Solar driven fan unit for a solar dryer

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Abstract

Drying cocoa is an important step in cocoa processing not only for preservative purposes but also for improvement of flavour and quality of cocoa products. Results showed that in clear sunny conditions, temperatures in the solar drier can obtain around 60°C. Temperatures in the solar drier are always higher than ambient about 10 to 15°C even at night. In the sunny season, cocoa beans can be dried only in 4 to 5 days and 6 to 7 days in the rainy season. When cocoa beans were effectively dried, they also helped to avoid over-fermentation and reduced mould contamination.

Upon fermentation, cocoa beans need to be dried to remove the moisture, to reduce bitterness and astringency and to develop a chocolate brown color. Direct sun drying has been used widely in many cocoa producing countries and may last as long as 2 weeks. Artificial drying can reduce this process to 20 hours. In a dryer hot air is produced by kerosene, biomass fuel fired stoves or solar air heaters.

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Further improvement can be achieved by generating forced air flow by means of a fan. In a preliminary specification of a solar driven fan unit the electric power consumption of the fan is fixed to 300 W peak.

Keywords: *Drying Cocoa, Photovoltaic Solar Panel, Solar Driven Fan Unit, Modeling and Simulation of Solar Driven Unit.*

1.Introduction

West Africa is the main cocoa producing area with about 72% of the world cocoa production. Four major West Africa countries are Côte d'Ivoire, Ghana, Nigeria, and Cameroon. Pacific Asia accounts for about 15% and America is 13% of the 3.5 million tons cocoa beans in over the world (Global Cocoa Market Study, 2021). According to the ICCO, the world will be lack about 102,000 tons cocoa bean in 2010 - 2011 because of the decreasing of cocoa bean in 2008 - 2009 crops. There are some reasons that lead to the decrease of cocoa production are insecurity politics, natural calamity, old and stunted cocoa trees, lack of land in some main cocoa producing countries. In nine decades, global cocoa production has increased steadily and consistently to keep with the ever-increasing needs for cocoa bean. Cocoa consumption has increased on average by 3.5% per annum over recent years and is projected to increase by 1.5 - 3.5% per annum over the 5 years coming (Knight, 1999).

In 1998, the Ministry of Agriculture and Rural Development carried out an investigation about cocoa production and set a new goal of having 100,000 ha of planted cocoa by 2010. Vietnamese Cocoa Development team was established in March 2005. The aims are promoting the development of cocoa cultivation and recognizing the cocoa as a new long-time industrial tree in Vietnam. By the end of year 2006, the total cocoa has been inter-plant on plantations about 7,300 ha with some major provinces are Ben Tre, Tien Giang, Ba Ria-Vung Tau, Dak Lak, and Binh Phuoc (Hoa, 2007).

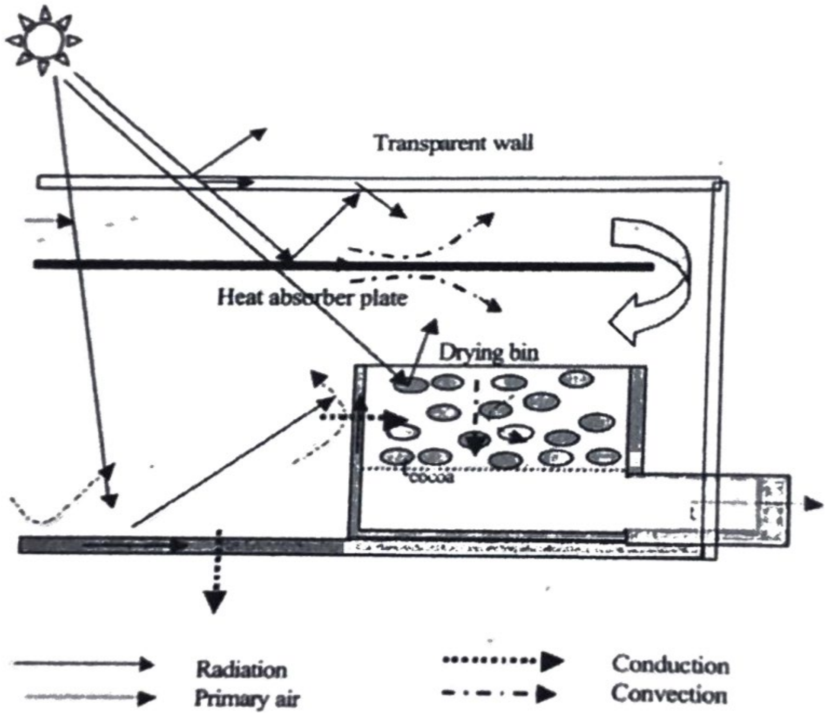


Figure 1: Concept sketch of a solar dryer.

Drying cocoa is an important step in cocoa processing not only for preservative purposes but also for improvement of flavour and quality of cocoa products. In many countries, including parts of Vietnam, sun drying is the main method to dry cocoa beans. This is a very simple method and the most effective way to dry cocoa beans. This reduces acids in the cocoa beans and enriches flavor in cocoa products. However, in the unfavorable condition of weather, especially in the rainy season, the drying may take longer which could cause over-fermentation and mould contamination. Then, the cocoa could have some off-flavours and lead to down-grading.

Three selected patents relevant for SBATS

1.1.1 Axial flow fan and fan orifice US 5273400 A

The present invention is an axial flow fan capable of use in a variety of applications including moving air in heating, ventilation and air conditioning systems and equipment. It produces reduced levels of radiated noise and requires lower input power to move the same amount of air as compared to prior art fans.

