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Design of a Solar Coffee Roaster for Rural Areas

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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. Another approach based on indirect heating is also proposed for future investigation.

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Keywords: Solar concentrator; solar coffee; roaster; thermal concentration; coffee roaster

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. 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

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 and it is focusing on a technology appropriated for the rural sector.

2.1 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 Figure 1: Traditional roasting in a pan on a woodstove 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.

Figure 1: Traditional roasting in a pan on a woodstove

2.2 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 Convención, región 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 Figure 2 shows the Scheffler concentrator of 2.7 m^2 of mirror surface used for the roasting experiments.

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.

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 2: 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 simplest system it was chosen to heat the coffee beans directly with sun light. 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 Experimental results

3.2.1 Organization of the experimental tests

Test campaigns Some preliminary tests were conduced 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.

Tests procedure More than 20 experiments have been conduced. To be able to compare results from the different experiments a procedure is established.

3.2.2 Experimental roasting time: 1 kg in 24 minutes

With a moderate sun radiation of 740 W/m^2 , 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.

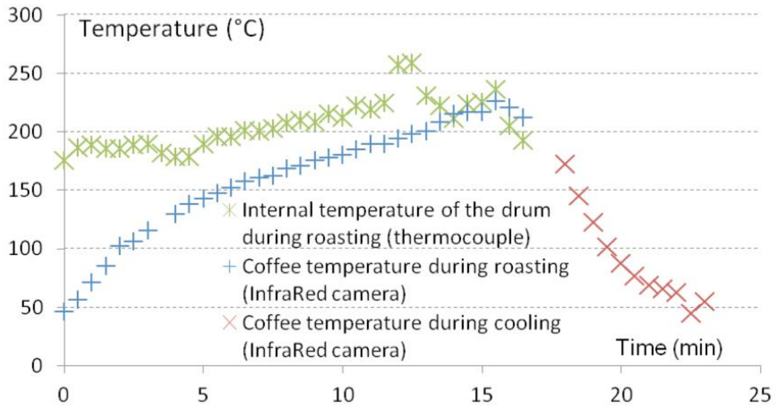

Figure 3: Typical evolution of temperatures during roasting and cooling process

3.2.3 Evolution of coffee temperature during roasting

The Figure 3 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.

Table 1: Size and ratios of cylinders considered

Drum	D (m)	L_t (m)	D/L_t (-)	S_p (m^2)	V_d (m^3)	V_{gc}/V_d(%)	V_{rc}/V_d(%)
small	0.2	0.23	0.87	0.18	0.0072	23.5%	47.0%
medium	0.25	0.275	0.91	0.27	0.0135	12.5%	25.1%
large	0.36	0.28	1.29	0.42	0.0285	5.9%	11.9%

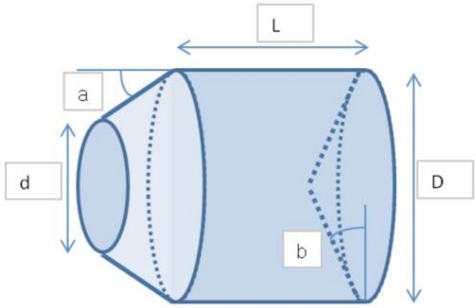

Figure 4: Roasting drum geometry

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, 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 Vgc/Vd of green coffee volume Vgc to the drum volume Vd is in the range of 24 % to 32 %. The beans close to double volume during roasting reaching a roasted coffee volume Vrc. This leads to a volume ratio Vrc/Vd of 48-64 %. 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 Vgc/Vd of 23.5% and high diameter to total length ratio D/Lt 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 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.

A compromise is found with an inclination of 15°. A diameter of 0.25 m is sufficient. The required depth is then Lt = 0.275 m, including the 0.025 cm conical part around the aperture with 45° angle. The D/Lt ratio is 0.9 and the fill ratio Vgc/Vd 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 Figure 4. Values for the small, medium and large drums are summed up in Table 2.

