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# Technico – economic study of an indirect solar dryer for Drying Cocoa Beans in Madagascar

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***ABSTRACT:*** *In this paper, the authors discuss the technical and economic feasibility of using an indirect solar dryer for drying cocoa beans after fermentation in the northern region of Madagascar after five years. Ambient air is sucked in by a fan and through a resistance installed at the sensor inlet to raise its temperature in case of insufficient heat from the sun inside the chamber. The circulation of hot air is one-dimensional, constant speed and ensured by a second fan placed at the entrance of the room. The purpose of our study is to accelerate the drying technique to improve the quality of the dried products until the moisture content reaches 8%. On the other hand, we present the variation of the solar power received by the absorber used during the drying of a day sunshine as well as the advantage procured using this apparatus in the face of the exploitation of others. types of energies Result is profitable, the investment is achievable because the net present value is positive at the discount rate of 15% used as an indicator of financial profitability.*

***KEYWORDS****: drying, solar energy, cocoa bean, economic study, forced convection.*

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## NOMENCLATURE

### Roman letters symbols

| | |
|---|---|
| $C_e$ | Mass fraction of water in the product in (%) |
| $C_v$ | Mass fraction of water vapor in (%) |
| $C_p$ | specific of heat transfert fluid, (J/kg.K) |
| $C_{pi}$ | calorific capacity of insulation, (J/kg.K) |
| $C_{pa}$ | calorific capacity of the absorber, (J/kg.K) |
| $C_{pv}$ | capacity capacity of the glass, (J/kg.K) |
| $D_h$ | hydraulic diameter, (mm) |
| ep | thickness between glass and absorber (mm) |
| $h_{cv}$ | conductive transfer coefficient of glass (W/m².K) |
| $h_{ci}$ | conductive transfer coefficient of insulation (W/m².K) |
| $h_{rvc}$ | radiative transfer coefficient between the glass and the celestial vault (W /m².K) |
| $h_{rav}$ | radiative transfer coefficient between the glass and absorber ( W /m².K) |
| $h_{rai}$ | radiative transfer coefficient between absorber and insulation ( W /m².K) |
| $h_{ris}$ | radiative transfer coefficient between insulation and floor, (W /m².K) |
| $h_{cv}$ | convective transfer coefficient of the glass (W / m².K) |
| $h_{cva}$ | convective transfer coefficient between glass and absorber (W /m².K) |
| $h_{cas}$ | convective transfer coefficient between drying air and absorber (W /m².K) |
| $h_{cai}$ | convective transfer coefficient between drying air and insulation(W / m².K) |
| I | solar constant (w / m²) |

| | |
|---|---|
| Io | radiation received by a horizontal surface outside atmospher($J/m^2$.day) |
| J | day number in the year |
| Q | mass flow rate of the fluid (kg / s) |
| Mv | half of the mass of the glass for $\Delta x$ (kg) |
| Mi | half of the mass of the insulation tor $\Delta x$ (kg) |
| Mn | mass of the absorber $\Delta x$ (kg) |
| Pv | power absorbed by the glass ($W/m^2$) |
| Pn | power absorbed by the absorber ($W/m^2$) |
| $T_a$ | ambient Temperature (° C) |
| $T_c$ | Temperature of the celestial vault (° C) |
| $T_f$ | air flow temperature(° C) |
| $T_{ii}$ | temperature inside of the insulation(° C) |
| $T_{ie}$ | temperature outside of the insulation(° C) |
| $T_n$ | temperature of the absorber (° C) |
| $T_s$ | temperature of the floor(° C) |
| $T_{ve}$ | temperature outside of the glass(° C) |
| $T_{vi}$ | temperature inside of the glass(° C) |
| $T_p$ | temperature Product (° C) |
| $T_g$ | temperature of the gas (° C) |

**Greekletters symbols**

| | |
|---|---|
| $\alpha n$ | absorption coefficient of the absorber |
| $\varepsilon$ | emissivity |
| $\rho$ | density of the fluid in [kg / m3] |
| $\sigma$ | Stephan Boltzmann constant |
| $\alpha v$ | absorption coefficient of the glass |

