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# Solar Cooker BISS



*25/01/2014 –Dar Bellarj Fondation – Marrakech - Medina*

**How to optimize the solar oven operating ?**

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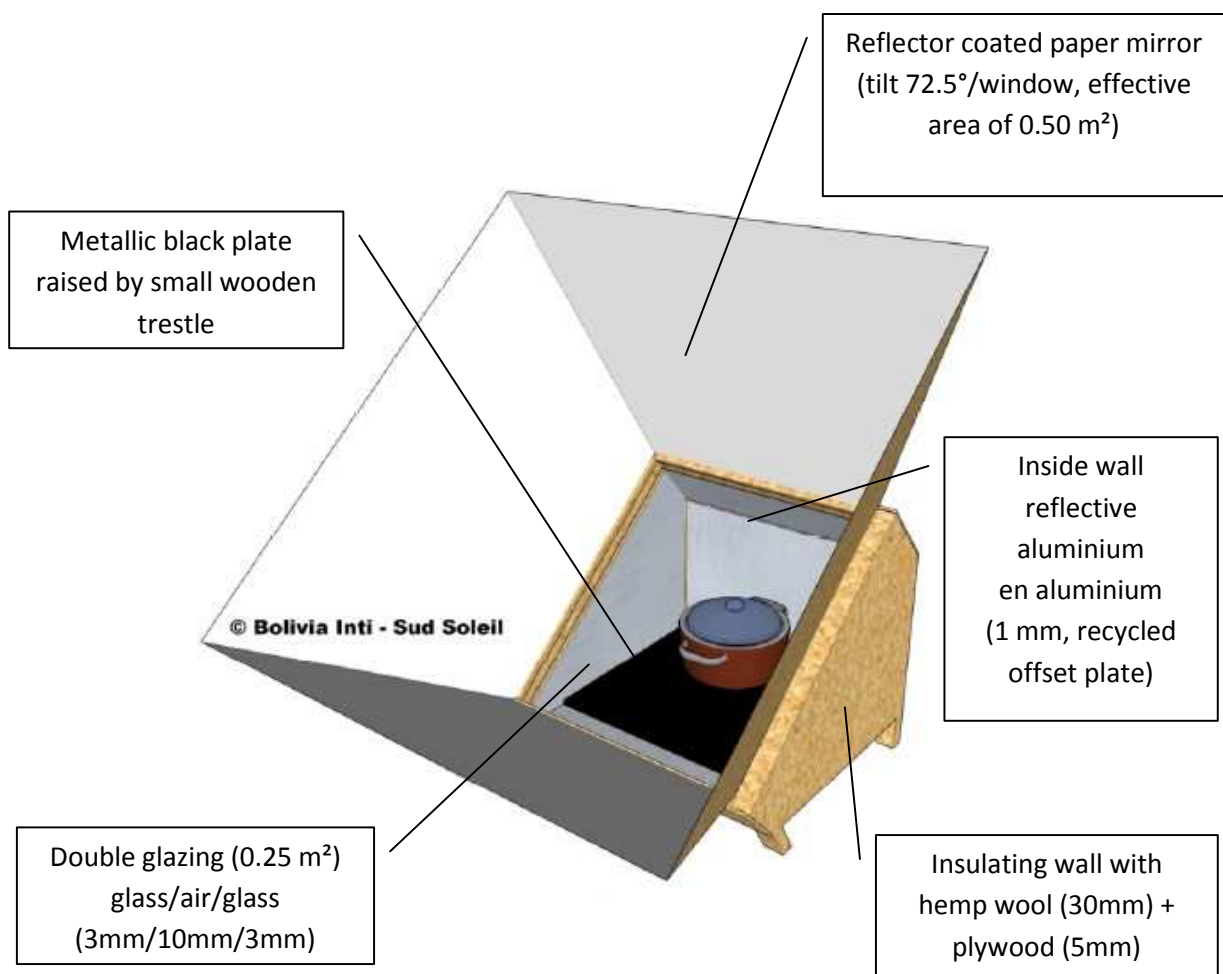
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# Introduction

When energy savings but also the ecological problems are important, the use of the solar cooker seems a good compromise in the sunny and developing countries. We decided not to build our own solar cooker because the researches around this device are plenty. Actually, we decided to deal with the particular characteristics of the model BISS developed by Bolivia Inti Sud Soleil, an association with which our high school is linked since the beginning of the French-Moroccan exchange in 2012. So, we decided to try to optimize the temperature inside the oven.

In a first part we shall see how the oven was built to optimize the solar energy captured to warm its inside. Then we shall see the means which were implemented to limit the losses towards the outside. We shall finally deal with some possible improvements to optimize its use in countries not as sunny, like France while not losing sight of the fact that this oven was built for developing countries, thus its cost and its maintenance have to remain reasonable.



Our Web site in English:

<http://www.vaucanson.org/php5/Accueil/index.php/solar-cooker-english-version>

Our website in French:

<http://www.vaucanson.org/php5/Accueil/index.php/four-solaire-et-principe>

Website of the trip to Morocco:

<http://www.vaucanson.org/php5/Accueil/index.php/echange-franco-marocain/838-voyage-au-maroc-2015>

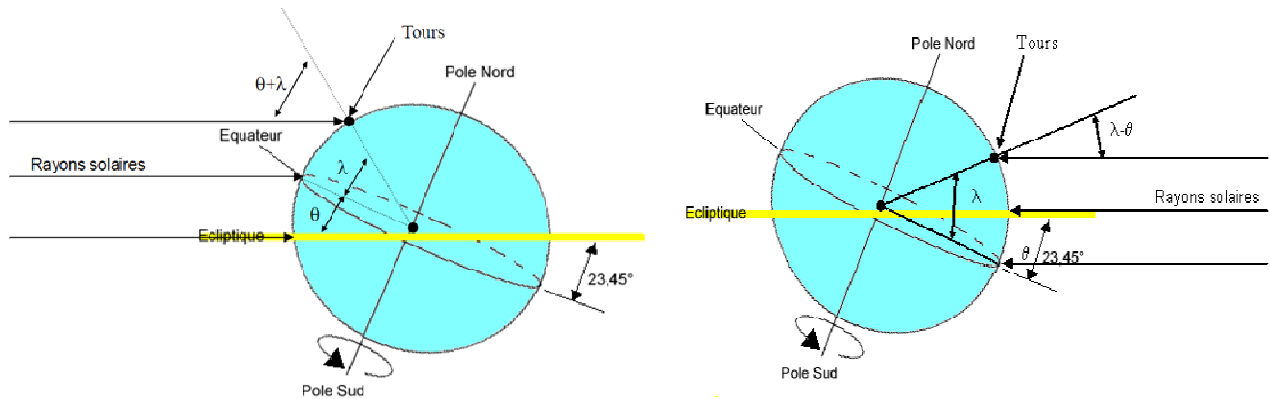
## A – How to capture a big quantity of solar energy ?

### 1) The oven's slope

#### a) Sun's position

At first sight, the oven is tilted. At first, this slope can seem logical because the Sun is not still for the same height in the sky according to the moments of the day but also according to the latitude of the place where we are, or still of the day of the year.

So in Tours, on December the 21st, the Sun rises at the most to  $19,1^\circ$  above the horizon, while it reaches  $60,1^\circ$  on June the 21st, values which we wanted to find thanks to plans below :



a) Winter solstice (in December, the 21st) then b) in the summer solstice (in June, the 21st) at 12 am GMT in Tours

We can also note that according to the hour, and the day of the year, the sunbeams will have a very different slope. To illustrate it, we can observe the graph opposite.

So we can observe that the sunbeams' slope changes according to the month and the day of the year. In June, it will be more important than in November for example. It would thus be imperative to know the average slope at the time of the day to direct the window of the solar cooker.

We thus wanted to realize a first experiment to prove the window's slope had a real importance in the maximal temperature reached inside the oven.

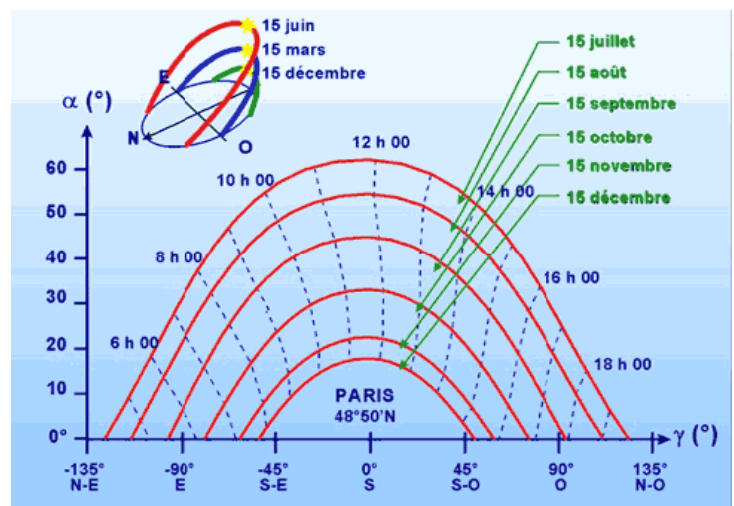


Diagram showing the sun's position depending on the day

**Experiment and hypothesis :** We verified at first that both ovens which we had, reached close temperatures in same conditions, that is to say same orientation as well as in the horizontal plan than vertical, and with identical reflectors for each.

**Protocol :** So, at first we placed them side by side, then we directed them in the same way in the horizontal plan thanks to their shadow on the ground. We finally verified the slope of their window, that is  $42,5^\circ$  compared with the vertical line, or  $47,5^\circ$  compared with the horizontal.

**Measures :**

| t (in min) | $\theta(^{\circ}\text{C})$ Oven n°1 | $\theta(^{\circ}\text{C})$ Oven n°2 |
|------------|-------------------------------------|-------------------------------------|
| 0          | 50                                  | 63                                  |
| 8          | 71                                  | 79                                  |
| 18         | 84                                  | 86                                  |
| 30         | 97                                  | 95                                  |
| 40         | 102                                 | 99                                  |
| 48         | 105                                 | 100                                 |
| 54         | 105                                 | 100                                 |

**Interpretation/conclusion :** By observing the results, we can notice that the oven n°1 reached a 5 °C temperature higher than the other . This difference is probably due to an insulation defect, which manifestes by more important losses on the number 1 than on 2. After, we thus tolerated a maximal gap from 5 ° C during our others measures.

