Design of a solar coffee roaster for rural areas
- version 1 -

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Abstract

Coffee is the first agricultural exportation product of Peru. Most of the added value is in the roasting process, which is usually done abroad. Concentrating solar energy provides a sustainable, clean and affordable mean of roasting coffee locally. The producers income could be improved with such a technology, enhancing their quality of life.

The design of a solar coffee roaster is detailed in this research work. The open-source Scheffler solar reflector is used to concentrate light on a roasting drum. Experiments and numerical simulations lead to an operational design capable of roasting 1 kg of coffee in 24 minutes with the 2.7 m² solar concentrator. The 25 cm diameter rotating drum ensures coffee mixing to achieve homogeneous roasting. A photovoltaic powered motor is used to rotate the drum. Light heats up directly the interior of the drum entering through a 20 cm diameter opening. Thermal performances are improved through: 5 cm cotton insulation, a cone at the back of the drum and absorbing internal walls (stainless steel loses its reflectivity after some time under high radiation).

People show high interest in the technology, as experienced during tests in the coffee production region near Cusco. Further improvement is encouraged on the current design. An other approach based on indirect heating is also proposed for future investigation.

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1 Introduction

This article explains the steps of coffee production. A review of the very few experiences of solar coffee roasting is established. Specific aspects of solar roasting for rural areas are studied.

Based on this context the tools and approach for detailed design of the roaster are presented. The Scheffler solar concentrator and the roaster concept chosen is explained. A physical model of roaster’s thermal balance is given. Optical modeling is also used for specific aspects. Experimental work further orientates the improvement of the design.

The roaster developed is then described in details: capacity, size, use of glass cover, inclination of drum, optical issues, mechanical aspects, thermal insulation. Support structure and secondary functions of the roaster are also described: feeding, extraction, cooling of coffee beans.

Design characteristics are summed up and perspectives for future work are given.

2 About Coffee

2.1 Coffee from field to cup

Coffee tree can only grow in specific regions at more than thousand meter over sea level. This is the first exportation product of Perú.

The coffee fruit is a red berry that reaches ripeness mostly from April to June.

Once collected, the fruit pulp is taken away and the seed composed of two coffee beans is usually cleaned with water.

The beans then need to be dried. The traditional way is to dry the beans in the sun, during the day. Coffee beans are spread on the ground, on plastic or textile foil or on concrete surface. Industrial drying also exist. It is very energy intensive. The drying phase consumes 84% of the total energy needed for the whole coffee process. Solar dryers can also be used to accelerate the drying and improve the coffee quality. It indeed protects from contamination from the environment (dust, animals...) and the lower probability to have development of microflora (mold and bacteria) that can reduce seriously coffee quality.

The dry bean can be stored, sold or exported as is. Before roasting, its shell has to be removed. Once the shell removed the dry green coffee bean is ready for roasting.

Roasting consist in a partial pyrolysis of the coffee beans. The organic matter is degraded without a flame. The flavor and taste of coffee is revealed during this process. This is a crucial phase of the process that gives the coffee its final characteristics. Depending of the region and culture, people like coffee more or less roasted.

In practice roasting consists in heating the coffee at a temperature of around 200 °C in 15-20 minutes. Faster roasting can be achieved by increasing the temperature at higher levels. A precise monitoring of temperature and visual control of the coffee has to be done to stop roasting at the exact state desired. Slower roasting tends to reduce the coffee quality.
To keep coffee flavor, glass or aluminum provide good packaging. One should wait at least one day before drinking the coffee, to let the CO\(_2\) escape from the roasted beans. If possible it should be ground just before making the beverage. Because the flavor escapes more rapidly once the bean is ground.

### 2.2 Roasting coffee with solar energy

There is very few experience on solar roasting.

**Solar Roast Coffee, USA** The most advanced work was achieved by the brothers Michael and David Hartkop in the USA. Since 2004 they are developing a successful business based on solar coffee roasting. Their first four prototypes used concentrating solar technologies. The table 1 summarizes the size evolution of Solar Roast Coffee’s prototypes. Their second prototype *Helios 2* of about 3 m\(^2\) could roast 1 kg of coffee in 20 minutes. The focus point has a 65 cm\(^2\) surface and can reach a temperature of 650 °C. The most advanced solar concentrator *Helios 4* of 36 m\(^2\) could deliver 20 kW of heat, enough to roast 13.6 kg in 20 minutes. A gas burner was providing energy in case solar energy was lacking. Figure 1 illustrates those prototypes.