**Financial Analysis**

| | |
|---|---|
| CF | Cash Flow |
| DNCF | Discounted Net Cash Flow |
| CDNCF | Cumulative DiscountedNet Cash Flow |
| NPV | Net Present Value |

# I. INTRODUCTION

As Madagascar is a country with an agricultural vocation with nearly 70% of the population comes from rural areas, its economy is also the source of its foreign currency depends on its food crop and sales cultures such as the export of raw coffee, dry cocoa beans, vanilla and clove. The requirement of foreign and local customers is to present a dry product with a moisture content according to international standards and with a mechanism of impurity. Moreover, in order to fight against shortage against season to allow face the demand of the customers, the mode of conservation by drying is the most adapted to the tropical climate decrease the cost to the operators of gross product under added value in order to be competitive in the local and international markets compared to other types of drying technology.

Numerous researches has already been published on the indirect solar drying of cocoa beans. Among them, Nghanhou, J. et al. [1] mathematically modeled the cocoa drying process in an indirect hot air dryer system in continuous operation. Scientifics work [2-4] corroborates their results. Ndukwu et al [5] studied the influence of drying temperature and drying air speed on the drying speed and drying constant of the cocoa bean. Komolafe C.A et al [6] show the development of a discontinuous drier of cocoa beans with natural heated air, which is inexpensive, simple to build and capable of reducing the problems associated with traditional drying in the sun. C.L. Hii et al [7] presented a comprehensive study and simulated the step drying profiles in a conditioned and humidified body. Nghanhou, J. [8] studied the modeling of mathematical equations concerning the transfer coupling phenomena involved in drying in a thick layer of forced convection cocoa beans. Then, it makes the quantitative comparison between a model of transfers and experimental results and affirms that this model constitutes a means of satisfactory description these phenomena of transfer. Other researchers like E. Alidina et al [9] propose to study the feasibility technical and economic of a large conventional corrugated iron hangar manufactured at a relatively low cost and available everywhere for paddy drying applied in Madagascar.

had regard of all this work, this study also presents, first, the establishment of this device suitable for drying Malagasy cocoa and Africa. Note that in Madagascar, cocoa produces only in the district of Ambanja (northern region of Madagascar) where the climate required by the cocoa culture is met. Moreover, it can be said the Madagascar cocoa is among the best quality and in most cases the crops qualify for an organic label due to the non-use of chemicals such as pesticide, insecticide and fungicide. Secondly, we present its economic profitability after five years because, according to the financial analysis, we find the Net Present Value (NPV) is positive at the discount rate of 15%.

## II. MATERIAL AND METHODS

### 2.1 System Overview

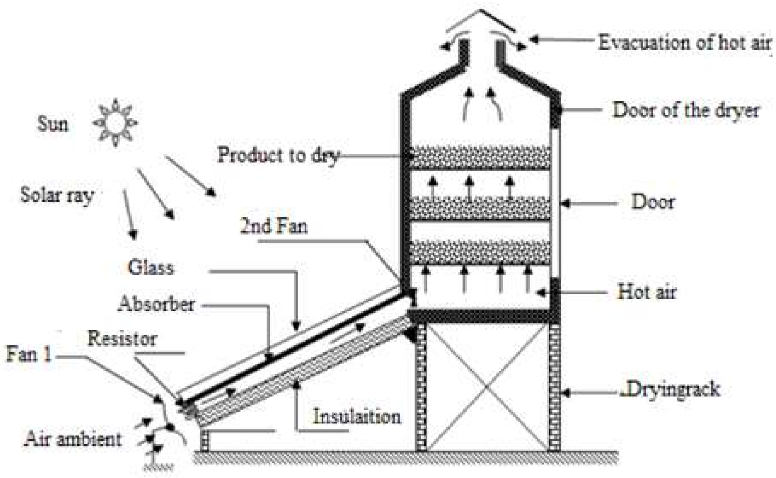


Fig 1 Presentation of the system

the

### 2.2. Description of the drying system

The indirect dryer consists of two parts: a hot air generator or suitable sensor for solar radiation in heat and a drying chamber contains the product (Figure 1). The hot air rises by forced convection to the drying chamber. The drying time depends on the characteristics of the product, furthermore the time is the reasonable.