**Hypothesis:** the slope of the oven, more exactly of the window, has an importance in the quantity of energy which it's going to capture and thus the temperature which it is going to reach.

**Protocol:** we directed the oven n°1 in front of Sun, i.e. the sunbeams arrive perpendicularly to the window. Having measured the inclination angle of the window, we adjusted the second one about 20 ° compared with the first one. We measured:  $\theta_1 = 58^\circ$  compared to the vertical line and  $\theta_2 = 38^\circ$  (for the second) at 1:48 pm.

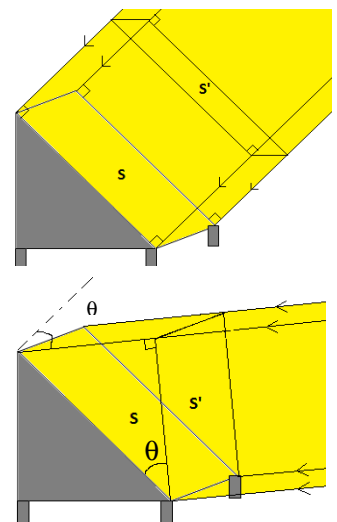
**Measures:**

**Conclusion:** The 20°C difference of temperature reached in both ovens is very superior than 5°C which

is the maximal error that we agreed. We can thus conclude that the slope has an importance on the quantity of solar energy collected by the oven. We then wondered what was the reason?

**Interpretation:** Indeed, at first sight, as the following drawing can highlight, if the sunbeams don't arrive at perpendicularly on a surface S of the window, the effective section S' of the sunbeams received by this surface decreases. According to this plan  $S' = S \cdot \cos\theta$ . So for a 20 ° slope, the new effective section is 0,93.S. So, the solar energy received by the surface decreases only about 7 %. That doesn't allow to explain the temperature difference measured of more than 20 °, that is to say 20 % of the gradient of temperature between inside and outside. How to explain a such difference?

| t (in min) | $\theta(^{\circ}\text{C})$ Oven n°1 | $\theta(^{\circ}\text{C})$ Oven n°2 |
|------------|-------------------------------------|-------------------------------------|
| 0          | 90                                  | 105                                 |
| 2          | 90                                  | 110                                 |
| 6          | 93                                  | 115                                 |
| 10         | 95                                  | 118                                 |
| 20         | 106                                 | 125                                 |
| 25         | 106                                 | 125                                 |



*Sunbeams arriving perpendicularly to the windows and other ones with a 20° incident angle.*

## b) The light's Refraction

**Experience :**

**Hypothesis:** To explain this difference, we thought to total reflection that we studied during our tenth level. Total internal reflection is a phenomenon that happens when a propagating wave strikes a medium boundary at an angle larger than a particular critical angle with respect to the normal to the surface. If the refractive index is lower on the other side of the boundary and the incident angle is greater than the critical angle, the wave cannot pass through and is entirely reflected.

**Protocol:** with a laser, we lit a window by making vary its slope.

**Observation:** Whatever the incident angle of the laser beam, this one goes out from the window

**Interpretation/Conclusion :**

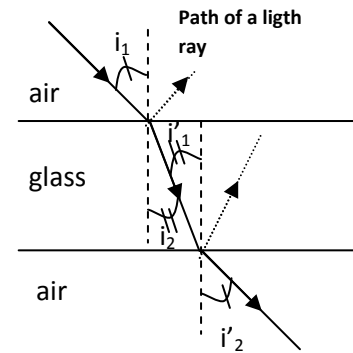
Whatever the incidence angle of the sunbeams on the window, these can enter in the oven. Indeed, according to the Snell-Descartes second law on the refraction,  $n_1 \cdot \sin i_1 = n_2 \cdot \sin i_2$ , on arrival, the sunbeams can always enter because the window index is upper than the air one, thus the refracted beam is going to get closer to the normal compared to the incident one ( $n_{\text{air}} < n_{\text{window}}$  thus  $i_{\text{window}} > i_{\text{air}}$ ).

However, at the exit of the beam, during the window/air passage, knowing that  $n_1(\text{window}) > n_2(\text{air})$ , so  $i_1 < i_2$ . The refracted beam goes away from the normal. So, it will be not refracted if  $i_2$  reached 90 ° and all the light will then be reflected: we speak about the phenomenon of total reflection. In the case of the

passage window / air,  $n_{\text{window}} = 1,5$ , there is total reflection if :  
 $i_1 > i_{1,\text{lim}}$ ,  $\sin i_{1,\text{lim}} = n_2(\text{air}) / n_1(\text{window}) = 1/1.5 = 0.67$  is an angle of  $42^\circ$ .

However, as the beam entered from the air, it means that  $i_2$  will be lower than  $41,7^\circ$  according to the Snell-Descartes 2de law, because at the most  $i_1 = 90^\circ$ , thus  $\sin i_{2,\text{lim}} = n_1/n_2 = 1/1,5$  thus  $i_1' = i_2 = 41,7^\circ$ .

So, whatever the incident angle  $i_1$  on the window, a beam will be refracted with an angle  $i_2'$  equal to  $i_1$ .

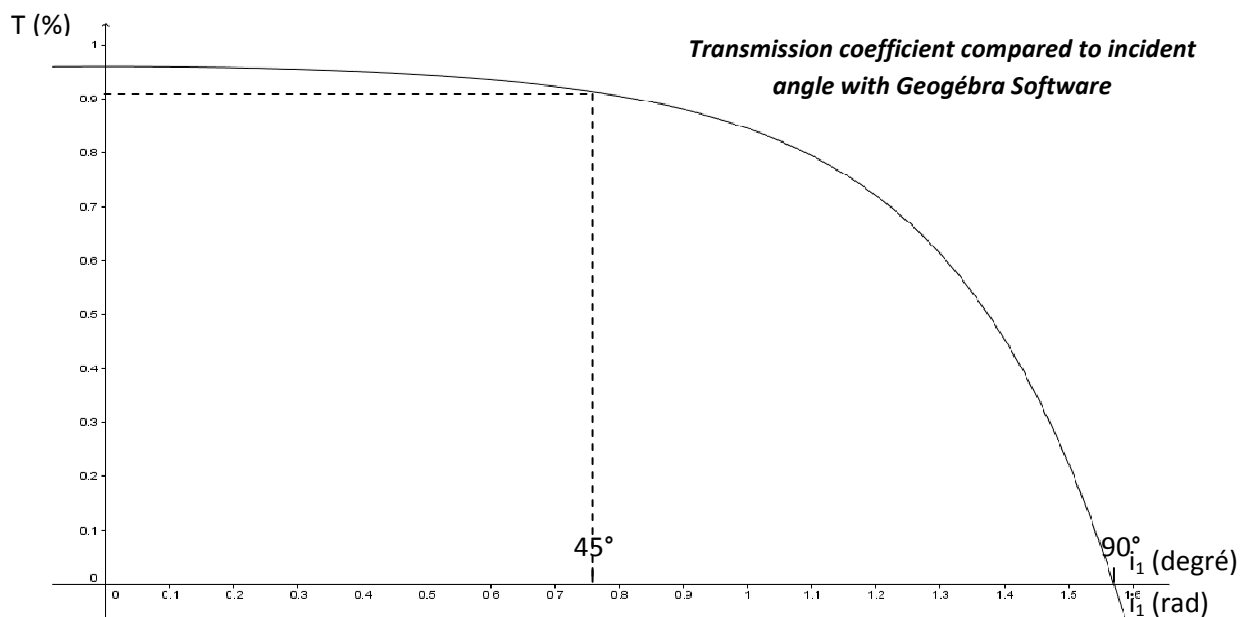


But Where does a such temperature difference come from ?

We observed every time there was a reflected beam, every time the spot which it gave was more or less bright. We discovered that the percentage of reflected light and/or refracted depends of the incident angle of beams on the diopter. Indeed, the reflected and refracted light percentages are given by the coefficients of Fresnel of reflection  $R$  and of transmission  $T$ . If the absorption ( $A$ ) by the window is nil,

$$A=0 \text{ and } R+T=1 : \quad R = \left( \frac{n_1 \cos i_1 - n_2 \cos i_2}{n_1 \cos i_1 + n_2 \cos i_2} \right)^2 \quad \text{et} \quad T = 1-R = 1 - \left( \frac{n_1 \cos i_1 - n_2 \cos i_2}{n_1 \cos i_1 + n_2 \cos i_2} \right)^2 \quad \text{with}$$

$$i_2 = \arcsin\left(\frac{n_1}{n_2} \sin i_1\right) \text{ according to Snell-Descartes law on refraction.}$$



**Observation:** we notice that as long as the angle of incidence is lower than  $45^\circ$ , more than 90 % of the light is transmitted. That is not coherent with our observations during our first experience for which we had observed that with an  $20^\circ$  incident angle, the oven 2 reached a clearly lower temperature than the oven 1 for which we had chosen a normal incidence on the window ( $i_1 = 0^\circ$ ). We wanted to confirm this observation.

**Experience:**

**hypothesis:** In the optics laboratory, we wanted to confirm this theoretical hypothesis saying that as long as the angle of incidence is lower than  $45^\circ$ , more than 90 % of the light is transmitted, or only 10 % is reflected.



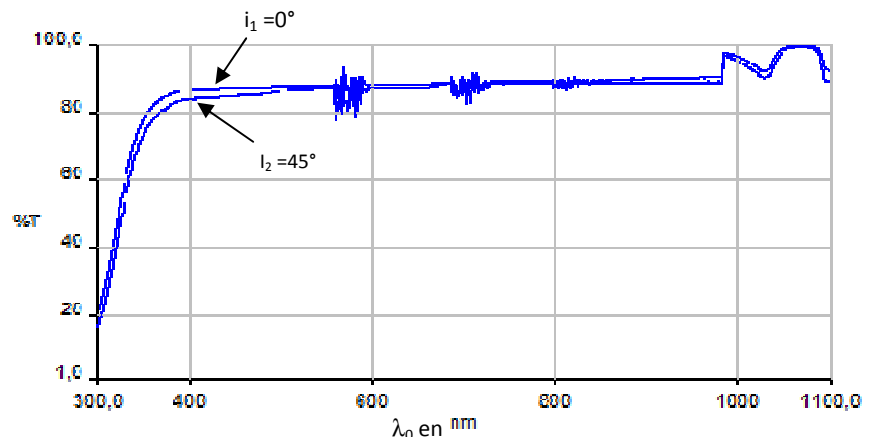
Interior view of a Spectrophotometer with a  $45^\circ$  tilted glass

**Protocol:** Thanks to the already existing bases, we placed in a spectrophotometer, for our first test, a window blade so that the incident angle of light was  $0^\circ$ .