In July 2012 they just put in operation a new hybrid coffee roaster electricity powered, with gas backup. A photovoltaic panels array connected to the grid is producing electricity for the roaster. Electricity from the grid or gas is used in case solar energy is not enough. The energy efficiency of the photovoltaic panels (15%) and the thermal efficiency of the electric roaster make the whole system less efficient than the solar thermal concentrator based technology. The photovoltaic system involves more advanced and expensive technology. But the brothers Hartkop argue that the photovoltaic system is producing energy all day long, even when the roaster is not operating. In this way, the electricity sold to the grid compensate the lower efficiency of the new system [?]. This approach is nevertheless not suitable for rural areas.

**Cocoa roasting, Mexico** Started in 2004, Chocosol is producing every year 260 kg of solar organic chocolate they sell on the market of Oaxaca. Cocoa beans as well as other
Table 1: Size evolution of the prototypes from Solar Roast Coffee

| Prototype | Surface of concentrator $\text{m}^2$ | Thermal power $\text{kW}$ | Mass of coffee per 20 minutes batch $\text{kg}/\text{20min}$ |
|-----------|--------------------------------------|--------------------------|----------------------------------------------------------|
| Helios 1  |                                      |                          | 0.45                                                     |
| Helios 2  | $\sim 3$                             |                          | 0.9                                                      |
| Helios 3  | 7                                    |                          | 2.3                                                      |
| Helios 4  | 36                                   | 20                       | 13.6                                                     |

Figure 2: “Solar Fire” used by Chocosol to roast cocoa in Mexico

Ingredients like peanuts are processed during the roasting season, about 8 to 9 months a year. They use a solar concentrator called “Fuego Solar”, Solar Fire, see image 2. The solar fire is an open-source project to develop solar technologies aiming at “radically reduce pollution, energy poverty and help solve The Thermal Problem”. The solar oven has a power of 3 kW and can reach a peak temperature of up to 950 °C [?].

Experiments of Scheffler, Germany The Scheffler family, who invented the Scheffler concentrator used in the present project, experiments a lot with the sun. They roasted coffee in a box-cooker with 4 mirrors on the sides to increase solar power on the box and reach the necessary 200 °C for roasting. The coffee beans were placed in a glass container with glass tap to avoid mist to appear on the glass cover of the cooker box. The system works and seems to give very evenly roasted beans [?].

2.3 Focusing on a technology appropriated for the rural sector

The project Intikallana, which means “solar roaster” in Quechua, the local language in the Andes, aims at providing a clean and economic technology to coffee producers.

2.3.1 Economical aspects

In the communities of the Andes mountains, the producers mostly sell their production of coffee as dried green beans. The prices vary a lot. In 2011, dry green coffee was sold at
just over 3 $/kg (380 soles/quintal), whereas at the time of this study (2012), the price went down to 2.3 $/kg (280 soles/quintal) according to producers. Moreover most of the added value of the coffee is in the roasting process. Roasted coffee on the market can be found at 20 soles/500 g (12 $/kg) for medium quality and up to 40 soles/500 g (24 $/kg) for high quality coffee in Peru. Roasting even part of his production can improve significantly a producer’s income and quality of life.

2.3.2 Roasting methods

Roasting is a key process in the production of coffee. It involves precise know-how to achieve good coffee quality.

Traditional way Local people practice it for their own consumption. The typical way for traditional roasting is using a pan on a normal wood stove as shown on photo 3. Good homogeneity of roasting is not always easy to reach with this technique. Being able to roast coffee with higher quality in an affordable and ecological way would help producers to improve their income and thus quality of life.

Drum with blades, batch process This is the most commonly used technology to roast coffee. A horizontal cylindrical drum rotates with the coffee inside. Blades ensure a good mixing of the coffee for an even roasting. The heat source is usually provided below the drum with natural gas. Some roasters, usually small models, are heated up with electricity. An air flux is fed into the roaster to bring heat per convection. It also helps remove the “silver skin”. This small layer falls off the grain during roasting. Its high nitrogen content and faster thermal degradation tend to modify the coffee taste.

Fluidized bed, continuous process Fluidized bed consist in maintaining the coffee beans in suspension thanks to a strong air flux fed below the coffee beans. Although it is not necessarily the case, this technique enables the roasting to be a continuous process. The
advantage of using a fluidized bed is that the bean heating is more homogeneous thanks to heat transfer through convection.