The fan has a plurality of identical blades. Each blade is strongly swept in one direction at its root and strongly swept in the other direction at its tip. This combination of blade sweeps allows for a large amount of sweep at the blade tip while producing low stress in the blade at its root. A large sweep in the tip region of the blade results in low turbulent noise coherence in that region.

The coherence is low because only a relatively small portion of the blade tip region is subjected to inlet flow turbulence at any given instant. The noise produced by inlet turbulence is thus diffused and reduced. Along the entire span of the blade, the maximum camber, expressed as the deviation of the blade camber line from the chord line, of the blade should be closer to the leading edge of the blade. This configuration promotes attached flow in the region of the trailing edge and thus reduces form drag and trailing edge noise. The number of blades on a fan constructed according to the present invention is not critical to fan efficiency, noise and overall performance. The fewer the number of blades, however, the greater the pitch that will be required in order for the fan to produce a given capacity at a given rotational speed. Fewer blades would also require increased mid chord skew angles and larger blade chord lengths to achieve the desired blade solidity (that is, the proportion of the total area of the swept disk of the fan that is covered by blades). The fan and orifice of the present invention may be manufactured out of any suitable material by any suitable process. It is however, particularly suited, assuming no blade overlap, to be produced in a suitable plastic by a suitable molding process.

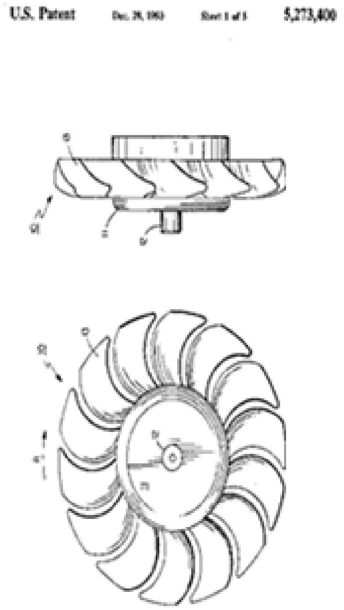


Figure 2: Front and side elevation view of one embodiment of the fan.

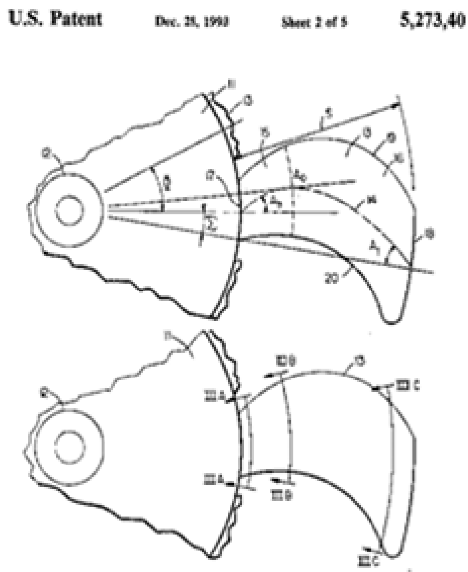


Figure 3: Front elevation views showing a portion of the hub and one blade of one embodiment.

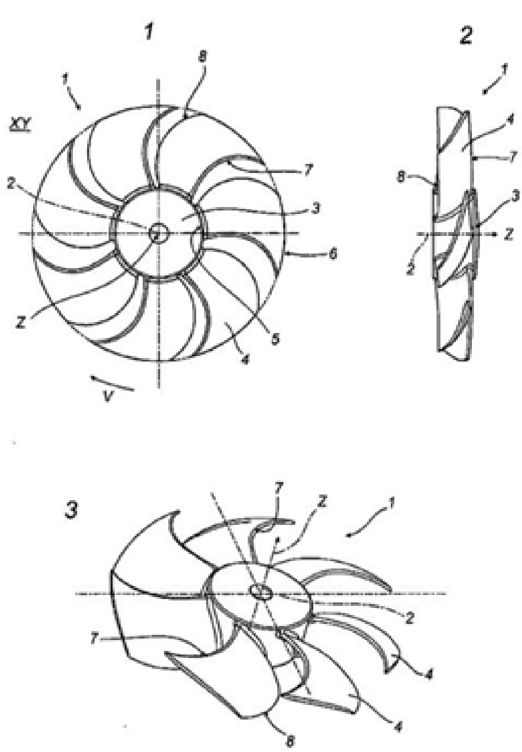
1.1.2 High efficiency axial fan EP 1797334 B1

An axial fan rotating in a plane (XY) about axis comprises a central hub, a plurality of blades, which have a root and a tip, the blades being delimited by a concave leading edge, whose projection in the fan plane of rotation (XY) is defined by two circular arc segments, and a convex trailing edge, whose projection in the fan plane of rotation is defined by one circular arc segment.

The blades are made from sections with aerodynamic profiles relatively extended Ing in the direction of their center line, providing a good flow rate and air pressure relative to the overall dimensions of the fan. Fans of this type must satisfy various requirements, including low noise level, high efficiency, compactness, capacity to achieve good pressure and flow rate values.

This patent presents a fan with blades delimited at the leading edge and trailing edge by two curves which are two circular arcs when projected in the fan plane of rotation. Fans constructed in accordance with this patent provide good efficiency and low noise but have limits as regards the possibility of achieving high pressure values, since the blades are made with profiles whose center line is relatively short compared with the blade radial extension. Moreover, fans constructed in accordance with the above-mentioned patent have a limited axial dimension, but a relatively large diameter.

For the exchange units of heating or air conditioning systems for the interior of motor vehicles the overall dimensions of the fan must be limited, which means that the diameter must also be limited, whilst good air flow rates are required with high pressure and low noise. For these reasons, in the above-mentioned ex changer unit's centrifugal fans are often used, which may have a relatively small diameter, but with a rather large axial dimension.