We then measured the percentage of transmitted light depending to the light wavelength. We did the same with a  $45^\circ$  incident angle.

**Measures:**

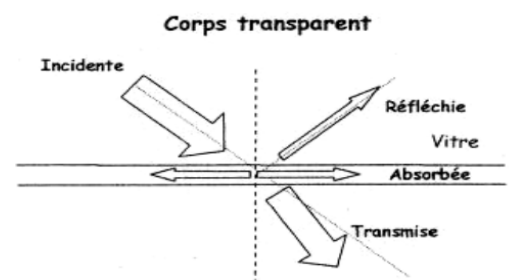
*Transmitted light Percentage depending to the wavelength*



**Observations:**

- we can note that the percentage of transmitted light is appreciably the same whatever is the wavelength included in the visible domain. It is actually slightly lower for an  $45^\circ$  incident angle but the difference does not exceed 3 %.
- we notice that the percentage of transmitted light is slightly lower than the one the theory plans: 96 % for a normal incidence against hardly moderate 90 % experimentally. This gives some explanation by the fact

**Conclusion:** so these measures validate our hypothesis saying that below a  $45^\circ$  incident angle approximately 90 % of the light is transmitted. However they do not explain that we observed a difference of very significant temperature during our first experience with a  $20^\circ$  incident angle compared to a nil one on the window.



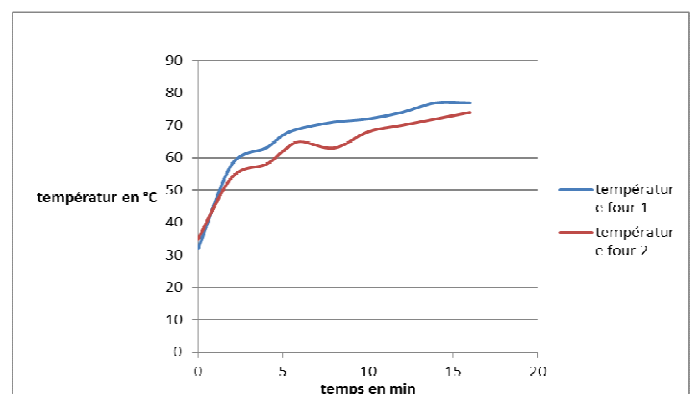
**Experience:**

**hypothesis:** the difference of temperature which we observed in the experience 1 was due to the presence of reflectors.

**Protocol:** we renewed the experience 1, but this time without reflectors.

**Measures:** Temperature during time with a slope different from ovens but without reflector

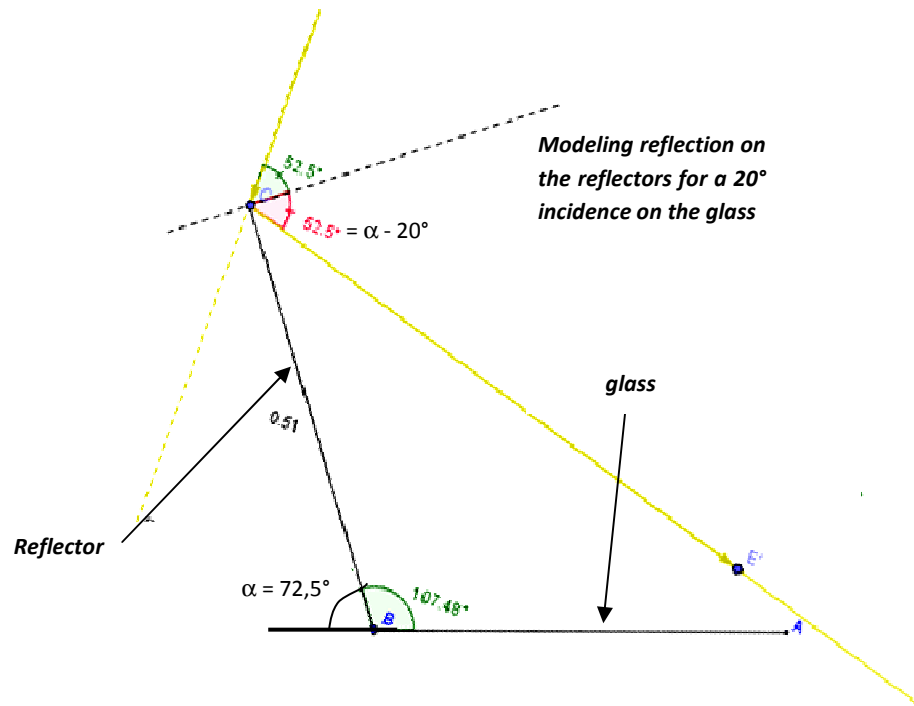
**Conclusion:** we observe that the percentages of light evolve appreciably in the same way for both incidences. We thus conclude that from it the important gap found in the first experience was well due to the reflectors. We thus confirm the fact that  $20^\circ$  of slope import little to reach maximal temperatures when that the oven does not arrange reflectors that there is a double refraction and a light percentage of the light is absorbed by the window.





With an incidence of  $20^\circ$  on the window, that is to say an angle of  $\alpha - 20 = 52,5^\circ$  on the panels:

So on this plan, we notice that all the beams are not reflected in the direction of the window because they arrives with a too low angle ( $52,5^\circ$ ). On the other hand, the angle of incidence on the window for the beams which reaches is of  $I = 180 - 2\alpha + 20 = 55^\circ$  there, thus not favorable because exceed  $45^\circ$ , thus an important percentage will be reflected when beams arrived to the window. Very quickly, when the Sun declines, the angle of incidence of the reflected light by reflectors is too important and thus a small quantity of light is going to enter in the oven. It is thus necessary to try to have an incidence the closest to the normal with regard to the window to allow to get back a maximum of energy.



### b) Materials constituting the reflectors

We chose to stay in the choice of reflecting materials. So we are asked us if the surface of the material changed the capacity of reflectors. To illustrate it, we took several more or less polished types of aluminum, to prove the importance of a smooth surface. We were able to observe that the diffusion of a beam, that is the dismissal of this beam in several directions and not in the only one as stipulates in the reflection law of Snell-Descartes, was more or less important according to the surface. So during the choice of the reflecting materials, the polishing is very important. But its cost is also more important.

### 3) Is not double glazing an obstacle to the entrance of light ?

Sunbeams cover various domains of wavelength. We can observe on the graph below that the peak of energy is situated in the visible domain (400nm in 800nm) and the close IR. Yet we know that the window is transparent for these domains. We also know that during the reflection, it absorbs approximately 3 % of the energy. We can thus conclude that in reality it is not a problem for the entrance of the beams in the oven. We shall see more particularly than this one allows a decrease of the losses.

**Hypothesis:** As 90 % of the light was transmitted

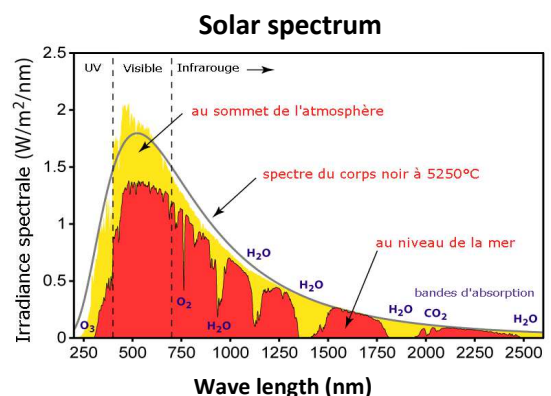
according to a previous experience, if we are two window, only 80 % of incident light will be passed transmitted.

**Experience:** Having removed reflectors, we measured the illumination above the windows and under the windows.

**Results:**  $E_{\text{ext}} = 72000 \text{ Lux}$  et  $E_{\text{int}} = 59000 \text{ Lux}$  d'où  $\%_{\text{transmis}} = \frac{E_{\text{int}}}{E_{\text{ext}}} \times 100 = 82\%$

**Conclusion:**

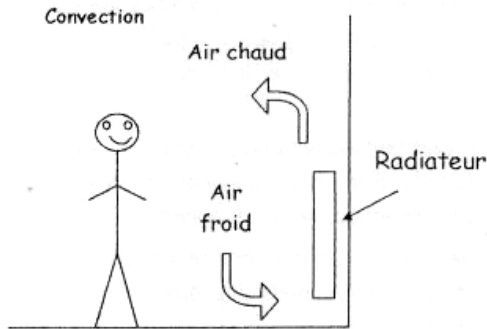
18 % of the light does not enter in the oven by absorption by windows and reflection. Actually, with four diopters, as we already stipuled,  $T_{\text{tot}} = (0,96)^4 = 0,85$ , so 85% of the light is refracted in normal incidence. 3 % are absorbed by the windows.



## B. How to minimize the losses of energy?

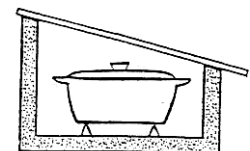
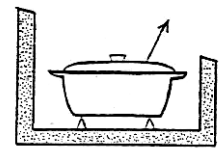
Now that we studied what were the means to collect a maximum of solar energy, we are going to study means to minimize the losses of energy inside the oven. Knowing that the transfers of heat towards the outside can be made by radiation, conduction and convection, we shall approach this second part in a slightly different way, by trying to analyze how are limited these three ways of transfer of heat through the elements which constitute the oven.

### 1) Reducing losses by conduction convection



This way of transfer of heat is reserved for the fluids, worth knowing liquid and gas. Indeed, a fluid is all the less dense as its temperature is raised. So, by warming itself, the air rises naturally giving way to the cold air which falls

: this is the way we can warm the floor of a house without radiator. In this case of the oven, the hot air being less dense thus lighter, will rise. To prevent it, we simply locked the air by means of a box as well as a window. So we decrease the losses by rise of the heat. Certainly the window limits the losses by convection but it also has a supporting role for the solar furnace.



