wires, one for power supply and one for communication. The metal chassis can be used for ground.

More precisely, each command sent by the central controler contains an address word. Address $= 1$ means the first controler in the series of the communication line.

When a controler receives a command, it first looks at the address word. If the value is greater than 1, it relays the command to the next controler down the communication line, subtracting 1 from the address word. Otherwise, it executes the command and sends back a reply that will be relayed upstream to the center in

the same way, with a reply address added by 1 at each node.

And the value 0 can be used to send a broadcast command to all controlers in the line.

Details of the controler design and the communications protocol are omitted.

Wind and hail resistance

It is not hard to let the collectors to continue the operation under a wind of force 8 ($75km/h$). This corresponds roughly to a wind pressure of $27kg/m^2$[23] if the opening of the box is perpendicular to the wind direction. However, this opening is mostly highly inclined in reality, so we can take the value of $15kg/m^2$ as the limit of the operating mode. This is just the same as the weight of the box, if glass and steel are used to form it.

When the boxes are put to the rest mode, a much higher wind resistance can be achieved. In fact, for whatever direction of the wind there is a rotation angle so that the opening is parallel to the wind direction.

In practice, a mechanical resistance level of $40kg$ per m^2 of collector opening should be enough for a wind resistance up to $150km/h$ in the rest mode. This resistance level is easy to meet for the box itself. For the chassis with standard rectangular hollow beams, around $5kg$ of beams per m^2 of collector will be enough, if the chassis size is limited to less than $10m$.

Resistance to hailstorms is easy. One has only to put the boxes to an almost vertical position to minimize the hail impact.

Heat transfer rate in the HCE

Here we make a computation of the heat transfer efficiency between the receiver tube wall and the HTF. More precisely, we will see that this efficiency depends almost proportionally on the HTF velocity, by computing the temperature difference between the tube wall and the fluid, ΔT_f.

This computation is not specific for our design, but we give it here for the reader's convenience.

The HTF flow in the receiver tube is generally turbulent with Re $\geq 10^4$. In such a case, the Dittus-Boelter equation[17, 18] gives

$$\text{Nu} = 0.023\text{Re}^{0.8}\text{Pr}^{0.4} = 0.023 \left(\frac{\rho v d}{\mu}\right)^{0.8} \left(\frac{C_p \mu}{k}\right)^{0.4} \; ,$$

where the notations are as follows.

Name	Meaning	Unit
Nu	Nusselt number	-
Re	Reynolds number	-
Pr	Prandtl number	-
ρ	HTF density	kg/m^3
v	HTF velocity	m/s
d	receiver tube inner diameter	m
D	receiver tube outer diameter	m
μ	HTF dynamic viscosity	$Pa \cdot s$
C_p	HTF heat capacity	$j/kg \cdot K$
k	HTF thermal conductivity	$W/m \cdot K$
w	width of the trough	m

And the properties of some common HTFs are listed below.

Fluid	ρ	μ	C_p	k	Pr	$Pr^{0.4}$	Sources
water@$50°C$	988	0.000547	4181	0.6	3.81	1.71	[19]
Therminol VP-1@$350°C$	762	0.000178	2450	0.0867	5.03	1.91	[20]

By the definition of Nu, the (virtual) thermal film thickness is $\tau = \frac{d}{Nu}$, and the heat exchange surface is $\pi d l$ where l is the length of the tube, hence the convection efficiency is

$$\varepsilon = \pi k d l/\tau = \pi k l \mathbf{Nu}[W/K] .$$

On the other hand, the concentration ratio $r = w/D$ is around 50 for low-end water heaters and 90 for large scale high temperature applications, the usual value for D/d is around 1.15, and the heat flux is around $600W$ per m^2 of collector surface. Combining these, we get the temperature drop of the film

$$\Delta T_f = \frac{600wl}{\varepsilon} = \frac{191w}{k\mathbf{Nu}} = \frac{8304w}{k\mathbf{Pr}^{0.4}} \left(\frac{\mu}{\rho v d}\right)^{0.8} = \frac{9290w}{k\mathbf{Pr}^{0.4}} \left(\frac{\mu r}{\rho v w}\right)^{0.8} ,$$

or

$$\Delta T_f = \frac{aw^{0.2}}{v^{0.8}}[K] , \tag{2}$$

where $a = 2$ for water, and $a = 10$ for VP-1.