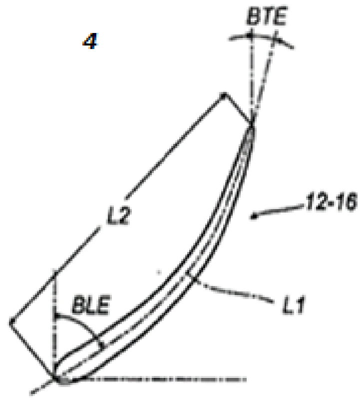


Figure 4: In front, side and perspective
and
view of the fan.

Figure 5: Cross-section of a profile
the respective geometric
characteristics.

1.1.3 Food dryer DE 102011111971 A1

By incident light through a transparent sled wall, an airflow is heated to dry groceries. Conditioned by forced convection which is generated by an aerator this is conducted over groceries. The heated air detracts the moisture from the groceries, and it cools itself through the absorption of the moisture. Subsequently the air is dried by an air dehumidifier and feed again in the dry air circle. An invention to desicate and therewith conserve groceries. It needs to be autarkic, effective, convenient and it should have a great drying performance and thereby have a little drying time. The sunlight is used to heat the air, the gathering of the moisture to cool the air and after the dehumidifying component has dried the air, the heated air is added to the circulation again. The drying component consists of convenient and clay bonded material and is still sufficient for its duty because of its capillary tubes in the material and the hereby possible water vapour transport. Once the component is completely filled with water, there will be an automatically transport of the moisture from the dehumidification room to the atmosphere by a capillary line.

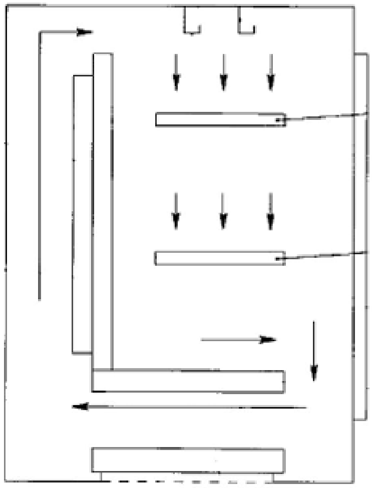


Figure 6: Food Dryer Drawing.

2. Design - Methodology – Result - Modeling and Simulation

Photovoltaic solar power plant

The first step to design a photovoltaic solar panel is to consider the location of the solar dryer. The main producers of cocoa beans regarding the ICCO Quarterly Bulletin of Cocoa Statis tics (Vol. XLIII, No. 1, Cocoa year 2016/17, Table 1) are in West Africa. The Cote d'Ivoire and Ghana are producing 60% of the world's cocoa beans, which leads to the idea to locate the solar dryer in this area and to use the irradiation data from West Africa.

Production of cocoa beans (thousand tons)

			Estimates		*Forecasts*	
	2014/15		*2015/16*		*2016/17*	
Africa	**3074**	**72.30%**	**2911**	**73.40%**	**3365**	**73.90%**
Cameroon	232		211		250	
Côte d'Ivoire	1796		1581		1900	
Ghana	740		778		850	
Nigeria	195		200		230	
Others	110		141		135	

Table 1: Production of cocoa beans related to geographic zones.

The average global horizontal irradiation at the CIV is about 1900 kWh/m² and approximately 2000 kWh/m² in the Western Africa zone (Figure 7).
The Electric Peak power consumption of the fan is fixed to 300W. That leads to an annual energy sum of 2628 kWh if a constant operation is assumed.

$$P_{peak} * 8760 \frac{h}{year} = 2628 \frac{kWh}{year}$$

Regarding the task an operation time of 20 hours is needed to dry one batch of cocoa beans. It is estimated that the remaining 4 hours of a full day are needed for charging, discharging and cleaning. The annual energy sum is reduced through this estimation:

$$P_{peak} * 7300 \frac{h}{year} = 2628 \frac{kWh}{year}$$

Average Temperatures above 30 °C and up to 10 hours of solar radiation per day (more than 6 in average) request robust solar panels.

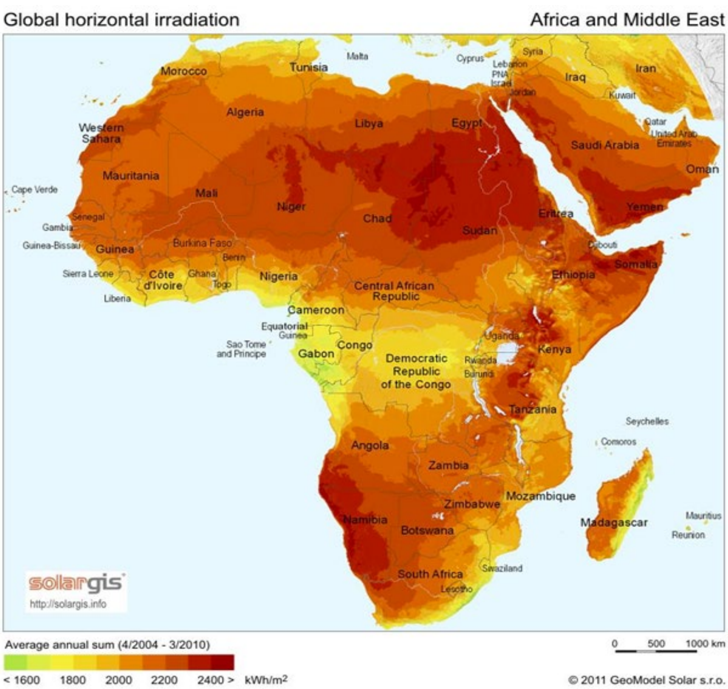


Figure 7: Global horizontal Irradiation in Africa according to SOLARGIS

The highest yield is obtained when the irradiation is rectangular to the solar panel. Because the CIV and western Africa are close to the equator one can assume the highest yield of the solar panel is obtained at a small angle of inclination. An angle of inclination of 0° would not be beneficial for self-cleaning effects through rain. An angle of 5° and a south-orientation is chosen (The CIV is a little northern from the equator).