Table 2: Parameters of the three reference size drums

Roasting drum size	Drum 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

4.1.3 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.

4.1.4 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 5 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 planed 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.

Figure 5: Final design of blades in the medium size drum to ensure homogeneity of coffee roasting

4.1.5 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.

4.1.6 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.

Cotton has a low thermal conductivity, cotton = 0.06W/m/K providing very good insulation. A layer of about 5 cm keeps the outer surface of the insulated drum at around 50°C.

4.2 Design of the support structure and auxiliaries

4.2.1 Support structure

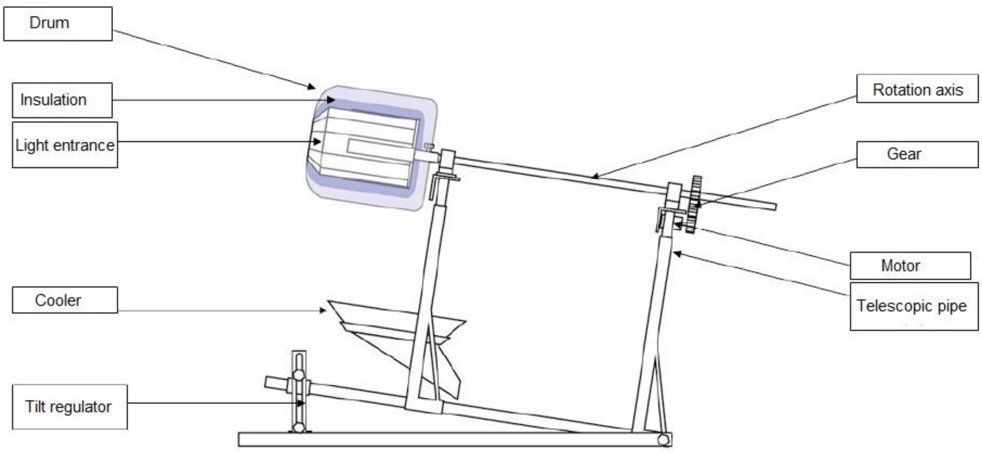

Figure 6: Schema of the support structure for the roasting drum and its mechanical system

4.2.2 Feeding and extracting the coffee beans

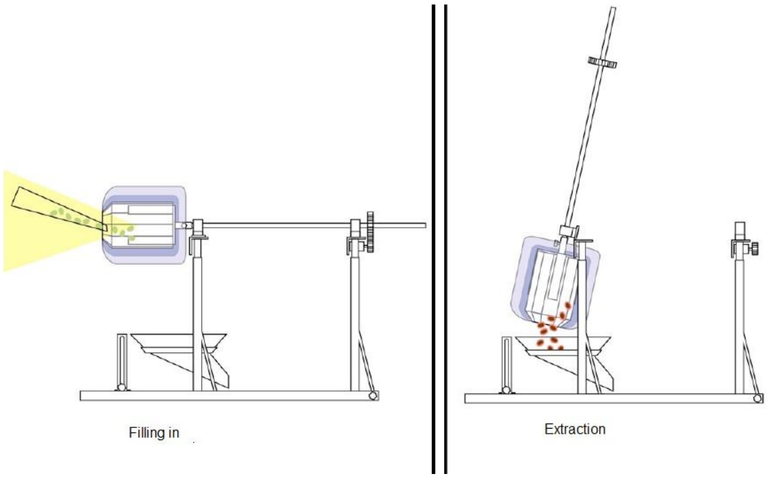

Figure 7: Schema showing principle of feeding (left) and extracting (right) the coffee in/from the roasting drum

4.2.3 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 system (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.

5. Conclusions 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 Figure 8. 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.
  - improve the cooling process of the coffee to ensure better quality of the coffee;
  - implement a temperature sensor for easy control of the temperature in the cylinder;
  - 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 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 in the alternative approach based on a closed cylinder heated from outside and protected by an insulating box.

• study the strategies to enter the market with such a solar coffee roaster

Figure 8: Results obtained in Lima on the 26 of June 2012

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