This formula means that ΔT_f is almost inversely proportional to the HTF velocity v ($w^{0.2}$ is very close to 1 in our case). For example, in order that $\Delta T_f \leq 10°C$, we must have $v \geq 0.13m/s$ for water, or $v \geq 1.1m/s$ for VP-1. Except that for water, we need a higher v to meet the condition Nu $\geq 10^4$. For example $v \geq 0.55m/s$ if $d = 10mm$.

Pressure drop and parasitics

The above computation gives a lower limit of v. Now we discuss the upper limit of v, and the question of how to configure the collector field in order to get the desired value of v.

In general, a collector field is composed of a number of parallaly connected primary HTF circuits, each of them connecting a certain number of collectors in series, as shown in Figure 6.
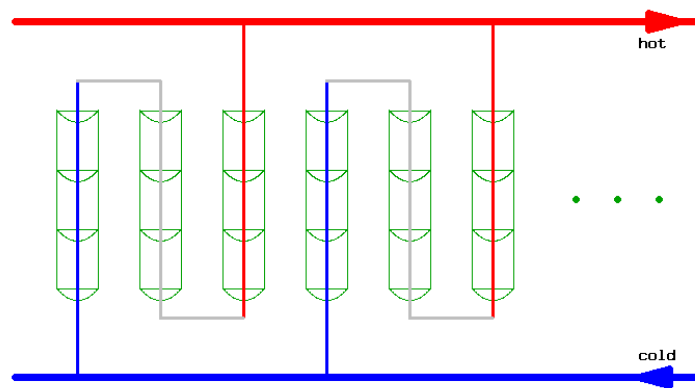

Figure 6: Primary circuits

It is clear that once the dimensions of the collector (width, tube diameter) are determined, the fluid velocity depends proportionally on the length of each primary circuit, and inversely proportionally on the temperature difference ΔT between the hot and cold ends of the HTF.

The fluid velocity leads to a pressure drop of the HTF, which a pump must compensate by consuming energy. This is a parasitic consomption which must be kept to a minimal level with respect to the amount of solar energy collected.

When ΔT is determined, the pressure drop is directly linked to the fluid velocity, hence to the length of the circuit. As a general rule, for a highly turbulent flow the pressure drop in a given length of tube is almost proportional to v^2. As a change in velocity is also accompanied by a proportional change in circuit length, the pressure drop is almost proportional to v^3.

This means that v should not be too important, unless ΔT_f is really too important. And the optimal length of the primary circuits is usually within a more or less narrow range once the other parameters of the system are fixed.

In order to get the relationship between the pressure drop and the parasitic consomption, let α be the value of pressure drop in Pa. The mechanical energy needed to compensate this pressure drop for $1m^3$ of HTF is αj. With an estimated efficiency of 25% for the pump (31% for the thermal-to-electricity transformation and 80% for electricity-to-mechanical work), this corresponds to $4\alpha j$ of thermal energy. On the other hand, $1m^3$ of HTF carries $\rho C_p \Delta T[j]$ of energy. Hence the rate of the parasitic consumption is

$$ P = \frac{4\alpha}{\rho C_p \Delta T} \ . \tag{3} $$

Now we give an example on the computation of v and the circuit length. We take $w = 1.5m$, $r = 90$, $\Delta T = 100°C$ ($400°C - 300°C$), with VP-1 as HTF, a classic situation of current parabolic trough power plants (except that r is slightly higher).

We have $d = 0.0145$, so the internal section of the tube is $A = 1.66cm^2$. The lower limit of $v = 1.1m/s$ given above corresponds to a flow volume of $183mL/s$ with a thermal flux of $35kj/s = 35kW$. As $w = 1.5m$, the solar energy collected is $900W$ per meter of collector length, so that the collector length should be $35/0.9 = 39m$. Adding 70% of header circuits, the total length of the primary circuit is $66m$.