The next step is the choice of a solar module to calculate the total area. To calculate efficiency and losses a Performance-Ratio of 75% is chosen regarding to a usual performance. The performance ratio of a photovoltaic system is the quotient of alternating current (AC) yield and the nominal yield of the generator's direct current (DC). It indicates which portion of the generated current can actually be used. The PR leads to the following nominal Power:

$$P_{nominal} = \frac{2190\frac{kWh}{year}}{0.75} = 2920\ kWh$$

The following Solar panel from Solar World is selected due to robustness at high temperatures and harsh environment: Sun module® Plus SW300 Mono

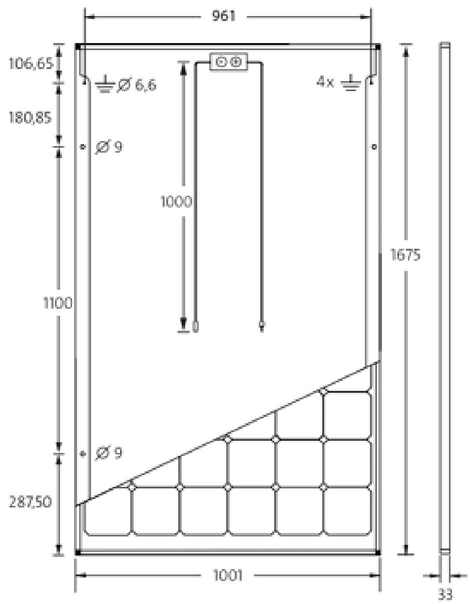


Figure 8: Drawing of the Solar panel from Solar World

The efficiency regarding the Datasheet (appendix) is 17,89 % and the maximum operating temperature is 85°C. The required area A total is calculated below:

$$A_{total} = \frac{P_{nominal}}{\eta_{Panel} * irradiation} = \frac{2190 \frac{kWh}{year}}{0.1789 * 2000 \frac{kWh}{m^2 a}} = 8.16\ m^2$$

The amount of solar panels N is calculated as follows:

$$N = \frac{A_{total}}{A_{panel}} = \frac{8.16\ m^2}{1.001\ m * 1.675\ m} = 4.867$$

The amount is rounded to 5 Solar panels. Regarding a total power of 300W per cell, a total power of 1500W is to be expected.
The Solar panels deliver a current at maximum Power of I_{mpp}= 9,31 A and a voltage of U_{mpp} = 32,6 V. A usual fan of 300W drive power has a usual nominal voltage of 200-240 V and a current consumption of 0,5-1,5 A at 50-60 Hz (Referring to EBM Papst axial fans, [14]). By means of a power inverter this gap can be overcome. A power inverter from Kostal (Piko 1.5 MP) for 1 Phase is selected. Wiring is not selected due to missing information regarding the construction site.

While the solar dryer will operate during the day and overnight as well, a battery and needs to be selected to ensure a constant energy supply. A Kostal Piko 6.0 BA (appendix) with 6 $LiFePO_4$ battery cells are selected and delivers 7,2 kWh of Power. While consuming 300Wh of electrical power per hour the battery is able to keep the system alive for at least 24h.

Fan design using dAX

The main goal of the project is to design an axial-fan. With the given parameters of Δp, V̇ and the rotational speed n = 15001 min / which is fixed through the frequency of the rectifier, the position in the Cordier-diagram can be calculated with the dimensionless numbers cf. For an adequate axial fan, the best diameters (Hub and Tip) must be chosen. In this case we assumed the tip diameter d_{tip} = 0.2m and the hub diameter d_{hub} = 0.4m to fulfill the sign point. The design point of the fan is in the axial area, and an appropriate safety factor is ensured.

For the project the design was calculated using software from the "Lehrstuhl für Strömungstechnik und Strömungsmaschinen des Instituts für Fluid-und Ther modynamik" of the University of Siegen called dAX. The program computes the fan with the parameters above in different steps. In the first step the required parameters that are calculated above (V̇, Δp_t, n, d_{tip} and d_{hub}) must be entered into the program.

The next step is the calculation of the position in the Cordier-diagram. If the design points suit the requirements the kinematics and efficiency are calculated. Especially the velocity triangles (Figure 10) are computed where u1 is the circumferential velocity of the rotor at the hub and u_2 the circumferencial velocity at the tip.

The meridional component of the absolute velocity at the inlet c1 and at the outlet c_2 is c_{m1} respectively c_{m2} and are calculated as follows:

$$c_{m1} = \frac{\dot{V}}{2\pi r_{Hub} * b_{Hub}} \qquad c_{m2} = \frac{\dot{V}}{2\pi r_{Tip} * b_{Tip}}$$

Where b is the width of the blades at the Hub res. the Tip. The tangential component of c_2 is calculated using the following formula:

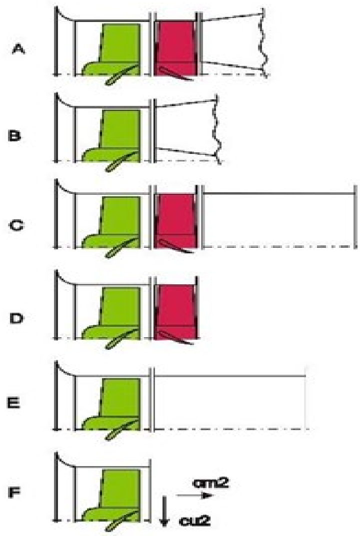
$$c_{u2} = \frac{\Delta p_{tt,B}}{\rho u_2}$$

The connection between u and c is the relative velocities w. For the calculations a spin-free feed at the inlet and a blade congruent flow at the outlet is estimated regarding to.