### 2.3. Hot air generator or sensor

The hot air generator used is a solar collector with single air circulation and single glazing. It consists of the following elements: a glass on the front face, a black painted metal sheet as an absorber, an insulator on its rear and side faces and two rectangular section ducts, the first of which, located between the glass and the absorber, is a confined air space. The second, located below the absorber, is the useful duct where the air circulates in forced convection by the admission of a fan at the input of the sensor and the other at the exit. The sensor converts solar energy into thermal energy. The fresh air collected from the external environment is heated by an electrical resistance powered by a current source when needed, an extra energy to ensure a temperature higher drying time for insufficient sunshine.

### 2.3. Drying chamber

In this work, the products (cocoa beans) in bulk are piled up in a convective dryer that behaves like a porous medium. The circulation of hot air in a mass of product placed in thick layers is provided by second fan. During drying the product to be dried is brought into contact with a moving gas.

## III. MATHEMATICAL MODELING

### 3.1. Simplifying hypotheses

In our calculations, we adapt the following simplifying assumptions.
the absorber being made of thin galvanized steel with a very high conductivity.
- Both sides of the glass are at the same temperature.
- the ambient temperature is the same around the sensor.
- the flow of the fluid is one-dimensional
- the soil temperature is taken equal to the ambient temperature.
- The walls of the dryer are adiabatic during drying.

the porosity of the porous medium is assumed to be constant during drying
- the air must flow between the underside of the absorber and the upper face of the thermal insulation.

**3.1 Modeling of heat exchanges**

In our simulation we use the step-by-step method which takes into account the temperature evolution of all the elements of the captor in fictitious slices of length dx in the direction of the flow of the fluid.

**3.1.2 Balance sheet of heat exchanges**

Outside face of the glass

$$\frac{M_v C_{pv}}{Surf}\left(\frac{dT_{ve}}{dt}\right) = \frac{P_v}{2} + h_{rve}(T_c - T_{ve}) + h_{vv}(T_a - T_{ve}) + h_{cv}(T_{vi} - T_{ve}) \qquad (1)$$

Inside face of the glass

$$\frac{M_v C_{pv}}{Surf}\left(\frac{dT_{vi}}{dt}\right) = \frac{P_v}{2} + h_{cv}(T_{ve} - T_{vi}) + h_{rnv}(T_n - T_{vi}) + h_{vvn}(T_n - T_{vi}) \qquad (2)$$

At the absorber

$$\frac{M_n C_{pn}}{Surf}\left(\frac{dT_n}{dt}\right) = h_{rnv}(T_{vi} - T_n) + h_{vvn}(T_{vi} - T_n) + h_{van}\left(T_{(j-1)} - T_n\right) + h_{rni}(T_{ii} - T_n) + P_n \qquad (3)$$

Inside face of the insulation

$$\frac{M_i C_{pi}}{Surf}\left(\frac{dT_{ii}}{dt}\right) = h_{vai}\left(T_{(j-1)} - T_{ii}\right) + h_{ci}(T_{ie} - T_{ii}) + h_{rni}(T_n - T_{ii}) \qquad (4)$$

Outside face of the insulation

$$\frac{M_i C_{pi}}{Surf}\left(\frac{dT_{ii}}{dt}\right) = h_{ci}(T_{ii} - T_{ie}) + h_{ris}(T_s - T_{ie}) + h_{vv}(T_a - T_{ie}) \qquad (5)$$

At the heat transfer fluid

$$\frac{QC_p}{Surf}\left((T_{(j)} - T_{(j-1)}\right) = h_{van}(T_n - T_{(j-1)}) + h_{van}(T_{ii} - T_{(j-1)}) = h_{van}(T_n + T_{ii} - 2xT_{(j-1)} \qquad (6)$$