*Limitation of convection losses*

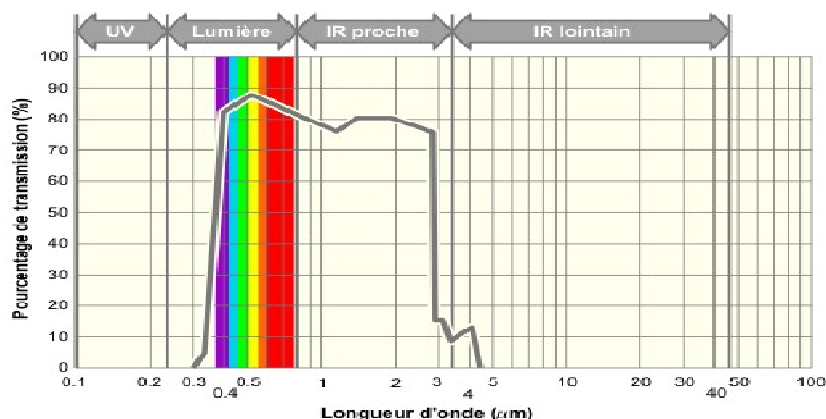
### 2) Reducing losses by radiation

#### a) The window and the green house effect

A quite simple observation intrigued us: why does the light enter so easily but does not go out again from the oven?

As we can observe the transmission spectrum of a glass below, the glass is transparent in the visible radiation and in the infrared but opaque with far infrared. In other words the window will have the same capacities as the atmosphere:

- it will allow to pass the visible light and the infrared resulting from the Sun;
- On the other hand it will block the thermal radiation emitted by objects because of their temperature.



*Transmission spectrum of a glass*

#### Experience and Hypothesis n°8:

We wanted to verify that the glass which constitutes the window is opaque in the infrared

which are emitted by a hot body.

**Protocol:** to prove this assertion, we placed a person behind a window.

**Observation:** this person emitting in far infrared, was not visible any more when we observed it by means of an infrared camera if the window is opaque in far infrared as atmosphere is.

Behind the window, we did not distinguish any more one of us.

**Conclusion:** the window is opaque in the infrared radiation emitted by a hot body.

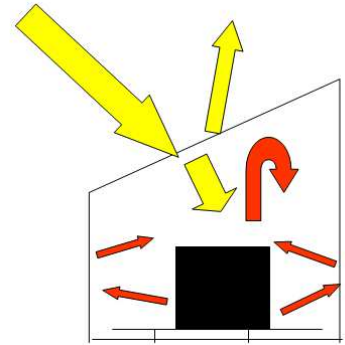
**Interpretation :** Typically, the objects which the temperature is between 20 and 100°C emit mainly a radiation between 7 and 10 μm. Indeed the law of Wien allows to find this assertion because it allows to link the wavelength of maximum of emission of a black body and its temperature:

$$\lambda(nm) = \frac{2,898.10^6}{T(K)}$$

-  $\theta = 20^\circ\text{C}$ ,  $\lambda = 2,898.106 / (20+273) = 9890 \text{ nm} \approx 10 \mu\text{m}$

-  $\theta = 150^\circ\text{C}$ ,  $\lambda = 2,898.106 / (150+273) = 6851 \text{ nm} \approx 7 \mu\text{m}$

The glass is thus opaque to the far infrared rays emitted by the internal elements, which are imprisoned into the oven. So the window allows the crossing of sunrays but prevent their exit after transformation in I.R. as the atmosphere for our planet.



#### b) the walls in aluminium to reflect

As we said it previously, inside the oven circulate rays of light which go from visible to far infrared serving to warm the bowl. To send back these lights , more than important for the speed of the cooking, aluminium sheets were placed on the internal walls of the oven. These being constituted by a reflecting surface are going to send back all the electromagnetic waves inward and thus towards bowls. As we observed it on reflectors, the aluminum reflects almost all of the light that it receives whatever is its wavelength. Contrary to the outside reflectors, the surface and the cleanliness of the aluminum matters little here. Indeed the reflecting lights do not absolutely need to be sent in a direction, if they are more reflected than absorbed by walls, even if as we can see it in the improvements, it would be preferable to send them back towards the bowl for cooking or the black plate.

#### c) The black plate which absorbed the sun lights

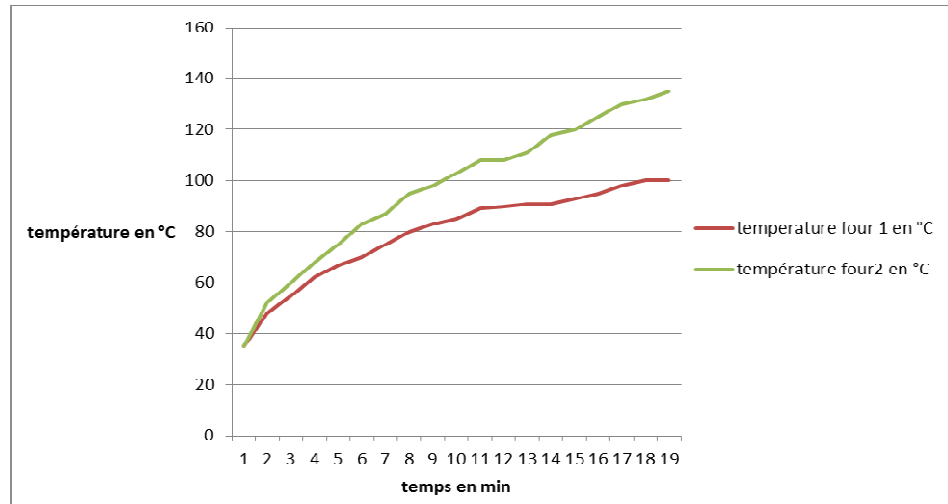
A black plate is put down at the bottom of the oven. Indeed, the light constituted by photon moves in the form of wave. A material of black color absorbs all the wavelengths (radio waves in X-rays if the body is perfectly black). The absorbed electromagnetic energy is going to give rise to a particular agitation which is going to be translated by an increase of the temperature. The black plate is thus going to release infrared rays, which led us to formulate a hypothesis as for the interest of this plate:

**Experience and Hypothesis n°9:** we suppose that, because of its quasi-total absorption, the black plate allows a higher temperature and the temperature rises quicker, limiting the multiple reflections inside the oven.

**Protocol:** to validate our hypothesis, we placed two ovens side by side and each in the same conditions except that the one was equipped with a black plate at the bottom whereas the other one not. Then we raised the internal temperatures of both ovens in time.

## Measures :

**Temperature  
depending to time  
inside ovens with and  
without black plate**



**Conclusion:** As we can notice it, there is a very clear difference of speed of increasing temperature between the oven 1 without plate and the oven 2 with one. So, the black plate is essential in the oven. Without it, incoming rays of light are not absorbed enough and reach to stand out from the oven for some of them before being transformed into infrared. The black plate can be substituted by a black bowl.

### 3) Reducing losses by conduction

Having solved the problem of radiation, we dealt with the second constraint: the conduction. Definition: the thermal conduction is a mode of thermal transfer caused by a difference of temperature between two regions of the same environment, or between two circles in contact, and coming true without global movement of material by opposition to the convection. It can be interpreted as the transmission step by step of the thermal motion directly linked to the temperature of the environment : an atom (or a molecule) gives up a part of its kinetic energy to the nearby atom. So the more an environment is dense, the more the conduction is going to be favored.

To limit the losses by conduction in the oven, the various techniques well known today have been organized.

#### a) The double glazing

The first one is the double glazing. Indeed the model of oven developed by Bolivia-Inti is equipped with one double glazing, that is two windows of thickness 4mm separated by a coat of air from 10 to 20 mm. Does this double glazing present a real interest?

**Experience and Hypothesis n°10:** the double glazing would limit the losses by conduction which would produce in the case of a simple window in direct contact with the atmosphere.

**Protocol:** we placed two ovens side by side and among which the conditions (slope, with blackplate) were identical, except the presence of a simple glazing on one of the two ovens to be known Number 1. Afterward, we decided to compare the temperature increase in these two ovens, but also the temperature of the outside windows of each of them and their temperature decrease by removing reflectors.

## Measures :

**Observations:** We do not observe a big difference at first. we suppose that the double glazing prevents the oven to warm itself quickly. Left one lower temperature, we note however that the oven with double glazing eventually catches up the other one and unfortunately, if we had waited a little, we think that we would have been able to notice one is higher in temperature. When we removed reflectors, we notice

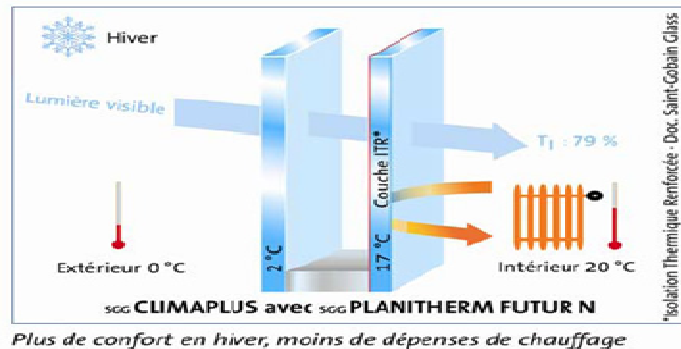
| temps<br>(en min) | température<br>four 1 (en °C) | température<br>four 2 (en °C) |
|-------------------|-------------------------------|-------------------------------|
| 28                | 89                            | 88                            |
| 32                | 95                            | 95                            |
| 36                | 100                           | 99                            |
| 40                | 104                           | 101                           |
| 44                | 104                           | 101                           |
| 20                | 114                           | 114                           |
| 24                | 96                            | 102                           |

that the fall of temperature of the oven not possessing the double glazing is faster. Moreover the difference of temperatures when they come to stagnate is around 9°C, to see more important because of 5°C if we take into account the gap which there was already in the same conditions between oven 1 and oven 2.

**Conclusion:** we can thus conclude that the double glazing has an importance in the oven but seems to be able to be optimized.