This technology is more advanced and rather applied in industrial roasting.

2.3.3 Using solar energy for roasting in rural sector

A solar technology is clean of emissions during use, in comparison with roasting with wood, which is the common energy source in traditional roasting. The objective is thus to provide a low tech process, for a robust technology that keeps costs low. Once the investment realized, the operation costs remain very low.

Close contacts are established with the village of Huyro, where the implementation of the technology is to take place first. Huyro is at one hour from Quillabamba, in the district of La Convencion, region of Cusco, Perú.

3 Tools and main considerations

3.1 Main characteristics of the approach

3.1.1 Scheffler solar concentrator

Taking into account the context of rural sector, the technology should be kept simple and robust, involve material easy to find locally, so as to facilitate construction, operation and maintenance of the process.

In this context the Scheffler reflector is chosen for being a good solar concentrator. Indeed, the Scheffler reflector is open source technology, which means anybody can copy it without paying for a patent. This is considered as a key advantage in the scheme of the project. The photo 4 shows the Scheffler concentrator of 2.7 m² of mirror surface used for the roasting experiments.

One important characteristic of the Scheffler reflector is that the focal point remains fixed. This is an advantage in comparison with the other technologies developed in the USA or Mexico (section 2.2). Indeed the roaster does not need to move, beside its own rotation of course.

The Scheffler concentrator requires only one axis tracking and is mechanically balanced on this axis. This makes manual tracking easy and automatizing it needs only one single small motor.

As open-source technology, extensive documentation on the characteristics and construction details of the Scheffler reflector are available online. Larger versions of 8 and 10 m² exist that will enable to upscale the technology developed in the current project for the 2.7 m² reflector.

3.1.2 Cylindrical drum with blades

The most appropriated technology for roasting in our case is using the widely spread approach based on a rotating drum with blades inside. This keeps the technology simple and ensures good homogeneity of the roasting.
Figure 4: Scheffler concentrator in the test field in Huyro, region of Cusco, Perú
3.1.3 Direct solar flux on coffee

To achieve the highest thermal efficiency with the most simple system it was chosen to heat the coffee beans directly with sun light. The concentrated light beam of the Scheffler reflector is coming horizontally under latitudes of Perú.

To allow the sun beam to reach the coffee a horizontal cylinder opened at one end is perfect. The opening enables the humidity and smoke produced to escape. According to the quality of the focal point a diameter of 20 cm is required for the opening.

3.1.4 State of the art, own experiments and modeling

The design of the roaster is based on various elements including:

- coffee roasting state of the art, although reduced.
- numerical simulations of solar roaster. Optical simulations have been carried out with SolTrace, developed by the NREL (National Renewable Energy Laboratory, USA). An analytical thermal model has been developed too.
- experiments carried out in this project. Using the Scheffler concentrator built in 2010 in the University, a solar roaster has been developed and constructed to study its performances. Tests has permitted gaining knowledge on the technology and optimizing the initial concept. First tests were performed at the University in Lima, with rather low solar radiation levels. These were nevertheless essential in the system’s improvement process. A test campaign was carried out in the coffee production zone of Huyro at the end of the project. Good and interesting results were achieved and further improvement perspectives have been provided.

3.2 Physical model

The designing process is guided by results of experiments and a physical model. The physical model is composed of two parts:

- an optical model developed in SolTrace (ray-tracing simulation tool from NREL) and
- a thermal balance of the process based on analytic model in Octave (open-source alternative to MatLab).

It gives information on the global behavior of the system. The system modeled is justified in the following section focused on the prototype design. In the same time, some elements of the simulation orientate the design of the prototype in the following section.

3.3 Experimental results

3.3.1 Organization of the experimental tests

Test campaigns Some preliminary tests were conducted in the University in Lima, making the most of the little sun radiation in the winter season. A more significant test campaign was realized in Huyro where the solar radiation is generous. 4 days of full testing enabled to get good results and permitted to establish guidelines for roasting and further optimize the coffee roaster.
Tests procedure More than 20 experiments have been conducted. To be able to compare results from the different experiments a procedure is established.