**3.1.2. Power absorbed by the absorber**

$$P_n = \alpha_n . \frac{P_{dir} . \alpha_{dir,v} + P_{dif} . \alpha_{dif,v}}{1 - (1 - \alpha_n) . \rho_{dif}} \qquad (7)$$

**3.1.3. Power absorbed by the glass**

$$P_v = P_{dir} . \alpha_{dir,v} + P_{dif} . \alpha_{dif,v} \qquad (8)$$

3.2. **Equation of drying**

Taking into account the simplifying assumptions made and the diagram of the principle of the porous bed (figure 2), the equations for heat and mass transfer in the bed composed of cocoa bean grains after fermentation inside the dryer are written [3].

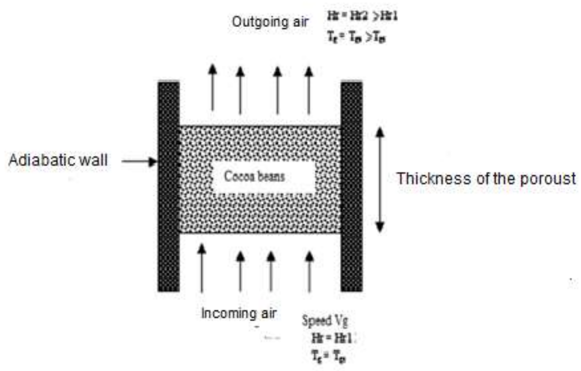


Fig. 2 Schema principe of the porous bed

- **Gaseous phase (g),**[8]

$$\rho_g V_g \frac{\partial C_v}{\partial x} = \frac{A}{\varepsilon} \rho_g h_{mgp} (C_{vp} - C_v) \qquad (9)$$

$$\rho_g C_{pg} V_g \frac{\partial T_g}{\partial x} = -\frac{A}{\varepsilon} h_{cgp} (T_g - T_p) \qquad (10)$$

- **Solid phase (p),**[8]

$$\rho_p \frac{\delta C_e}{\delta t} = -\frac{A}{1-\varepsilon} \rho_g h_{mgp} (C_{vp} - C_v) \qquad (11)$$

$$\rho_p Cp_p \frac{\partial T_p}{\partial t} = \lambda_p^{eff} \frac{\partial^2 T_p}{\partial x^2} + \frac{A}{1-\varepsilon}[h_{cgp}(T_g - T_p) - \rho_g h_{mgp} \Delta H_v^{eff}(T_p)(C_{vp} - C_v) \quad (12)$$

**Boundaries and initials conditions**

Initial conditions at t = 0

$$T_p(x, t = 0) = T_g(x, t = 0) = T_{amb} \quad (13)$$

$$C_v(x, t = 0) = C_{vo} \quad (14)$$

$$C_e(x, t = 0) = C_{e0} \quad (15)$$

Boundaries condition

a) For x = 0

$$\rho_g Cp_p \frac{\Delta x}{2}\frac{\partial T_p}{\partial t} = 2\lambda_p^{eff} \frac{\partial^2 T_p}{\partial x^2} + \frac{A}{2(1-\varepsilon)} h_{cgp}(T_g - T_p) \quad (16)$$

Concerning the product, we adopt the condition used by LEPALEC by integrating from 0 to Δx / 2 of the local equation of the thermal balance. With regard to the gas: according to the value of the outlet temperature of the coolant Tfs, the temperature Tco is taken to 60 °C, [8].

if$T_{fs} \leq T_{co}$

$$T_g(x = 0, t) = T_\infty \quad (17)$$

$$C_v(x = 0, t) = C_{ve} \quad (18)$$

if$T_{fs} \geq T_{co}$

$$T_g(x = 0, t) = T_{is}(t) \quad (19)$$

$$C_v(x = 0, t) = C_{ve}(t) \quad (20)$$

$C_{ve}$ being the mass fraction of water vapor at the entrance.