### Interpretation

The use of the double glazing is essential to reach and preserve a good heat of cooking. Indeed, the double glazing allows a good heat insulation, it is constituted by a blade of air which separates both windows. The air is a very good insulating material, much better than the window itself. This technique is going to allow to avoid that one of the windows is directly in touch with the inside and the outside of the oven: it thus limits the exchanges of heat between the outside and internal wall by conduction. Some techniques consist in adding gases less conductive than the air in the blade either to replace the air by the space.



Although this device optimizes the insulation, it presents a disadvantage. Indeed we saw previously that when a light crosses the window. There is a percentage of reflection and absorption, in the case of the dubbing, we have it twice more.

### b) Trestles to heighten the cooking bowl

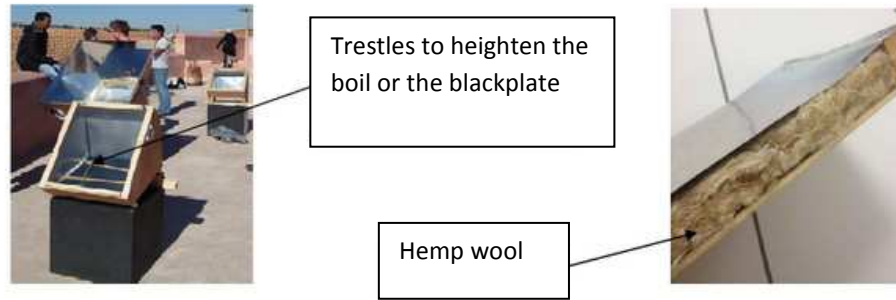
**Experience and Hypothesis n°11:** the black plate is not in direct contact with the bottom of the oven but heightened by wooden trestles to limit the conduction losses by the bottom of the oven.

**Protocol:** we arranged two ovens in the same conditions, without reflector, the same orientation, with black plate but the one put down directly on the bottom by the oven for the oven n°1 and the other one heightened by trestles. We raised the internal temperature of ovens after 30 minutes of exposure, and the outside temperature under the oven.

**Measures:** for the oven 1, the inside temperature reached 65°C, and the outside temperature under the oven reached 35 °. For the oven 2, the inside temperature is of 85°C, and the outside temperature under the oven is of 20°C. The remote outside temperature of ovens was of 16°C.

**Conclusion:** it is thus important that the black plate is not in direct contact with the bottom of the oven, because otherwise it favors the conduction losses and limits the temperature reached inside the oven.

**Interpretation :** as we saw it previously, the black plate warms itself by quasi-total absorption of the radiation) that it receives whatever is its wavelength. Only, this heat should not get lost by conduction with the bottom of the oven. So, to solve this problem, there is nothing more simple. Indeed, it is just necessary to heighten this plate with wooden trestles. The choice of the wood justifies itself by the fact that it is one of the least conductive solids of big rigidity which exists. Actually, when we compare the thermal conductivity of the wood of average  $0,7 \text{ W.m}^{-1} \cdot \text{K}^{-1}$ , it is lower than that of a metal such as the steel which is worth  $46 \text{ W.m}^{-1} \cdot \text{K}^{-1}$  for example. On the other hand, we use trestles to limit the contacts between the black plate or the bowl and the aluminum bottom. We can thus conclude that from it trestles to heighten the black plate or the bowl are essential and that from it the wood is one of the best solids for these trestles.



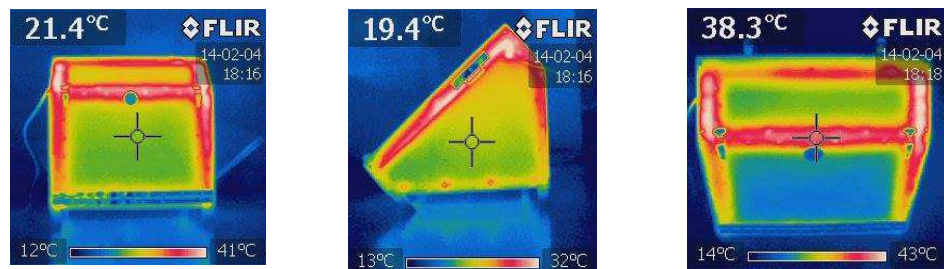
### c) The hemp wool walls

The walls of the oven are constituted by an aluminium sheet 0,5 mm thick, 30 mm of hemp wool and 5 mm of plywood. Has the hemp wool a real interest?

**Experience and Hypothesis n°12:** the hemp wool is a very good heat insulator which limits the conduction losses.

**Protocol:** We arranged an oven in which was present a heating plate. Having made warm this one, and reached a limit temperature inside the oven, we took photos of the various walls of the oven by means of a thermal camera to observe the places where the heat escapes.

**Measures:**



**Conclusion:** on these images, the red is used to represent high temperatures zones, while the blue is used for colder zones. We thus notice that the edges of walls strengthened by pieces of wood under the plywood are up to 20 °C warmer than the center of the walls at the level of which, behind the plywood is the hemp woolen. We note also, that the metallic structures which constitute the oven, as hinges or still screws are important thermal sources of decrease.

Indeed, the wool of hemp is a very good heat insulator because it has possesses a  $0,045 \text{ W.m}^{-1} \cdot \text{K}^{-1}$  thermal conductivity while the the wood used to make the structure of the oven has a  $0,5 \text{ W.m}^{-1} \cdot \text{K}^{-1}$  conductivity. We thus conclude that from it the hoped effect of the hemp wool is reached.

### d) Thermal Resistance of the oven

Problem: how to see if heat losses by walls are proportional or not to the difference temperature between inside and outside of the oven? How to estimate the thermal resistance of the oven?

When the oven reaches a constant temperature, the energy received by the inside of the oven compensates exactly the losses through its walls in the direction of the outside. We can then write that the received power  $P_{\text{received}}$  is equal to the thermal flow  $\phi$  through the walls:

$$P_{\text{reque}} = \Phi$$

As  $\Delta T = \Delta \theta = R_{th} \cdot \Phi$ , so knowing the temperature difference between inside and outside, we will be able to draw the temperature difference  $\Delta \theta$  according to the thermal flow  $\phi$  and verify or not that there is proportionality between these two data and to deduct the thermal resistance of the oven.

**Protocol**

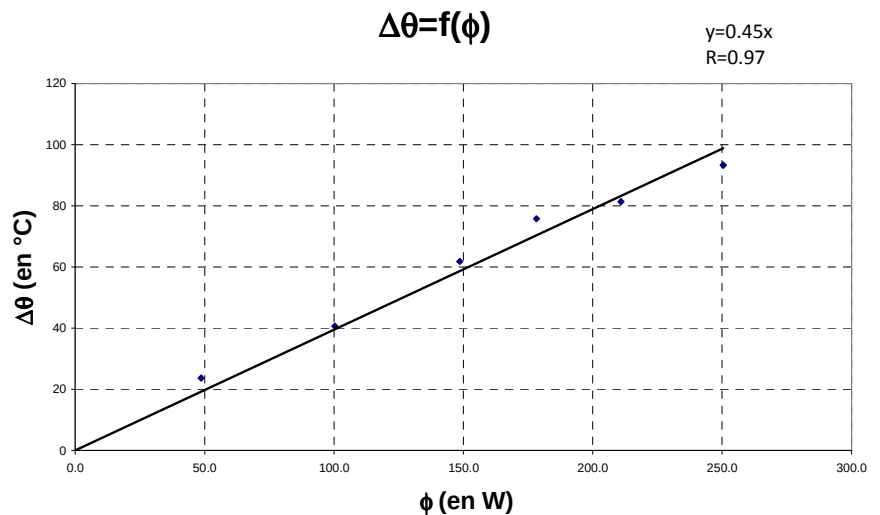
- To bring a given energy, use a resistance installed inside the oven fed by a generator of adjustable alternating voltage;

- Measure the effective intensity and the effective tension by means of two multimeters in alternative mode;
- Wait that the oven reaches a constant temperature indicating that there is balance between the losses and the supply;
- Measure minimal inside temperature in the bottom of the oven and maximal at the top to calculate an average;
- To Measure also the outside temperature of the oven to obtain the difference of temperature  $\Delta\theta = \theta_{\text{int moy}} - \theta_{\text{ext}}$  ;
- Renew the experience for various supplied powers  $P = U_{\text{eff}} \cdot I_{\text{eff}}$ .

#### Measures :

**Observation :** We obtain a straight line passing by the origin, thus the temperature difference is proportional to the thermal flow through the walls of the oven.

**Interpretation :** It is possible to estimate the thermal equivalent resistance of the oven walls by taking into account the constitution of walls and that of the double glazing..



Definition :  $R_{th} = \frac{e}{\lambda \times S}$

$e$  : Thickness of the wall in m ;  $S$  : Surface of the wall in  $m^2$  et  $\lambda$  : Thermal conductivity of the material in  $W.m^{-1}.K^{-1}$ .

| Dimensions                     | Value               |
|--------------------------------|---------------------|
| Window                         | 0,43 * 0.54 m       |
| Inside surface in aluminum     | 0.70 m <sup>2</sup> |
| Glass thickness                | 4,0 mm              |
| Air thickness (double glazing) | 1,0 cm              |
| Woolen thickness of hemp       | 3,0 cm              |
| Aluminium thickness            | 0,50 mm             |
| Plywood thickness              | 5,0 mm              |

| Material | Thermal conductivity in $W.m^{-1}.K^{-1}$ |
|----------|-------------------------------------------|
| Plywood  | 0,15                                      |
| Woolen   | 0,043                                     |
| Aluminum | 237                                       |
| glass    | 1,0                                       |
| Dry air  | 0,0262                                    |

When we stack various materials, the thermal resistances add up themselves. So :

The walls :

$$R_{th\_parois} = R_{th\_alu} + R_{th\_laine} + R_{th\_bois} = \frac{e_{alu}}{\lambda_{alu} \times S} + \frac{e_{laine}}{\lambda_{laine} \times S} + \frac{e_{bois}}{\lambda_{bois} \times S} = \frac{1}{S} \left( \frac{e_{alu}}{\lambda_{alu}} + \frac{e_{laine}}{\lambda_{laine}} + \frac{e_{bois}}{\lambda_{bois}} \right)$$

$$R_{th\_parois} = \frac{1}{0,70} \left( \frac{5,0 \cdot 10^{-4}}{237} + \frac{3,0 \cdot 10^{-2}}{0,043} + \frac{5,0 \cdot 10^{-3}}{0,15} \right) = 1,0 K.W^{-1}$$

Remark: we would have been able to neglect the conductivity of the aluminum compared the hemp wool.