Additionally, there are two preliminary design criteria that need to be fulfilled named the diffusion criterion after De Haller and the hub dead water or Strscheletzky criterion:

$$De\ Haller: \frac{w_{2Hub}}{w_{1Hub}} \leq\ g_{DH,}\ where\ g_{DH}\ \approx 0.55\ to\ 0.75$$
$$Strscheletzk: \frac{c_{m2Hub}}{c_{u2Hub}} \leq g_{ST,} where\ g_{ST}\ \approx 0.8\ to\ 1$$

These criteria are also used to define the optimal Hub and tip diameters.



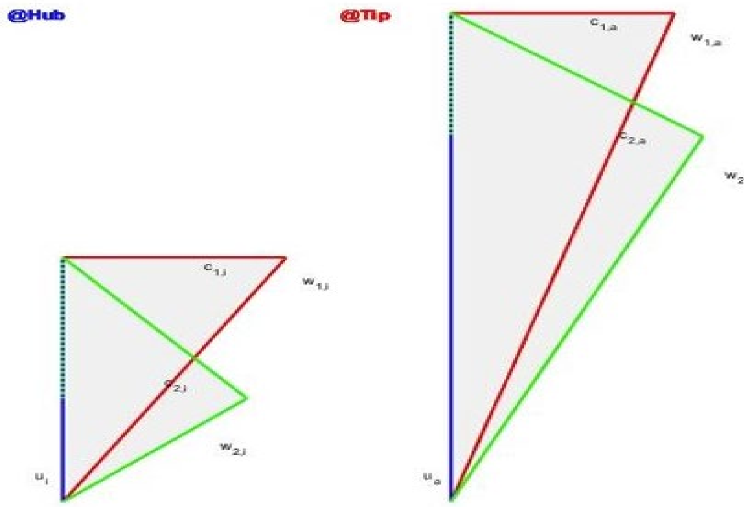
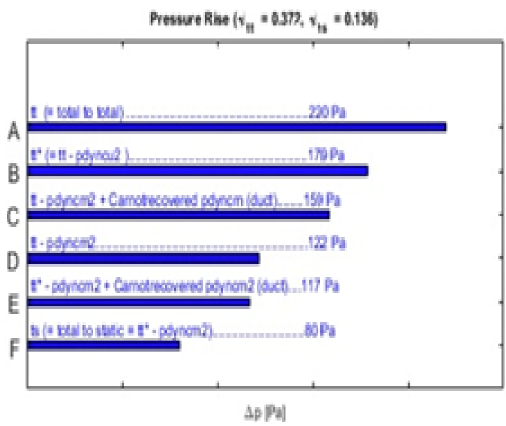


Figure 9: Various Fan periphery types. **Figure 10:** Velocity triangles.

For more, the program generates some different model types of the fan and its periphery shown in Figure 9:

B: Fan with an endless ideal diffusor.
C: Fan with guide vans and diffusor.
D: Fan with guide vans.
E: Fan with diffusor.
F: Just the fan.

After comparing the efficiencies and values of the pressure rise from the different types to the needed values, the model type C became the type of choice because the pressure rise is high enough to reach the value of 144 Pa, which is calculated for two layers of cocoa-beans and the power is below the value of PW = 300W. Options A and B are based on the principle of an infinite diffuser which is not applicable in a real machine.



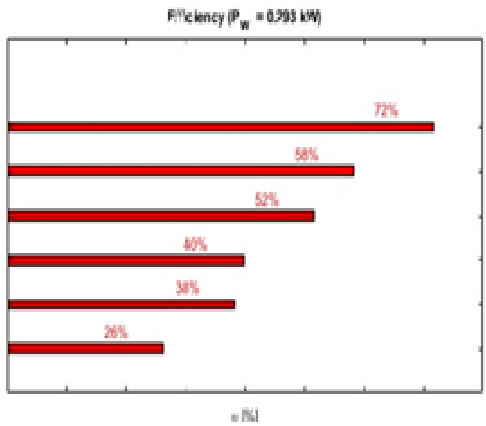


Figure 11: Pressure rise and efficiency of the different model types A-F

Now we must choose the blade geometry of the fan. Since the fan is operating at any time during the day, the temperatures, the air conditioning and the air speed outside the system change and affect the conditions inside the system. Because of that, we must design the fan robust based on its operating characteristics.

An Airfoil type which ensures similar flow characteristics from hub to tip needs to be chosen. The airfoil that suits these requirements is the FX 60-126 (SPK1 - mod.) and it has also a very low Lift to Drag coefficient (Figure 13).

Other airfoils like NACA 0010 may have higher lift coefficients, but they often have varying flow distributions. About the angle of attack α we could define the workspace. For security reasons we choose an angle α-hub of 6° and an angle α-tip of 3,5°. This ensures enough distance to the stall area at an angle of α = 10°.