b) Exit conditions for x = Ls

$$\left\{\frac{\partial T_p}{\partial x} = \frac{\partial T_g}{\partial x} = 0 \quad (21)\right.$$

$$\left\{\frac{\partial C_e}{\partial x} = \frac{\partial C_v}{\partial x} = 0 \quad (22)\right.$$

3.3. **Physical properties of cocoa beans**

The physical properties of cocoa beans are shown in the table below

| Thermophysical properties | Expressions | Réf |
|---|---|---|
| $C_p$(J.kg.K$^{-1}$) | $0.1569.T^2 - 102.51T + 18806$ | [7] |
| $\lambda_p^{eff}$ (W.m$^{-1}$K$^{-1}$) | $0.0987\left(\frac{X}{X_0}\right) + 0.0513$ | [4] |
| $D_{eff}^v$ | $12.10^{-4}\exp(\frac{-3800}{RT})$ | [7] |
| $\rho_p$ | $-0.008.T^2 + 4.7188T + 408.42$ | [7] |

**Table 1: Thermophysical properties of cocoa beans**

The relative humidity of the air at equilibrium is given by the following expression.

With Tp is Product temperature (K)

$X = \frac{m(1+X_0)}{X_0} - 1$,Relative humidity of the instant product. (23)

$X_0$ is Relative humidity of the initial product.

The equilibrium moisture content was expressed using Equation (12) :

$$X_{eq} = \left(\frac{1}{0.1560}\right) \text{Ln}\left\{\frac{-(T-7.3988)}{190.44} \ln\left(\frac{RH}{100}\right)\right\} \quad (24)$$

3.4. **Financial analysis**

| Nominations | Needed |
|---|---|
| Capacity of the fresh product | 200 kg |
| Temperature in the dryer | 65 to 70°C |
| Drying time | 15 to 36 h |
| Energy used | Sun, Electric |
| Ambient temperature min/max | 23°C / 32°C |
| Ambient relative humidity min/max | 40 to 60 % |
| Lifetime | 5 years |
| Solar intensity min/max | 200 / 1500 w/m$^2$ |

**Table 1: Characteristic of the dryer**

| Nominations | Needed |
|---|---|
| Life time | 5 years |
| Initial water content | 50 to 55 % |
| Final water content | 7 to 8 % |
| Temperature of product | 22°C |
| Drying temperature | 65 to 70 °C |

**Table 2: Product Characteristic**

| Energies spent | Daily | | Monthly | | Annually | |
|---|---|---|---|---|---|---|
| Value | kw/h | Cost USD | kw/h | Cost USD | kw/h | Cost USD |
| Solarenergy | 3,84 | 0,142 | 115,2 | 4,275 | 691,20 | 25,647 |
| 02 Resistors | 6 | 0,222 | 180 | 6,678 | 1080 | 40,073 |
| 04 Fan | 3,3 | 0,122 | 99 | 3,673 | 594 | 22,040 |
| Dally | 13,14 | 0,486 | 394,2 | 14,626 | 2365,2 | 87,761 |

**Table 4: Energy Loads**

- Depreciation Rate: DR = 100 / Lt (25)

with Lt = 5 years (life time)

- Amortization period: a = C.I / D (26)

with I.C = 884.21 dollar (investment cost)

- Discounting Coefficient: D.C = $(1 + d)^{-n}$ (27)

with

n: number of years of amortization of the investment

d: discount rate that currently 15%

- Cash Flow: C.F = Revenue - Expenditure (28)
- Rental cost of dried products:0.263 USD / kg
- Quantity of products to be dried: 200 kg / 2 days, i.e. 3000 kg / month or 18 tons per year
- Quantity of dry products: 1020 kg / month or 6 120 kg / year
- Monthly recipe of dry goods: 268.421 USD
- Annual revenue of dry products: 1610.526 dollar for 6 months favorable
- NPV is the Net Present Value determined from the following formula:

$NPV = \sum_{i=1}^{n} FNTAC_I xDC$ (29)

## IV. RESULTS AND DISCUSSION

The figure.3 illustrates the curves representing the powers variations of the glass and the absorber. The absorber curve is important because of its higher absorption coefficient than the glass because of its optical properties, allowing the heat to pass through with a high transmission coefficient. Figure 4 shows that the value of the direct, diffuse and global powers varies with the positioning of the sun. The more the distance between the sun and the sensor is reduced, as is generally the case at 12 o'clock. If the radiation is high there is less atmospheric mass. On the other hand, if the sensor is in an inclined position, the solar radiation is less important.

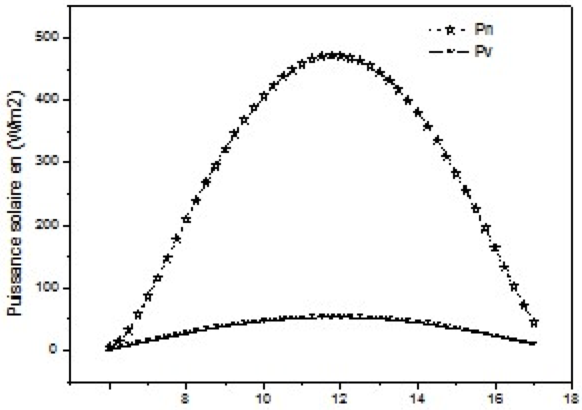


**Fig. 3**: *Evolution of the powers of the glass (Pv) and the absorber (Pn) against of time*

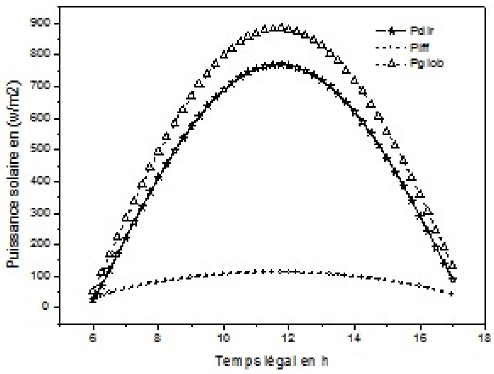


**Fig. 4**: *Evolution of the direct, diffuse and global solar powers on the inclined plane as a function of time*

The curve in figure.5 represent the evolution of the temperature of the fluid leaving the sensor during a day of sunshine. It grows gradually and reaches the higher value around noon due to the higher absorption coefficient. In figure 6,we have also presented the evolution of the ambient temperature necessary to heat up to perform the drying operation. The value of the ambient temperature is still low at the beginning so the heating of the air is carried out by an electrical resistance to quickly increase its temperature and their flow is ensured by an external fan. The temperatures of the absorber and the coolant depend on the performance of the solar air collector.