- The double glazing :

$$R_{th\_vitres} = R_{th\_verre} + R_{th\_air} + R_{th\_verre} = \frac{e_{verre}}{\lambda_{verre} \times S} + \frac{e_{air}}{\lambda_{air} \times S} + \frac{e_{verre}}{\lambda_{verre} \times S} = \frac{1}{S} \left( \frac{2e_{verre}}{\lambda_{verre}} + \frac{e_{air}}{\lambda_{air}} \right)$$

$$R_{th\_verre} = \frac{1}{0,23} \left( \frac{2 \times 4,0 \cdot 10^{-3}}{1,0} + \frac{1,0 \cdot 10^{-2}}{0,0262} \right) = 1,7 K.W^{-1}.$$

1 m<sup>2</sup> of double glazing would have a resistance of 0,70 K.W<sup>-1</sup>, against 0,39 KW<sup>-1</sup> for 1 m<sup>2</sup> of walls.

To find the thermal resistance global or equivalent of the oven:

$$\Phi_{tot} = \Phi_{parois} + \Phi_{vitres} = \frac{\Delta T}{R_{th\_parois}} + \frac{\Delta T}{R_{th\_vitres}} = \Delta T \left( \frac{1}{R_{th\_parois}} + \frac{1}{R_{th\_vitres}} \right) = \frac{\Delta T}{R_{th\_eq}}$$

$$D'où \frac{1}{R_{th\_eq}} = \frac{1}{R_{th\_parois}} + \frac{1}{R_{th\_vitres}} \text{ ou } R_{th\_eq} = \frac{R_{th\_parois} \times R_{th\_vitres}}{R_{th\_parois} + R_{th\_vitres}} \text{ soit } R_{th\_eq} = \frac{1,0 \times 1,7}{1,0 + 1,7} = 0,63 K.W^{-1}.$$

So in theory, the thermal resistance of the oven is 0,63 K.W<sup>-1</sup>, while experimentally we estimated 0,45 K.W<sup>-1</sup>. This difference of more than 30 % is easy to understand :

- Walls are stiffened by wooden supports, material more of three times as conductive as the wool. Indeed our infrared images, were able to show us important losses on edges.
- On the other hand, the same images showed us important losses by the double glazing. Indeed to be effective, a double glazing requires a dry and motionless air. Yet, there is no joint at the level of windows, thus convection losses can take place.
- We were able to notice also losses by screws in stainless steel.

## C- How to improve the performances of the “ BISS ” model?

Having more or less understood the functioning of this model of solar furnace, we dealt with tracks of improvement in order to optimize its functioning in countries having less sun as France.

### 1) How to collect more sunbeams ?

#### a) Reflectors dimensions

Further to our reflectors modelling in the part A, we wondered what would be the maximal panels height, without modifying the slope because it is rather favorable to not much reflection, which would reflect all the beams towards the window with a normal incidence. Indeed when we modify it, we also modify the solar power which the solar oven receives.

AB= b= 0,50 m the window' length and a = L the pannel's height .

$$\sin \alpha = \frac{CD}{a} \quad \cos \alpha = \frac{DB}{a} \quad \tan \alpha = \frac{CD}{DB}$$

$$\tan \left( 2\alpha - \frac{\pi}{2} \right) = \frac{CD}{AD} = \frac{a \sin \alpha}{a \cos \alpha + 0.5} \quad \Leftrightarrow \quad \frac{2 \cos^2 \alpha - 1}{2 \sin \alpha \cos \alpha} = \frac{a \sin \alpha}{a \cos \alpha + 0.5}$$

$$-(2 \cos^2 \alpha - 1)(a \cos \alpha + 0.5) = 2a \sin^2 \alpha \cos \alpha$$

$$-(2 \cos^2 \alpha - 1)(a \cos \alpha + 0.5) = 2a (-\cos^2 \alpha + 1) \cos \alpha - 2a \cos^3 \alpha + a \cos \alpha - \cos^2 \alpha + 0.5$$

$$= -2a \cos^3 \alpha + 2a \cos \alpha - \cos^2 \alpha - a \cos \alpha + 0.5 = 0$$

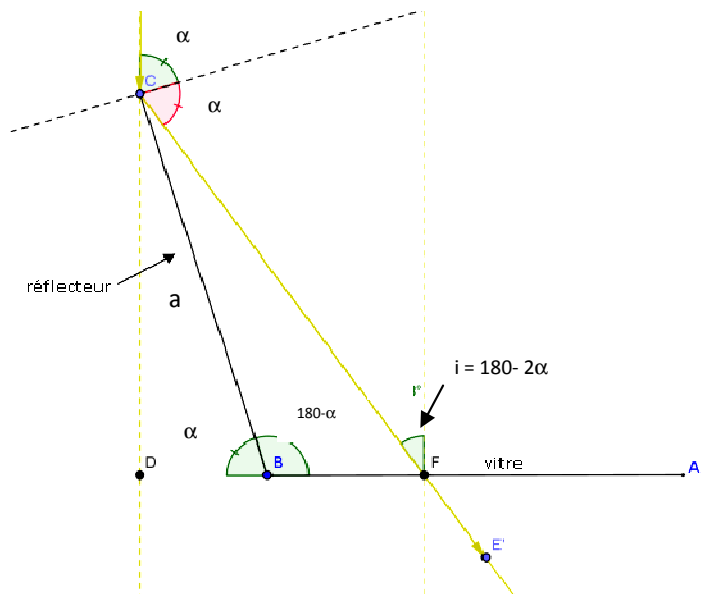
$$2 \cos^2 \alpha + 2a \cos \alpha - 1 = 0 \quad \Delta = 4a^2 + 8 = 4(a^2 + 2)$$

$$\cos \alpha = \frac{-2a + 2\sqrt{a^2 + 2}}{4} = \frac{-a + \sqrt{a^2 + 2}}{2}$$

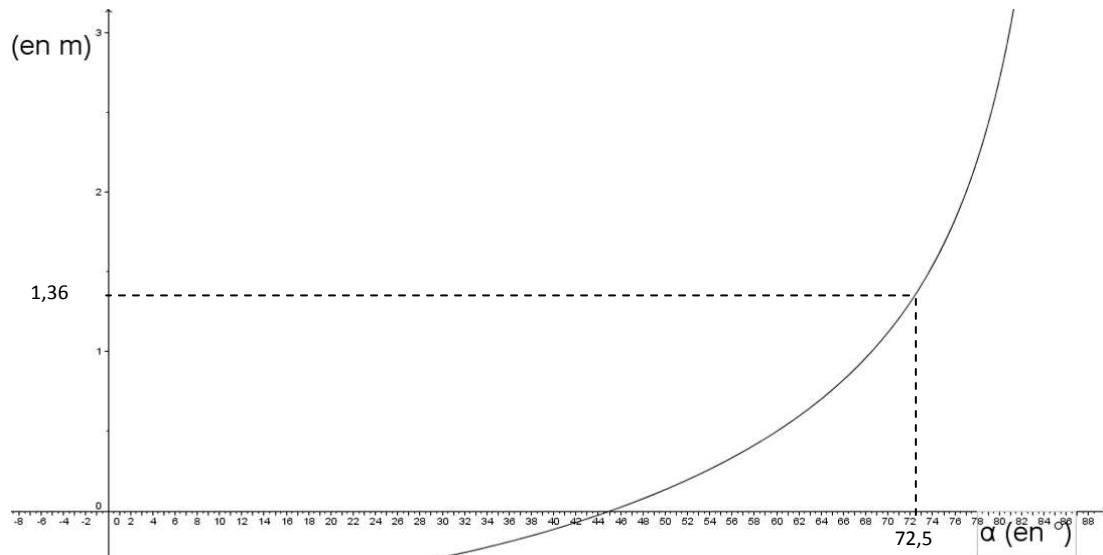
Si a fixed height

$$\alpha = \frac{1 - 2 \cos^2 \alpha}{2 \cos \alpha}$$

If α is fixed



With  $\alpha = 72.5^\circ$  donne:  $\alpha = 1.362m$



*Maximal length of the reflectors depending on their angle with the glass*

So we can note that the reflectors could be much more impressive than they are, that is to say a 1,36 m height and not only 0,51 m as at present.

On the other hand, by reading the curve the other way, we notice that we could gain surface solar energy by tilting them more because with a height of 0,51 m, panels could be tilted by  $60^\circ$  compared with the window. However, the angle of incidence of the sunbeams would be then of  $i = 180 - 2\alpha = 60^\circ$  what would not be convenient to an important percentage of refraction towards the oven.

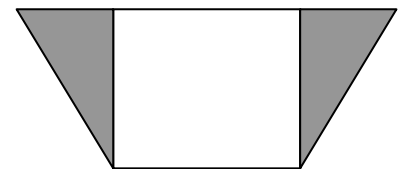
**Conclusion:** At the end of the calculation, we obtain an optimal slope about  $72.5^\circ$  which turns out the most profitable for the length of the reflectors.

#### b) Reflectors shape

Thus reflectors could be much more impressive than they are.

However the oven would become fast unstable and cumbersome.

However, all the beams which come to strike the usual reflectors, are not reflected towards the window as we were able to notice with a laser. All the cornersplaces surfaces, refelected the beams towards another reflector, reaching the window with a not convenient incident angle. Some of them, are reflected towards the atmosphere.



*Parts reflectors that do not reflect directly toward the glass*

**Experience and hypothesis n°15:** Reflectors with "broken corners" should allow to reach a more important temperature because they would allow to reflect more beams towards the oven.

**Protocol :** To test this hypothesis, we decided to put simply corners in the existing reflectors, before buiding more sophisticated reflectors. We installed two ovens with the same reflectors and in the same conditions at first to be sure that they reached the same average temperature, then we added corners.

**Results:** When that we installed settled both ovens in the same conditions, we were able to notice that the reached  $145^\circ\text{C}$  maximal temperature ( $21^\circ\text{C}$  outside temperature). With corners in one of the ovens, we observed that its maximal temperature reached  $151.5^\circ\text{C}$ . So, the temperature difference increased from  $124^\circ\text{C}$  to  $130.5^\circ\text{C}$ , that is to say a 5 % increase.