3.3.2 Experimental roasting time: 1 kg in 24 minutes

With a moderate sun radiation of 740 W/m², the tests show 1 kg of coffee can be roasted in 24 minutes with an inclination of 19°. With a high radiation of about 900 W/m², 1.5 kg can be roasted in 36 minutes. It is not recommended to roast much more than 1 kg as the more time the roasting lasts, the lower the quality tends to be. Indeed the ideal time is to roast in 15 to 20 minutes.

The roasting time depend a lot on the radiation level and the quantity of coffee.

3.3.3 Evolution of coffee temperature during roasting

The figure shows how the coffee temperature evolves during roasting and cooling. In this case 621 g of roasted coffee were yielded from 750 g of green coffee (17% mass loss). The detailed design of the roaster is explained in the following sections. The result presented here aims at showing the principle of the roasting process.

It can be observed that the heating slows down when the temperature increases. But once 160°C is reached after 7 minutes, the coffee bean is completely dry (1% of humidity) and the roasting chemical reactions start to take place. As the coffee color starts changing from light green to yellow and darkening brown, the coffee bean absorptivity increases. This explains the maintained heating efficiency at higher temperatures. The famous “first crack” was heard at 13 minutes. It is caused by the changing structure and volume expansion of the bean during the roasting. The coffee bean can double volume.

Additionally to the effect of increasing absorptivity the reactions tend to be exothermic in the last roasting phase. For that reason and to avoid overheating of the coffee, at 15.5 minutes the Scheffler concentrator is defocalized which lowers the heating power. It is observed a light decrease of the coffee temperature in the following minute. The coffee is extracted from the roaster after 17 minutes. The cooling process takes 5 minutes to lower the temperature from 200 °C down to 50 °C.

4 Design of the solar coffee roaster

4.1 Design of the roaster

4.1.1 Drum sizing

To define the size of the roaster the thermal power available with the concentrator needs to be known.

According to the prototype Helios 4 from Solar Roast, it needs about 1.5 kW to roast one kilogram of green coffee in 20 minutes (20kW for 13.6kg). Their collector measures 36 m². Ours has 2.7 m² of aperture, which gives a theoretical power of 1.5 kW that makes it possible to roast 1 kg per batch.

Measurement has been taken of the power heating a mass of water (0.5 kg) in a dark pot placed in the focal point of the concentrator. Under 680 W/m² of direct radiation the maximum power measured was of 1046 W. Assuming linear variation of the power with direct
radiation, a 1000 W/m² sun would provide up to 1535 W. This measurement is consistent with the previous calculation.

Sizing the drum for a maximum of 1 kg coffee is done accordingly to existing roasters. On the roasters observed, the ratio $\frac{V_{gc}}{V_d}$ of green coffee volume $V_{gc}$ to the drum volume $V_d$ is in the range of 24% to 32%. The beans close to double volume during roasting reaching a roasted coffee volume $V_{rc}$. This leads to a volume ratio $\frac{V_{rc}}{V_d}$ of 48-64%. The diameter to total length ratio $\frac{D}{L_t}$ vary from 0.5 to 0.8 depending on the technologies observed.

The size of the focal point of our concentrator imposes a minimal diameter of 0.2 m. Keeping this minimal diameter, a length of 0.23 m gives a roaster with low fill ratio $\frac{V_{gc}}{V_d}$ of 23.5% and high diameter to total length ratio $\frac{D}{L_t}$ of 0.87. This size is our small drum reference as summarized in table 2. Such a design imposes to tap the drum by a glass cover to let the light enter the cylinder and keep the coffee inside.

### 4.1.2 Delicate use of a glass cover

Some tests have been conducted with a glass closing the opening. The aim is reducing thermal losses from convection and infrared radiation. But an opening has to be provided to evacuate humidity. It is also good the thin silver skin that falls off the grains during roasting can be eliminated. Although the horizontal cylinder approach eliminates only partially this silver skin, adding a glass cover worsen the situation. From thermal performances point of view,
test results show the glass cover helps. It enabled successful roasting with radiation as low as 480 W/m²: 0.5 kg roasted in 21 min in the small drum.

But as the light entering is also reduced by reflectivity and transmissivity of the glass, the benefit is reduced: see optical simulation page 12. For security reasons it is also better not to get glass involved. Especially considering the high temperatures experienced by the glass. Normal window glass has been tested and breaks systematically: a tempered glass is required. In the end it is chosen not to use the glass cover for coffee roasting.