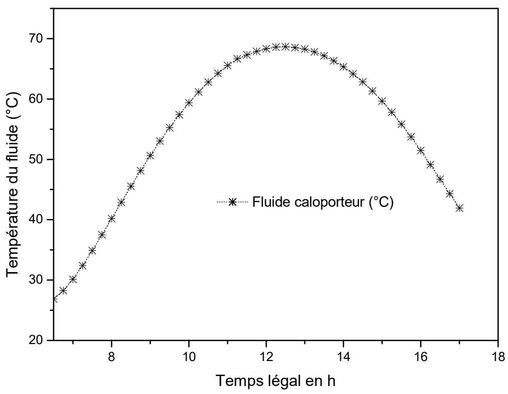


**Fig. 5:***Evolution of the temperature of the fluid leaving the sensor as a function of time*

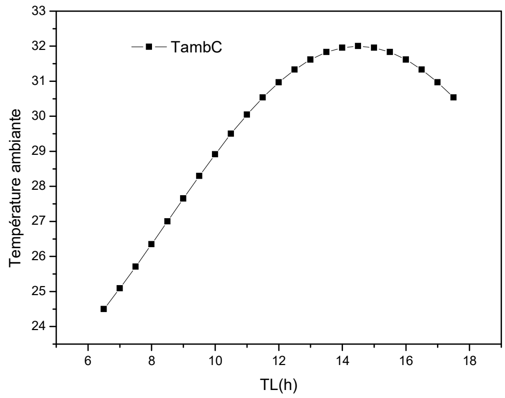


**Fig. 6**: *Evolution of the ambient temperature outside the sensor as a function of time*

Figure 7 shows the annual solar power received by the absorber. The variations curve decreases these value to June and it does increasing gradually until to December. This pace is due to the variation of the season and follows the period of sunshine favorable on the other hand. These variations affect the cost of the solar energy used during drying. Moreover, the curves of temperature variations of these elements were obtained and correspond to the governing physical laws, thanks to the study of the superior quality of the materials used in the design and realization of this prototype. Indeed, we can confirm the realization of the device on a large scale is possible because of the availability of existing local materials in the region.

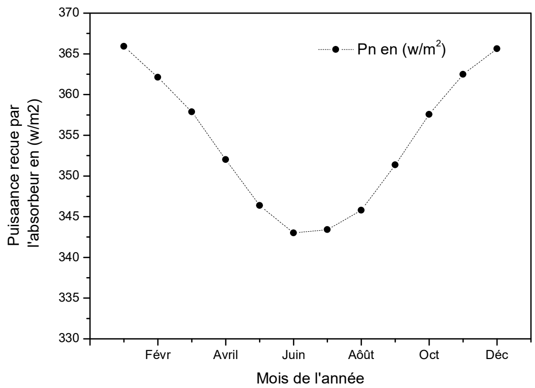


**Fig. 7**: Variation of the power received by absorbed during 12 monthof the year as a function of time

The table below represents the revenues and expense for each year of activity. we invested 1028.57 dollar for starting the activity with 3 tons of dried cocoa beans per month to have 1.02 tons of dry product. The rental of the dry product is estimated at 0.25 USDper kg. According to calculation in the last line of the table, starting from the second year of exercise, we find the NPV is positive so the activity is thus benefit.

| | **year1** | **Year2** | **Year3** | **Year4** | **Year5** |
|---|---|---|---|---|---|
| **RECIPES**USD | **805.263** | **1 610,53** | **1 610,53** | **1 610,53** | **1 610,53** |
| EXPENSES | | | | | |
| 1 - Coat of maintenance | 26,315 | 31,578 | 39,474 | 52,632 | 39,473 |
| 2- Economy of electric energy | 142,261 | 142,261 | 171,053 | 171,053 | 171,052 |
| 3 -Coat of Solar Energy | 96,176 | 96,176 | 96,177 | 96,177 | 96,176 |
| 4- Personal salary | 394,736 | 394,737 | 473,684 | 657,895 | 789,474 |
| 5 -Coat of Amortization | 210,526 | 210,526 | 210,526 | 210,526 | 210,526 |

| | | | | | |
|---|---|---|---|---|---|
| 6- Other consumption | 26,315 | 23,684 | 19,737 | 15,789 | 13,157 |
| **Total expenses**(in dollar) | **896,333** | **756,703** | **1 010,65** | **1 204,07** | **1 319,86** |
| Before Tax Return (RAI) | -91,07 | 853,823 | 599,875 | 406,454 | 290,667 |
| IBS = 20% of RAI | -18,214 | 170,7646 | 119,9751 | 81,291 | 58,133 |
| RN (Net Result) = 80% of RAI | -72,856 | 683,0584 | 479,9 | 325,164 | 232,532 |
| CA F (RN + Depreciation) | 137,67 | 893,5847 | 690,426 | 535,69 | 443,058 |
| Investment | 1 052,63 | | | | |
| CF (Cash Flow) | -914,961 | 893,585 | 690,4269 | 535,69 | 443,058 |
| FNTC | -914,961 | -21,376 | 669,05 | 1 204,74 | 1 647,77 |
| Discounting cost 15% | 1 | 0,0001 | 0,0001 | 0,0001 | 0,0001 |
| DNCF (Discounted Net Cash Flow) | -914,961 | 777,03 | 522,062 | 352,225 | 253,3202 |
| CDNCF (Cumulative Discounted Net Cash Flow) | -914,961 | -137,931 | 384,131 | 736,3559 | 989,6709 |