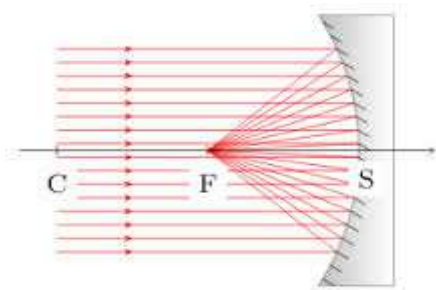
**Conclusion:** corners arranged in reflectors allowed to reflect more sunbeams in the oven and so to get back more energy.

### c) Capturing of sunbeams through the bottom of the oven

At first, having studied the subject on several Roger Bernard's books (a professional of the solar cooking), we wanted to create a system allowing to get more sunbeams. The first objective was to admit some light by the bottom of the oven. To do it, we glazed the base of the oven, by removing the insulating wall. The heat rising naturally, we emitted the hypothesis that the losses by the base were less important, what infrared images had proved. We added a double glazing and put the black plate over by means of small brackets..



Afterward, the problem was to reflect sunbeams towards this window. We wished to use a TV parabola covered with paper mirror, because it would allow to get back a more important power than reflectors plans. Before pursuing our works, we looked for the parabola focus F (that is 70 cms of the summit S) which is the point where converge parallel incident beams. Indeed, it was necessary, because it needs to avoid concentrating light on the window.



**Light reflexion by a parabola – Breaking of the glass result in a concentration of energy**

Unfortunately during our first tries, due to the lack of supervision of beams reflected towards the window, this one broke further to a too important concentration of the light in a point as we can see on the photography above. On second thought, we arrived at the conclusion, not finding parabola of different focal length, which it was necessary:

- Let be to heighten the oven, to take away the parabola and avoid that the focus is too close to window. To move closer to it is not possible because then we would have been bothered by the shadow of the oven and would have collected less sunbeams.
- Let be to move slightly the parabola forwards to increase the distance between the window and the parabola. However this solution will decrease clearly the efficiency of the device, pulling a slope of beams on the window which will not be convenient but also of parabola, thus a loss of collected solar power because the effective solar section will decrease.

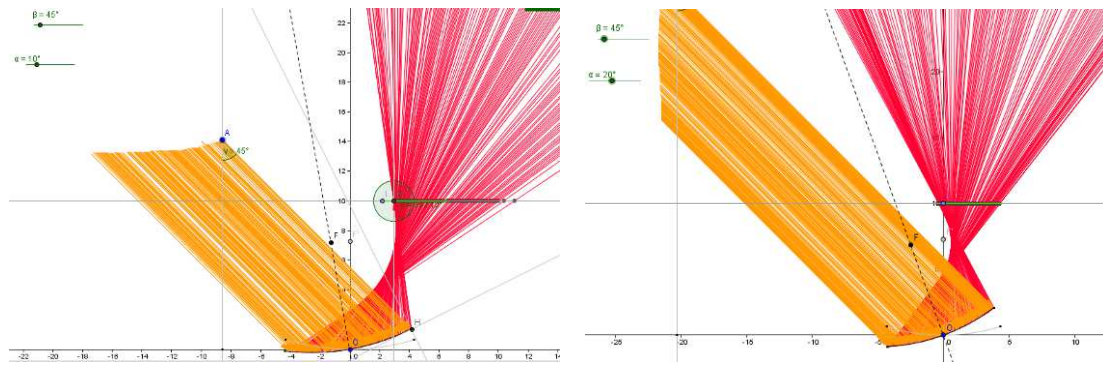
We wished to model these situations by means of GéoGébra software to be able to envisage them and plan the spot obtained at the bottom's oven. We created three cursors to modify at the same time the beams' angle  $\alpha$ , the parabola angle  $\theta$  compared with the ground and a cursor to modify the oven's height.

With an oven heightened by a meter, a parabola with 70 cms focal length, tilted by  $10^\circ$  or by  $20^\circ$  with compared with the ground and the sunbeams arriving with an  $45^\circ$  angle compared with the vertical line, we thus obtain modellings below. Sunbeams (in yellow) are reflected (in red) by the parabola). We can expect to have a spot which covers all the oven's bottom because the green segment represents it. We note that with a parabola tilted with a  $20^\circ$  angle, this one has to be situated under the oven. This situation seems more



**Final device**

favorable because allows to collect a more important solar power, and to reflect sunbeams with a more favorable angle to cross both windows without too much reflection.



*Modeling of solar reflexion by the parabola depending to its inclination*

If beams arrive with a more important angle, it will be necessary to tilt undoubtedly more the parabola. For example for beams which arrive with a 60 ° angle, a 20 ° angle for the parabola is the most appropriate. Thus the parabola must be removable..

**Experience and hypothesis 16:** the parabola is going to allow to increase considerably the internal temperature of the open oven downward.

**Protocol:** we let go up the oven's temperature until stabilization with a normal incidence on the window. Then we add the parabola in the same conditions while verifying that the illumination does not vary.

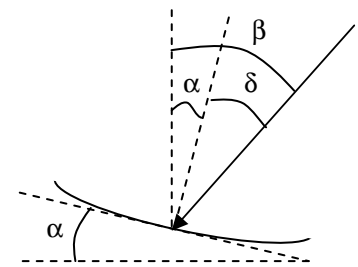
**Results and interpretations:**

- Device without contribution downward with a normal incidence on the window: 145°C;

- With contribution downward: 175°C with a 20°C outside temperature, are an increase of 30 ° on a gradient of temperature of 125°C, thus a 24 % gains.

The parabola was tilted of  $\alpha = 7^\circ$  with compared with the ground, then beams arrived an angle  $\beta = 37^\circ$  with compared with the vertical line, that is  $53^\circ$  with the horizontal. We thus deduct according to the plan above that from it sunbeams arrived with an angle of  $\delta = \beta - \alpha = 30^\circ$  compared with the optical axis of the parabola. So, at best, the parabola gets back a solar power  $P_{lum} = E \cdot S' = E \cdot S \cdot \cos \delta = E \cdot \pi \cdot R^2 \cdot \cos \delta = 850 \times \pi \times (0,47)^2 \times \cos 30 = 510 \text{ W} = 0.51 \text{ kW}.$

This power did not enter altogether the oven because the incidence.



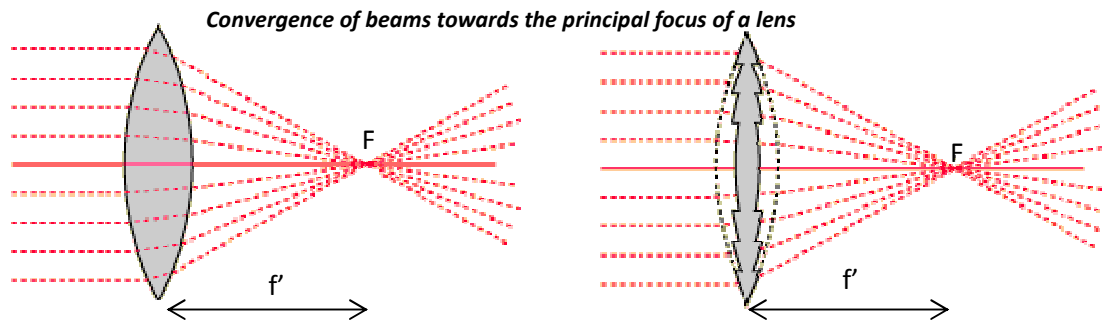
*Solar beams arriving on the parabola*

## 2) How to limit the energy losses towards the outside ?

### a) How to limit the losses of light by reflection towards the outside?

As we have just seen it before, it is possible to let enter a big quantity of visible and infrared beams to the oven. However some of them won't reach the bowl or the black plate at first time and will be reflect by the wall. Because of these reflections, they loose power before reaching the bowl or redirecting towards the outside. We thus thought of using a lens of Fresnel to concentrate the entrance light towards the bowl of cooking.

The Fresnel's lens principle is quite simply because it bases on a convergent lens. Indeed, when it is crossed by beams of parallel light, it makes them converge in a point called focus of the lens  $F'$ . The distance between the focus and the lens' center is called lens focal length  $f'$ . The advantage compared with a single lens, is that its thickness is clearly reduced by cutting it a set of concentric rings of prismatic section known by the name of "zones of Fresnel". For each of these zones, the thickness is reduced, so the global surface of the lens is not smooth any more but consists of several surfaces of the same curvature, separated by discontinuities.



**Experience and hypothesis :** So, we thought that a Fresnel's lens, would allow to concentrate beams towards the cooking bowl without absorbing too much energy. We would just have to place it on the first window of the oven. Of course, it make us ask many questions on the properties of the lens : certainly we wish to converge sunbeams entering towards the bowl, but they must not be concentrated in a point, at the risk of melting the bowl, or only burning the food. That is why, a focal length of 30 cms, seemed to us a good compromise whether it is for a pressure-cooker which can be located to only 10 cms of the window or a cake plate which will be it at the bottom of the oven or in 50 cms of the window.

**Protocol:** We exposed an oven until stabilization of its temperature. Then we added a Fresnel's lens concentrating beams on the black plate.

**Results:** The oven did not reached a higher temperature. On the contrary, it would have even lost two or three Celcius degrees.

**Conclusion:** the lens of Fresnel does not allow to increase the internal temperature of the oven, probably because it absorbs a not insignificant proportion of light.

**Hypothesis and experience 17 bis:** it is possible that if we concentrate the light on a black bowl containing some water, the watter's temperature will grow faster.

**Protocol:** we let go up in temperature two ovens in the same conditions (normal incidence on the window + reflectors), then we introduced 1,00 L of water into everyone. On the window of the first one, we added a lens concentrating the light on the black bowl.

**Results :**

Case n°1: in 20 min, the water's temperature increased from 21,3°C in 41,7 °C with a 106°C average temperature and an 21°C outside temperature. So we can found the power received by the water:

$$P_{eau} = \frac{Q}{\Delta t} = \frac{m_{eau} C_{eau} \Delta T}{\Delta t} = \frac{1000 \times 4,18 \times (41,7 - 21,3)}{20 \times 60} = 71W$$

Case n°2: in 20 min, the temperature of the water increased from 21,3°C to 36,9 °C with an 112°C average temperature in the oven and a 21°C outside temperature.

$$P_{eau} = \frac{Q}{\Delta t} = \frac{m_{eau} C_{eau} \Delta T}{\Delta t} = \frac{1000 \times 4,18 \times (36,9 - 21,3)}{20 \times 60} = 54W$$

**Conclusion:** By concentrating more beams on the bowl, the water absorbs more heat, what decreases the internal temperature of the oven at the same time, thus the losses towards the outside.