With these data, the pressure drop on the circuit can is about $45hPa$[21]. According to (3), we have $P = 0.01\%$. This is negligible, and leaves quite some room for increasing v and improve ΔT_f.

Of course, this is only part of the pressure drop of the collector field. In general, in a big collector field a much higher pressure drop will take place within the interconnecting circuits, due to cost considerations.

On the other hand, we can, say, take the value of 0.5% as the upper limit of the pressure drop within the primary circuit. At this value (3) gives $\alpha = 2300hPa = 2.3bar$, corresponding to $v = 2m/s$, on a circuit of total length $120m$ among which $69m$ are within the collectors. For this value, we have $\Delta T_f = 6°C$.

So in practice, the primary circuit's total length can be anywhere from $66m$ to $120m$, with an optimisation taking other factors into account.

Leak detection

Leaks will inevitably occur in the circuits, and all leaks will go into the annular insulating space between the two tubes.

An important leak of air will reduce the insulation of the space and increase thermal loss. When the HTF (VP-1) leaks into the space, the latter will be filled by its vapor at a pressure at least equal to the vapor pressure of the coldest point of the outer tube. If this point has a temperature not less than $60°C$, the vapor pressure will be comparable to that of the filler gas, so the thermal loss will also increase.

Therefore it is possible to use a temperature sensor to detect the signs of a leak.

Thermal expansion of the circuits

For a working temperature up to $400°C$, the steel tube will extend up to 0.5% due to thermal expansion. This makes $3cm$ for a total length of $6m$.

Besides the classic method of using bellow tubes to absorb the thermal expansion, one can also increase the diameter of the outer tube and leave room for mouvement of the inner tube.

Interconnecting circuits

The long open parabolic troughs have primary HTF circuits of total length $600m$ or more, with a return in the middle. This configuration allows a pair of straight line connecting circuits to serve fluid for collectors in a band of width $600m$ or more.

The closed model has much shorter circuits, therefore a two-level interconnecting circuit system will be necessary.

A first level circuit connects the primary circuits. It usually will run north-south, and each circuit can serve a band of width around $80m$ ($40m$ at each side). As it is hard for the primary circuits to have returns, the cold and hot circuits at this level will run through different locations, in an alternating manner.

The length of the first level interconnecting circuit can be between $300m$ and $500m$, using pipes with internal diameter up to $13cm$. Each circuit can connect up to $20000m^2$ of collectors.

Then a second level interconnecting circuit collects the ends of the first level circuit. The technical requirements for this level is similar to the interconnecting circuit for the long open troughs.

Field density and alternating orientation

Current parabolic trough installations have field density around 40%, with something like rows of $5m$ wide troughs distanced at $12.5m$ from each other. The low density keeps the row-to-row shadowing to the minimum in order to maximize the use of the costly collectors, but increases the cost of the interconnecting circuits and land use.

In our new design, the collector cost is reduced, so the factors of interconnecting cost and land use become more important. Moreover, the tilted installation introduces a new north-south density that is related to the seasonal variation of the output. These considerations call for a bigger row-to-row (east-west) density, to the range of $50\% - 70\%$.

In this case, a mechanism of alternating orientation can be installed when the sun's angle is low, with every one in two rows oriented towards the sun, the other being put to a rest position. As shown in Figure 7.
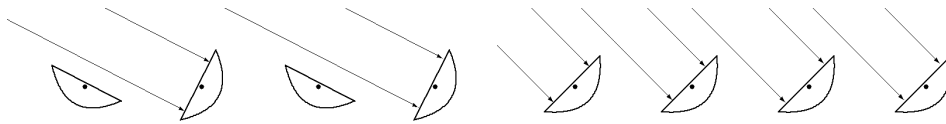

Figure 7: Alternating orientation of rows

5   Cost comparison

Here we make a preliminary comparison with the open parabolic trough design, for the case of a power plant application.

The designs are different. So we make the following correspondence table, which is a little bit arbitrary.