**Table IV. 5:** Change in NPV for each year of activity

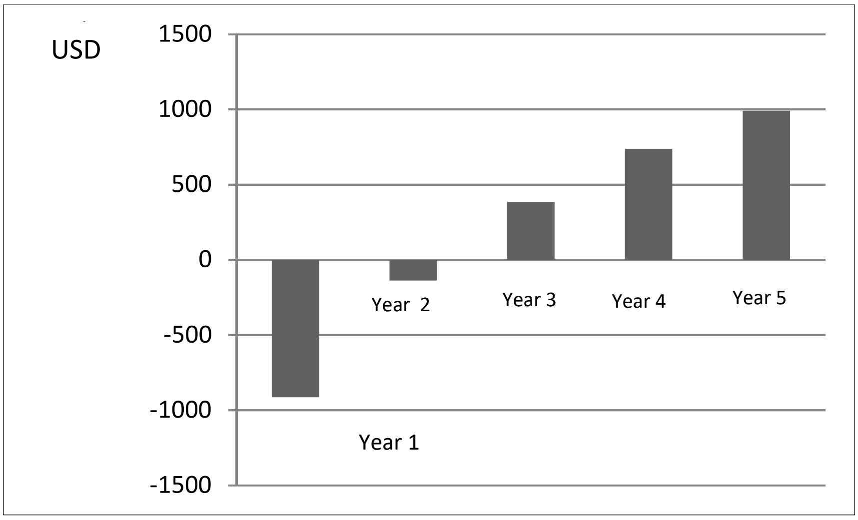


**Fig. 8:** Variation in NPV for each year of activity

**Importance in the international market**

Madagascar is especially well known around the world by an owner who holds the label "fine cocoa". It currently has about 33,000 cocoa farmers, mainly smallholders located in the Sambirano region. They produce about 6,000 to 8,000 tons of cocoa beans. Globaly, Malagasy cocoa is thus ranked among the best. However, for the moment the problem of the sector is still practically at the artisanal stage, with actors who are small agricultors. Indeed, 95% of cocoa production comes from a peasant family farming living from one to three hectares of cocoa plantation.

| | 2015 | 2016 | 2017 | May 2018 |
|---|---|---|---|---|
| Sold Products (Ton) | 6 000 T | 7 000 T | 8 000 T | 4 000 T |
| Price of fresh beans one ton | 460 dollar | 930 dollar | 1080 dollar | 2 000 dollar |
| Rebatecollected(4%) | 110 400 dollar | 260 400 dollar | 345 600 dollar | 320 000 dollar |

**Table 6.** Annual Rebate Revenue in the Sambirano Region

The export of the cocoa sector gives some advantages, not only on the producers but also on the economic development plan of the region like an increased source for local government and population drawback yield and others.

## V. CONCLUSION

Our study describes the behavior of elements of an air solar collector by simple pass between the absorber and the insulation for drying agro-food products using numerical modeling of heat exchange equations. It can be seen that the theoretical results of the sensor obtained by simulation of the program generally depend on the physical characteristics of the dimensions of the sensor, the location, the meteorological conditions and the application field (heating, drying or others). This sensor couples with a drying chamber and the temperature of the air at the outlet of the sensor is then equal to the air inlet of the drying unit. It is observed that, the results have confirmed the behavior of the generator responds perfectly to the process required by the product. In general, the beans had to be fermented before being dried. Then, the temperature variation curves of the heat transfer fluid regularly corroborate the demand of the studied product. According to the financial analysis, it can beseen the transition from traditional technical drying to indirect solar drying influences the socio-economic of users. After five years of activity, the system is amortize.

## ACKNOWLEDGEMENTS

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