### b) How to limit the heat losses by convection?

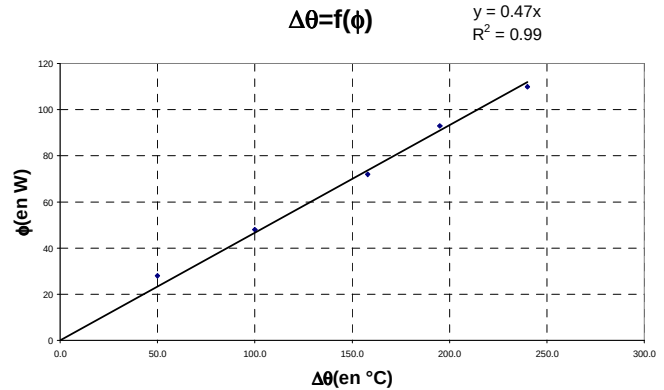
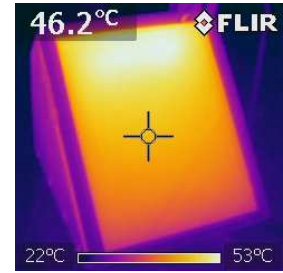
Thanks to our infrared pictures, we were able to notice that there were important losses due to the lack of air impermeability of the double glazing.

**Experience and hypothesis n°18:** So, we wondered if the use of joints would limit these losses due to convection ?

**Protocol:** to verify it we have to renew the experience of 3) d) intended to estimate the new thermal resistance of the oven.

**Measures / interpretation:** we can notice that the guiding coefficient, thus the thermal resistance, passed from 0.45 to 0.47  $\text{K.W}^{-1}$ . So, the resistance is bigger with the joints which led more low losses thus our hypotheses is verified.

$$E.R. = \frac{|R_{initiale} - R_{final}|}{R_{initiale}} \times 100 = 20\%$$



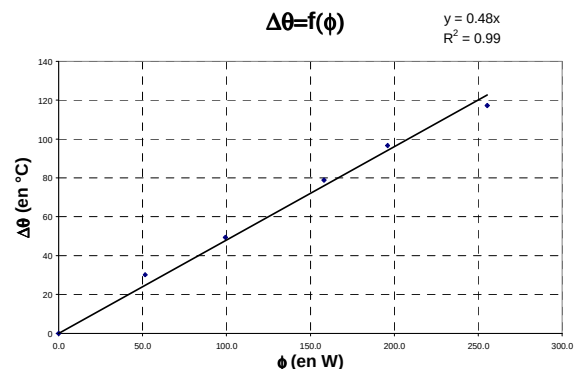
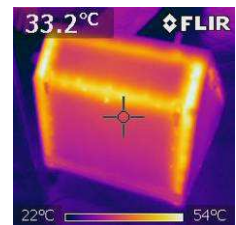
### c) How to limit the heat losses by conduction?

As we can see it on infrared camera's photos, there are important losses on the corners of the oven. We noticed that the aluminum of walls was folded up on corners. It is thus close from the outside. The inconvenience is that the aluminum possesses a very important thermal conductivity ( $237 \text{ W.m}^{-1} \cdot \text{K}^{-1}$ ).

**Experience and hypothesis n°19:** we can suppose that this aluminum generates losses by conduction. By transforming the walls to obtain only the desired aluminum, we hope to decrease these losses.

**Protocol:** We thus renewed the previous experience, to determine the new thermal resistance of the so transformed oven.

**Measure/Conclusion:** further to the success of the air impermeability of the double glazing, we expected a clear improvement of the thermal resistance of the oven. This one does not vary almost in passing from  $0.47 \text{ W.m}^{-1} \cdot \text{K}^{-1}$  to  $0.48 \text{ W.m}^{-1} \cdot \text{K}^{-1}$ , difference which could be simply attributed to the uncertainties of our measuring devices, see in a slightly different positioning of the thermometers.



## Conclusion

So, we can assert that the solar furnace BISS was built to reach an optimal internal temperature or to collect an important quantity of solar energy. Indeed, through our various experiences we were able to notice that materials and geometry of the various components of the oven have their importance at the same time in the collection of a maximum of solar energy but also in its preservation within it.

It is with the big curiosity that we pursue this project today with the aim of driving some improvements in the oven and certain tests are still in progress. Of course, We do not forget that this oven was thought to have a minimum cost and bring an help to developing countries which have a good period of sunshine.

## Thanks

We would never have arrived at such a file without the help of many people. So, we would want to thank at first our two professors Mr Thibault and Mrs Letissier who helped us, and especially spent time to read a number of time our file by suggesting us modifications to emphasize our approach initiative and connect our various experiments. But that's not all, we wish to tell one Thank you the Foundation Dar Bellarj, in particular her director Maha Elmadi who welcomed us with a remarkable generosity. We also thank Maryvonne Grunberg who welcomed us in her magnificent Riad in the center of the Marrakesh medina; Yves Martin de Bolivia Inti, who supplied us two new ovens of his personal stock; Mr Belzanne and Mrs Moust, respectively professors of physics and mathematics at our high school who gave us informations; Pascal Chiron, former president of Bolivia Inti, who helped us to perfect our protocols at the beginning of this project.

## Appendix n°1: How to adapt the solar oven to the drying of food?

This request was made by the president of the association DARNGH, Ali OUAUZIZ. This association aims at developing economically and socially the rural and poor areas of the region from Marrakesh to Morocco. The solar oven had to keep its first function, worth knowing to cook, but was to be able to be transformed into solar airdryer thanks to detachable parts.

### What is the principle of the solar dryer?

The solar dryer allows ,as its name indicates, to dry food and keep it in a " natural " and " healthy " way. The drying is made by a heat not exceeding 60°C otherwise food cooks. However, every food possesses different time of drying according to the quantity of water which it contains. For example, a fig will be dry in less time than a tomato which contains a lot of water. The solar hairdryer possesses numerous advantages due to its construction and its use: It is easy to build ; it requires simple and little expensive materials (wood, laminated) ; it is economic and autonomous because it requires only the presence of the sun ; it is simple of uflisafon ;it is adaptable to the oven ;it is neither cumbersome, nor heavy

### The stages of the construction:

We thought first of all about plans which allowed the adaptation of the hairdryer to a solar oven. Helped then by a volunteer close to the foundation Dar Bellarj in Morocco, further to the discussions with the volunteers of the association Bolivia Inti and our companions, we completed these plans which allowed us to arrive at the final idea rather quickly. For that, we had to make modifications on the solar oven. Indeed, it was necessary that of the air can circulate, that's why we created openings on the top and the bottomof the oven with an adaptable system established by a wire netting.

It was then necessary to begin the construction and to find materials. We chose some wood and the plywood for the manufacturing of the structure of the dryer. We built the box with several railings inside where we can put food as well as a door to open if needed and to have access to food. It was also necessary to plan an air outlet at the top of the structure. For it we left an opening protected by a fine and adjustable wire netting to regulate the air outlet according to the need



## Appendix n°2: How to adapt the solar cooker to the distillation of essential oils?

In Morocco, or in other developing countries, numerous farmers cultivate plants for their essential oil, however for lack of ways, they cannot buy the material necessary for the distillation to produce oil and have to pass by companies which distil in their place, which reduces their thin margins. We thus looked for a way of distilling which requires few resources at the request of the association DARNGH. Yet to distil, it is necessary to boil some water, and to use some wood to warm it would be a very bad idea for the environment. We thus turned to the solar oven. However the sun being not with us this winter, all the measures requiring solar furnaces were taken in Marrakesh. We left with another group which studies only the functioning of the solar oven with whom we had to share three ovens.

Our product does not have anything to see with that of the laboratory, and it was necessary to carry out a research work of materials and understanding of the plant itself. Our results proved that to obtain some essential oil of lavender from the solar furnace is completely possible. We also notice that in France, our assembly is valid only in summer, because in winter the period of sunshine is too low. A solution to distil throughout the year would be to use a solar satellite dish, known to reach powers superior to those of the solar furnace.



### Annexe n° 3 : Vaucanson High School on Marrakech's roofs

La Nouvelle République - 05/02/2014

<http://www.lanouvellerepublique.fr/Indre-et-Loire/Communes/Tours/n/Contenus/Articles/2014/02/05/Vaucanson-sur-les-toits-de-Marrakech-1784569>



*The studious work of the high school students to test solar oven installed on the foundation roof*



*Emmanuel Thibault, teacher, Chloé Fabre, Justine Morel, Théo Ballu, Maxime Tanghe, Léopold Réchou, Maha Elmadi, manager of the fondation et Léo Touchard. - (dr)*

Within the framework of the continuation of the French-Moroccan exchange and their educational personal work, six pupils of eleventh grade from Jacques de Vaucanson" high school ", accompanied by their physics-chemistry teacher, Emmanuel Thibault, were invited in Marrakesh from 24 till 27 January to realize measures on solar ovens installed in 2012 and on their adaptation to distil essential oil from plants. A group of three pupils worked on choices made by Bolivia Inti in the BISS model of solar oven and the other one groups on an adaptation of the solar oven to the hydrodistillation of lavender essential oil.

#### **Let's go to the medina**

They have been welcomed to the « Dar Bellarj » fundation located in Marrakech medina and managed by Maha Elmadi. Ils were able to realize measures with the tree ovens which have been installed on the fundation roofs. Several tests were necessary to verify if they answered the technical expectations from the oven's slope, check of reflectors and double glazing of the oven (etc.)... Then first distillation attempt of lavender which didn't give any oil but a water perfumed in the lavender. Our high school students persisted and thanks to technical modifications they were able to increase the temperature of ovens and managed to realize a rose distillation.

The stay of six high school students financed by the relatives and organized by Maryvonne Grunberg, representative of the Tours' City to Marrakesh, was punctuated with visits and sharing times with young Moroccan of the foundation and there will be certainly a continuation for this project of solar ovens.