Open trough	Closed box
Support structure	Chassis
Mirror	Box
HCE	receiver tube
Tracking	Tracking

The other items have exact correspondences. This allows us to make a comparison on corresponding items, for unit collector surface ($1m^2$).

1. Support structure / chassis. The material weight and cost is divided by 4, and the labour cost is divided by an even higher rate. So the total cost will probably be divided by 10 or more.

2. Mirror / box. The amount of materials is comparable, as well as the manufacturing complexity. To the exception that the formation of a sheet is technically easier than forming a glass, so that more competition can be installed for the manufacturing of the box, driving the price lower. For the time being, we may consider the costs of this item to be equivalent.

3. HCE / receiver tube. The integrated HCE is now replaced by separated item tubes. The materials cost and the labour cost for connecting the tubes are very limited. And our price investigations indicate that the coatings (selective absorption and anti-reflection) are also of very low cost compared to the high price of the integrated HCE tubes. The installation cost advantage of this item should be more than 70% for the closed model.
   The added vacuum pump is shared by many collectors, so its price represents only a fraction of an euro per m^2 of collector. For O&M, the cost of filler gas renewal is negligible compared to the high failure rate and high cost of the integrated HCE.

4. Tracking. According to our industrial experience on microcontrolers, it is estimated that the microcontroler based control module for individual boxes can be had for a quantity industrial price of just a few euros. And it is used to control a box from $2m^2$ to $3m^2$ of collector surface. Adding wires and central controlers, the cost per m^2 of collector is at most 2 to 3 euros. The corresponding cost for the existing parabolic troughs is 10 times more.

5. Foundation work. The chassis now has a very low requirement on precision, to the point that esthetics becomes the principal precision consideration. And the lower profile reduces wind load. These will reduce the cost of ground work of the foundations.

6. Header piping. Corresponding to the sophisticated moving piece for the open trough, we have the header circuits connecting adjacent rows that run through the lower and upper borders of the chassis. These circuits use the pipe-in-pipe configuration based on common material. At $0.6m$ per m^2 of collector, the cost should not exceeed the level of 3 to 5 euros, which is less than that of the open trough.

7. Interconnecting circuits. The added level of interconnecting circuits adds to the cost, which is partly compensated by a denser installation. The pipe-in-pipe configuration may also be more expensive, but it is clear that the method will be applied only if the benefit (savings on thermal loss) overweighs the extra cost. So we can give an estimation of 40% overcost for the closed model, to be compensated by savings on the foundation and the header piping.

As for the collector efficiencies, the cover of the closed box brings a loss of 8%, part of which will be recovered by a silver reflective coating. And a bigger row-to-row density brings another $5\% - 10\%$ loss due to more row-to-row shadowing despite the alternating orientation method. The remaining efficiency factors are equivalent with minor and compensating differences. Therefore the closed box has an efficiency penalty of $10\% - 15\%$.

Combining the above, one can say that a division by two of the solar field installation cost for the closed model should be easy to obtain. As the solar field accounts for about 60% of the total installation cost of the power plant[5], this amounts to a 30% reduction of the installation cost of the plant.

Besides these, an important factor is the reduced seasonal variation of the closed model. The tilting angle can be chosen so that the maximal output is reached during spring and autumn, and that for other seasons the drop of output is very limited (20% or so for a very short period). The average (sunny) daily output level can be well over 90% of the maximum.

For the long open troughs on a site with latitude between $30°$ and $40°$, the (sunny) daily output level varies from 23% to 100%, with an annual average of about 65% of the maximum. This means that the annual capacity factor of the whole system, including power block and thermal storage, improves by more than 30% for the closed model. Or equivalently, an economy of the same level for the levelized electricity cost that will be added to the 30% installation cost reduction of the collectors. That means a combined cost reduction of about 50%.

The capacity factor is not the only benefit of a reduced seasonal variation. The fact that this allows the power plant to better meet the demand is of equal importance. If solar electricity is to gain a non-negligible part in power supply, one cannot tolerate that they close the door during the winter, when the demand is often at its highest level.

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