However for special applications, the glass cover happens to be necessary. For example for producing pop-corn, the test without glass provides food to the operator as corn grains are popping out of the drum! In this case using a tempered glass cover fixed the inconvenience and gave very good results. The grains popping early do not degrade as their white color reflects most of the radiation.

4.1.3 Sizing without glass, inclining the drum

To be able to fit 1 kg in the drum without putting glass cover, the drum has to be a bit oversized. Inclining it can limit the increase of size. But inclination has to remain small to avoid high convection losses through the aperture.

To fit 1 kg without inclination, a drum is designed with a $D = 0.36$ m diameter and $L_t = 0.28$ m length including an 0.08 m conical part on the aperture side with a 45° angle. This drum is the large version. Poor thermal performances lead to difficult roasting when radiation is low.

A compromise is found with an inclination of 15°. A diameter of 0.25 m is sufficient. The required depth is then $L_t = 0.275$ m, including the 0.025 cm conical part around the aperture with 45° angle. The $D/L_t$ ratio is 0.9 and the fill ratio $V_r/V_d$ falls at 12.5 %, reaching 25% at the end of the roasting. This drum is the medium reference. It is a compromise between the too small and too big one. It enables roasting of the maximal quantity the concentrator’s power allows without requiring a glass cover.

These three reference drums are defined with geometrical parameters of schema 6. Values for the small, medium and large drums are summed up in table 3.
Roasting drum size
| Drum size | D (m) | L (m) | d (m) | Cone at the front a (°) | Cone at the back b (°) |
|-----------|-------|-------|-------|-------------------------|------------------------|
| Large     | 0.36  | 0.2   | 0.2   | 45                      | 0                      |
| Medium    | 0.25  | 0.25  | 0.2   | 45                      | 25                     |
| Small     | 0.2   | 0.23  | 0.2   | 0                       | 30                     |

Table 3: Parameters of the three reference size drums

4.1.4 Optical absorptivity of the material

An absorbing material is better than a reflective one. This is especially true in the first phase of the roasting, when the coffee beans have a clear color. A dark surface absorbs more radiation and brings more heat to the coffee per conduction. The stainless steel is a good candidate in this sense: from reflective when new, it turns brownish after some minutes of exposition at high solar radiation.

4.1.5 Optical simulation

**Benefit of a cone at the back**  It is observed a significant part of the radiation is lost per reflexion on the back side of the drum. Reducing reflectivity of the internal wall is a solution. Implementing a conical surface at the back ensures that no ray can be lost by single specular reflection inside the drum. For this reason it is calculated that the medium scale drum requires a cone of 25° and the small one 30°. Simulation results as shown in table ?? quantify the benefit of the cone.

On the small roaster the cone reduces reflection losses from close to 18% to less than 5%. A similar effect is observed on the medium size roaster.

**Effect of glass cover**  The glass cover is especially useful on the small drum to fit more coffee inside. 10% of the power available at the focal point is absorbed on the glass. This leads to reduced power absorbed on the drum’s internal wall. Assuming half of the power absorbed on the glass contributes to the thermal exchange inside the drum, 85% of the power is transferred inside. 10% less than in the configuration without glass (95%). Of course this simulation does not include losses per infrared radiation. The balance is not as bad with the glass, but this lower power available inside is to be taken into account.

4.1.6 Blades design and rotational speed

Blade design is important to guarantee that the coffee beans move continuously. Cardboard prototypes are built to validate theoretical design. The inclination is taken into account, to avoid that beans get stuck at the back of the drum or in contact with the hot surface of the drum. Figure 13 shows the final design of the blades. It can be noticed the coffee is situated more on one side of the drum than on the other due to the action of the blades. As a consequence, it can be beneficial to change slightly the orientation of the drum to focus more light on the side where the coffee is situated (not facing exactly the axis of the Scheffler concentrator).
The coffee behaves differently in the drum depending on the rotational speed of the drum. The present blades are suitable for rotational speed from 5 to 20 rpm (revolution per minute). Cartridge pre-prototypes were built to validate the planned behavior of coffee.

Most tests have been carried out at around 10 rpm. This speed showed satisfying mechanical behavior of the coffee. In some experiments small traces of burning on the grains were observed. These are due to prolonged contact with the drums surface. A higher rotational speed is advisable to improve coffee quality.

4.1.7 Material of the drum: stainless steel

Stainless steel is chosen for being widely recommended in food processes. It does not interact chemically with food. Under high radiation, stainless steel changes color: from reflective, it turns opaque with a brownish-violet like color. This reduces its reflectivity and improves the thermal efficiency of the roasting. Especially in the beginning when coffee is of clear green color.