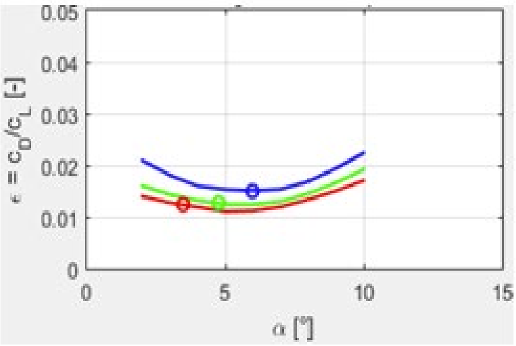


Figure 12: Lift/Drag Polars (SPK1-mod)

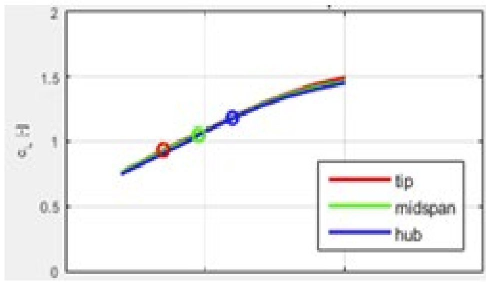


Figure 13: Lift coefficients of FX 60-126

In the next step the number of blades is estimated. Less than five blades will lead to an unfavorable Reynolds number domain. More than five blades will lead to a rise of the resistance coefficient C_D because the distance between the blades will be lower and friction will rise. Through this knowledge we choose five blades for our fan (Figure 14).

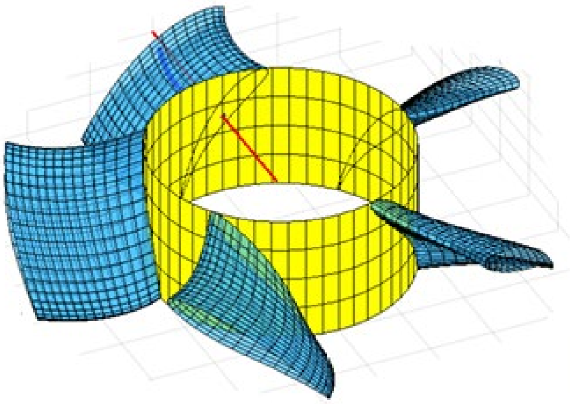


Figure 14: Fan geometry with 5 blades

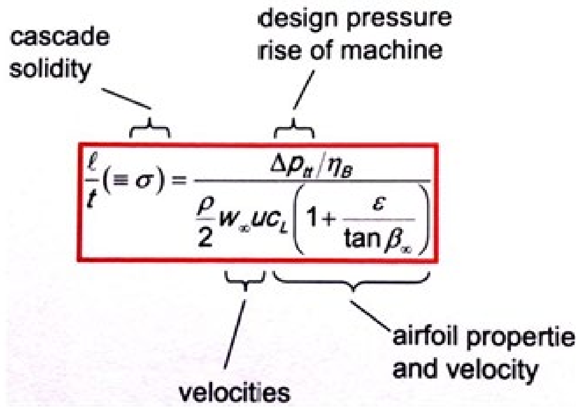


Figure 15: Key equation to calculate solidity

After the number of blades are selected, the solidity is calculated using the equation in Figure 21. The chord length l as well as the stagger angle $\gamma = \beta_\infty+\alpha$ is calculated and the blade section is drawn.

Next, we had to design the guide vans. The number of blades is related to the acoustics of a fan. The same or a multiplicity number of blades of guide vans would result in an overlap withevery rotation of the fan and a pressure shock would be generated that would result in noise. The most suitable combination of fan and guide vans is one which has propagating modes as few and high as possible.
Figure 16 shows that there is more than one option for the number of blades in the guide vanes, for example, seven, nine, eleven, seventeen, and eighteen.

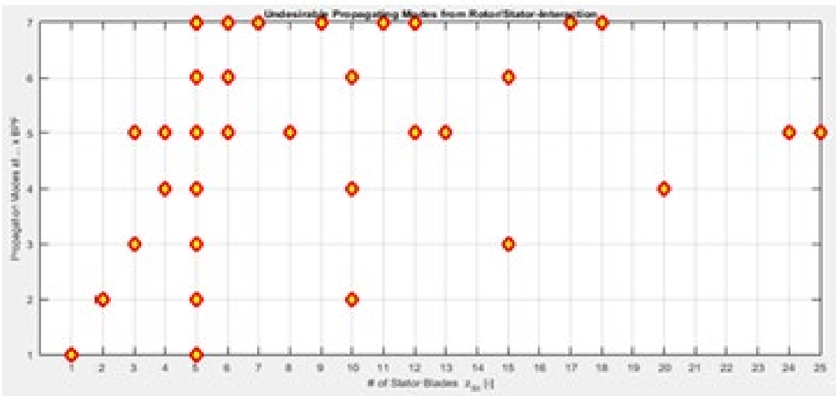


Figure 16: Undesirable Propagating Modes from Rotor/Stator- Interaction

Another criterion is the solidity according to the Blade-Element-Momentum (BEM) theory for low pressure axial fans. Only eleven blades reached the expected ratio of one and a camber angle below 65° (Figure 17).