Aluminum does migrate in food and has proved impact on health. Nevertheless for its excellent thermal properties it is decided to study the behavior of an aluminum drum.

Comparison of tests number 7 and 11 gives indication of the different behavior of those two materials. Both tests are roasting 750 g of coffee under high direct solar radiation 930 W/m² and 941 W/m² respectively. Test 7 is with the stainless steel drum without insulation and test 11 with the aluminum drum with thermal insulation. The surprising result is the roasting times are similar respectively at 15 min and 17 min. Test 10 at 920 W/m² needed 31.5 min to roast the same quantity of coffee in the non-insulated aluminum drum. Although the concentrator tracking was not perfect and affected this test, it is clear the material plays a role. High thermal conductivity of aluminum increases a lot the thermal losses when the drum is used without insulation.
4.1.8 Thermal insulation

Thermal insulation is an important way to reduce heat losses and improve the roaster efficiency. A textile is chosen for its neutrality with food: recycled cotton textiles are used. Although the temperatures the insulation faces are at the limits of the material resistance. Special precautions are taken:

- aluminum foil protection is placed around the focal point aperture,
- a layer of jeans is placed in contact with the metal of the drum.

Cotton has a low thermal conductivity $\lambda_{cotton} = 0.06 \text{ W/m/K}$ providing very good insulation. A layer of about 5 cm keeps the outer surface of the insulated drum at around 50°C. This is consistent with the predicted values of a calculation of thermal resistances.

Alternative material would be mineral or glass wool. If such a material is chosen, it is recommended to carefully enclose the insulation to ensure no fiber can be mixed with the coffee. This would lower the quality, possibly putting in danger the consumer’s health.

4.2 Design of the support structure and auxiliaries

4.2.1 Support structure

The support structure is shown on figure 8.

4.2.2 Feeding and extracting the coffee beans

The coffee is fed into the roaster and extracted as illustrated on figure 9.

4.2.3 Mechanical system

An electrical motor is ensuring the rotation of the drum. Various power sources can be used to have it rotate:
Figure 9: Schema showing principle of feeding (left) and extracting (right) the coffee in/from the roasting drum

- a manual rotation of the axis. It is similar to moving the coffee with a spoon in the traditional procedure. Think a roasting batch lasts only 20 minutes. This is how we did it in the first tests.

- an electric motor powered by a photovoltaic panel and small battery: is convenient, can be implemented anywhere, but also expensive. The advantage is the system can be used for other purposes when the roaster is not in use. The battery can provide peak power for efficient cooling of the coffee.

- a bicycle based mechanical system.

- a hydro wheel powered by a nearby water stream when available.

- an electric motor powered by a generator or the grid when available.

### 4.2.4 Cooling of roasted coffee

Once the coffee is roasted it needs to be cooled rapidly immediately after being extracted from the drum. The coffee should be brought to a temperature of 50°C in 3 minutes. A mechanical system with strong aspiration sistem (using a vacuum cleaner achieves cooling of 1 kilo of coffee in less than 3 minutes. But the feasibility for rural areas is not satisfactory.

A manual cooling gives reasonable performances. The coffee has to be spread on a large area to maximize contact with ambient air. Cooling was carried out on a large piece of cartridge. Creating artificial wind on the coffee accelerates significantly the cooling in comparison to letting it cooling by natural convection. For example in test 13, 1.5 kg was cooled down to 50°C in 7.5 min. 0.75 kg was cooled down in 4.5 min (test 15).
Improvement could be achieved using a stainless steel grid. Metal is a good material as heat can be evacuated rapidly and the grid holes enable elimination of the remaining silver skins. Stainless steel respects the food quality.

4.3 Synthesis of roaster design

4.3.1 Study of design parameters

Effect of drum size The size of the cylinder proved to have a significant effect on the roasting time. A smaller cylinder gets better results because the surface for thermal losses is reduced. A compromise is to be found between the size of the cylinder and the quantity that can be roasted. To reduce its size, keeping the opening of 20 cm diameter, the cylinder can be inclined. An inclination of up to 19° showed to have relatively low effect on the thermal performances of the process. Thus a cylinder 28 cm deep with a 25 cm diameter can roast up to 1.5 kg of coffee.

Effect of drum material Stainless steel seems to be a good material for the inner surface of the cylinder. Tests were conducted with aluminum which performs well too, provided a good insulation is used. Without insulation, the high conductivity of aluminum leads to bad results.

Optical absorptivity of the material An absorbing material is better than a reflective one. This is especially true in the first phase of the roasting, when the coffee beans have a clear color. A dark surface absorbs more radiation and brings more heat to the coffee per conduction. The stainless steel is a good candidate in this sense: from reflective when new, it turns brownish after some minutes of exposition at high solar radiation.

Effect of thermal insulation The influence of thermal insulation is clear. It proves to be a simple and worth way to improve the thermal performances of the roaster.

4.3.2 Recommended characteristics of the solar roaster

A cylinder in stainless steel 28 cm deep with a 25 cm diameter, see photo 4 for dimensions, gives good results. A bigger size does not bring any benefit. The cylinder should be insulated with about 5 cm of insulation. A glass cover is not necessary. To fit up to 1.5 kg of coffee in the cylinder it can be inclined at up to 20°.

4.3.3 Foreseen improvement

Learning from coffee quality The quality of the coffee obtained is good for a first step. Small imperfections indicate some ways of improvement:

- preheating the cylinder at no more than 180 °C: indeed over-roasting on the outside and under-roasting in the heart of the grain is observed in some of the tests. It is probably due to over-preheating of the drum. Thus when introducing the coffee the grains tend to burn on the outside, before the heart can be heated up;
Figure 10: Example of test on a prototype with insulation (left) and without insulation before the installation of the motor (right), test field of the support group for the rural sector, Pontificia Universidad Católica del Perú

- rotating faster the drum: darker traces on the flat side of the grains is the indication of a too low rotational speed of the drum. With around 10 rpm grains remain too long in contact with the hot surface of the cylinder.

**Alternative approach to be investigated** An alternative approach consists in heating the solar roaster drum from the outer surface. The cylinder would be black at least on the outside so as to absorb as much light as possible. Holes in the cylinder would enable elimination of the silver-skin, water vapor and other gases produced during the process. The drum would be located in an insulated box with a hole that should be inclined downwards to limit convection losses. Having a cylinder totally closed enables a size reduction for the same amount of coffee, further improving the thermal performances of the system.

Charging coffee could be done as always per gravity and discharging could be done by clever blades in the drum that extract coffee beans simply by reversing the rotational direction.

This alternative approach has not been investigated yet for time constraint and because the focus was on developing the most simple and efficient system. But the results obtained in the current study encourage both improving the current prototypes and investigating seriously in this alternative direction.

### 5 Conclusion and Perspectives

Further applications can be developed based on this technology. It was demonstrated the coffee roaster can be used to roast cocoa and broad beans too. Pop-corn can even be produced easily, provided a tempered glass is placed in front of the cylinder to prevent the corn beans to pop out of the cylinder! The same concentrator can be used for cooking and other application can be developed, such as milk pasteurization, essential oil extraction...

The current state of development of the technology is very promising. The concept proved to yield good results like illustrates photo 11. The technology raises attention and people from the community seem interested. The perspectives of this solar roasting technology are great.
But there is a lot to do to improve this first generation of prototypes. The foreseen steps to follow in next phase of this project can be summarized as follow:

- improvement of the prototypes developed:
  - improve the structure that supports the roasting cylinder, including the system that enables easy extraction of the coffee at the end of the roasting;
  - improve the cooling process of the coffee to ensure good quality of the coffee;
  - implement a temperature sensor for easy control of the temperature in the cylinder;
  - implement the photovoltaic power unit to supply the motor that ensures the rotation of the roasting cylinder; the same power unit could provide energy for the cooling process;
  - design a robust electrical system to resist the humidity;

- provide a user guide and organize a workshop on how to use:
  - the Scheffler reflector and
  - the solar roaster, specific know-how is required to obtain coffee of good quality. Although with little experience, it is possible to learn and get decently good coffee;

- further experiment with better monitoring of the variables of interest. This will enable comparison with the physical model, leading to a better understanding of the system. In this way the design of the technology will be surely further optimized.

- investigate seriously in the alternative approach based on a closed cylinder heated from outside and protected by an insulating box.
  - develop a physical model inspired by the existing one,
  - develop and build prototypes to validate expected results

- study the strategies to enter the market with such a solar coffee roaster
Figure 11: Results obtained in Lima on the 26 of June 2012