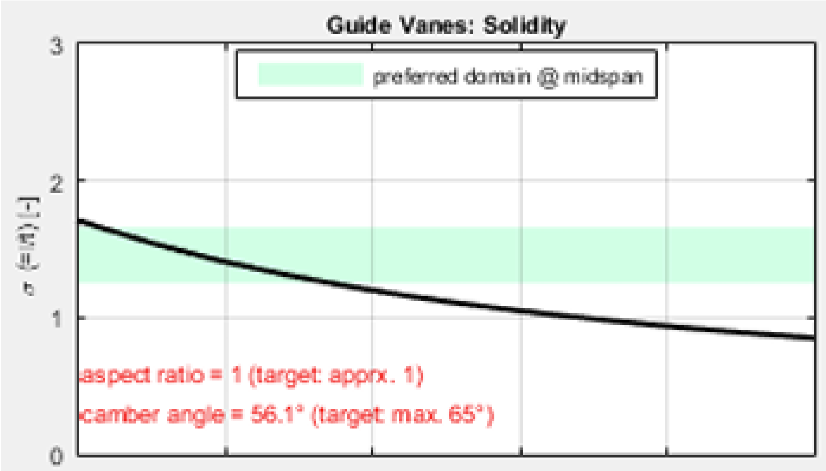


Figure 17: Solidity for eleven guide vans

To reduce the costs of our system, we choose guide vans without own Airfoils. Because our system is not a high-performance system and the added value of Airfoils is too small as it would justify the additional costs (Figure 18).

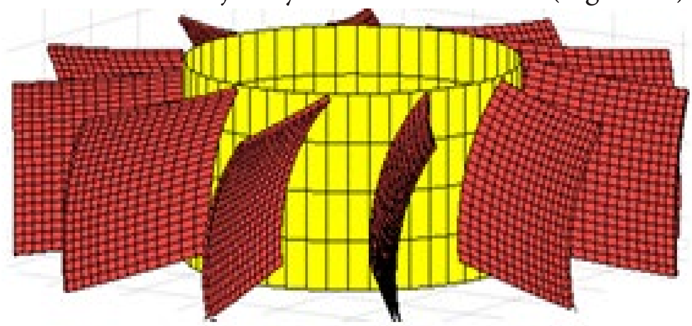


Figure 18: Guide vans with eleven blades

Three millimeters thickness for the blades is estimated to reduce flow resistance. With eleven blades of this thickness, it should be possible to create a welding connection between the guide vans and the channel.

Solar Dryer – Concept

Diffuser, inlet nozzle and blow out

A diffuser is in general a conical component of a channel that converts dynamic pressure to static pressure. To prevent shocks right after the guide vans, where the profile of the channel changes abruptly, a transition diffuser is chosen. The design calculations are based on Figure 20 referring to Dixon and Hall which is based on the work of Sovran and Klomp.

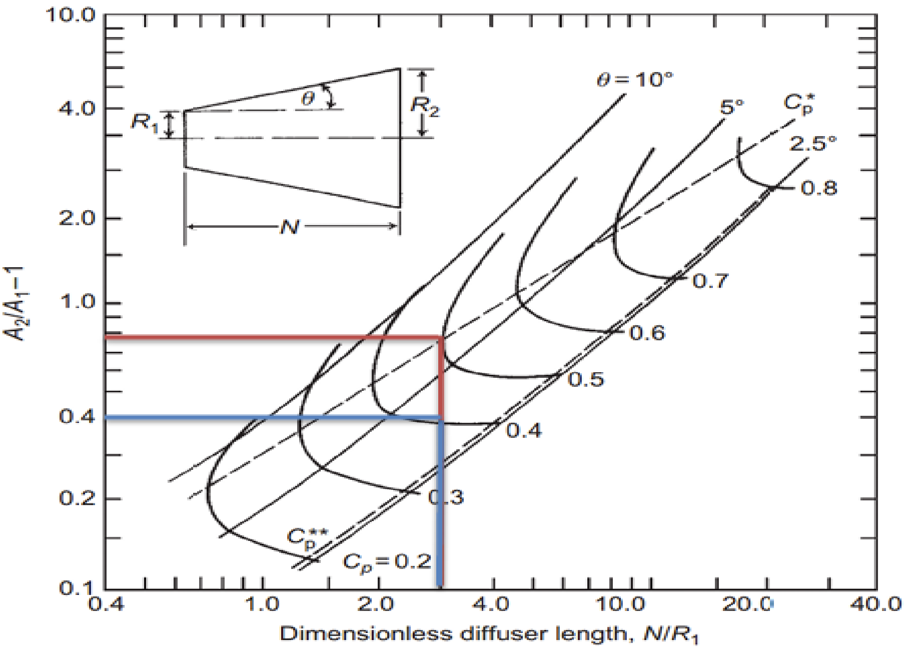


Figure 19: Diffuser design chart referring to Dixon and Hall

The C_p^* line defines the diffuser area ratio A_R, producing the maximum pressure recovery for nondimensional length N/R_1. For the first Iteration (red) an N/R ratio of 3 is chosen which leads to a C_P of 0,5 and an A_R of 1,75 and the following equations:

$$\eta_D = \frac{C_P}{C_{P,id}}$$

$$therefore: \ \eta_D = 0.743$$

The geometric expression gives the angle 2θ:

$$2\theta = 2\,tan^{-1}\left[\frac{R_1}{N}\left(A_R^{\frac{1}{2}} - 1\right)\right] = 12.28°$$

Regarding Dixon and Hall and total angle of 6-7° should not be exceeded due to separations at the boundary layer. A second iteration is necessary (blue). For the second Iteration (blue) an N/R ratio of 3 is chosen which leads to a C_P of 0,4 and A_R of 1,4 and the following equations:

$$\eta_D = \frac{C_P}{C_{P,id}} \qquad where: \ C_{P,id} = 1 - \left[\frac{1}{A_R^2}\right] = 0.49 \qquad therefore: \eta_D = 0.816$$

The geometric expression gives the angle 2θ:

$$2\theta = 2\tan^{-1}\left[\frac{R_1}{N}\left(A_R^{\frac{1}{2}} - 1\right)\right] = 6.99°$$

The efficiency is even better with the second iteration, and the angle fulfills the requirement. The diameter of the designed fan is 400 mm and the gap at the tip is approx. 5mm which leads to a R1 of 205mm.
The diffuser length is calculated to 615 mm (Figure 20).

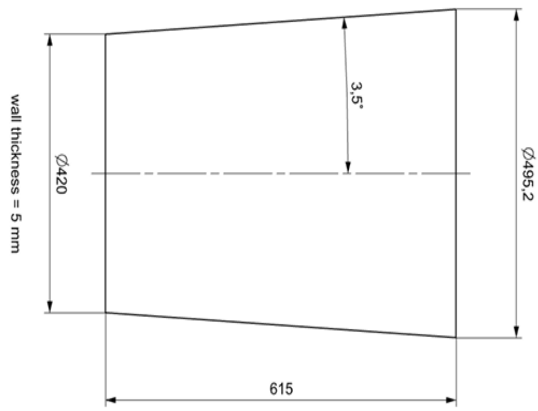


Figure 20. Designed diffuser, dimensions in millimeters

The hub diffuser that is located right behind the stator is calculated to ensure the same profile of the channel. An angle of 14° is calculated which leads to the following dimensions of the fan section:

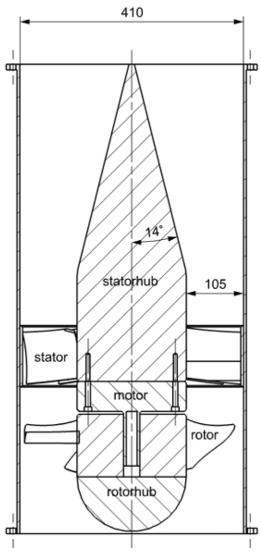


Figure 21. Cross-section of the fan unit

The inlet nozzle is designed according to the ¼ thumb law which sets the radius of the inlet to ¼ of the channel diameter. The general function is to reduce the turbulence at the inflow and create a uniform inflow.

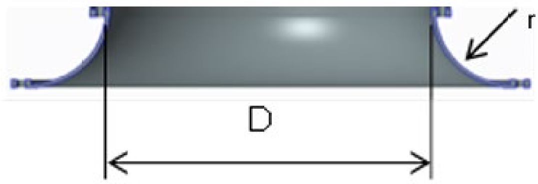
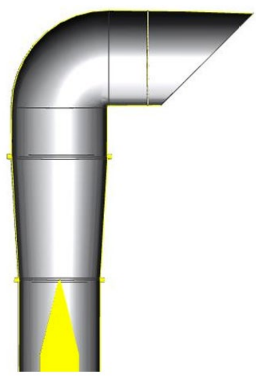


Figure 22. Inlet nozzle with r/D ratio of 0.25

The curved blow out (Figure 23) should prevent the system from environmental influences and losses due to flow deflection.



Dryer

The next section is the drying area.
For a good distribution of the airflow through the cocoa beans the air inlets are located at two fronts (Figure 30). For dimensioning the mesh for the cocoa beans, a filing height of 0,02m is estimated and the pressure rise which the fan must perform is:
$\Rightarrow \Delta P_{tt} = 220$ Pa of fan $\Rightarrow h = 0.02$ m
Now the real power of our fan with the power at the drive shaft and a hydraulic and volume efficiency of the fan can be calculated:
$\Rightarrow \Delta P_{tat} = P * \eta hyd * \eta vol = 300 \text{ W} * 0.9 * 0.8 = 216\text{W}$
The volume flow is the product of the real power, and the volume flow is calculated as well:
$\Rightarrow \Delta P_{tat} = \frac{\dot{V}}{\Delta Ptt} \Rightarrow \dot{V} = 0.954\ m^3/s$
With a required flow rate of v ≈ 0,45-0,55 m/s (regarding to existing solar dryers) the related:
$\Rightarrow A = \frac{\dot{V}}{V} \approx 2\ m^2$
Due to the quadratic design of the drying area the length and the width are equal:
$\Rightarrow 1 = b\ \sqrt{A} \approx 1.4$ m
The drying mesh is sealed to ensure full operating pressure.

Figure 24: Concept Drawing of a dryer with air inlets at two fronts and a drying mesh

2.3.3 Heating concepts

The requirements for the drying systems are to supply airflow with a temperature of 45-55°C to dry the cocoa beans. To reach such temperatures different types of air heating are discussed.

The first idea is a heat tunnel where the air flows through and is heated by thermal radiation and convection (Figure 25). The sun's irradiation permeates the cover plate of glass, and the air is heated by absorption. The copperplate on the floor of the tunnel is heated by irradiation as well. It also heats the air through convection but has to be isolated from the bottom. The copperplate emits thermal radiation with another wavelength than the sunlight which can't permeate the plane. So, the system theoretically heats more and more up, but the airflow of our systems takes the heat flow, and the temperatures increase to the target temperatures.

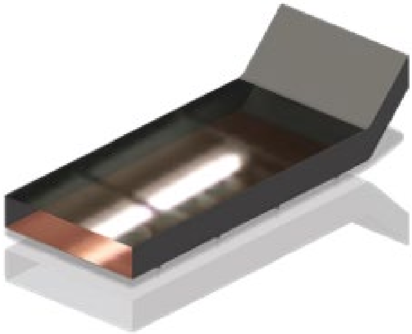


Figure 25: Heat tunnel concept drawing with a pane and a copperplate to generated heated
air through thermal radiation and convection

The second idea is a system similar to the well-known concept of a parabolic concentrating solar power plant. A reflector concentrates the sunlight on the focus where the absorber tube is located. The tube should have a black surface to absorb the sunlight. An Airflow through the absorb tube is also heated according to the heat tunnel concept by thermal radiation and convection.

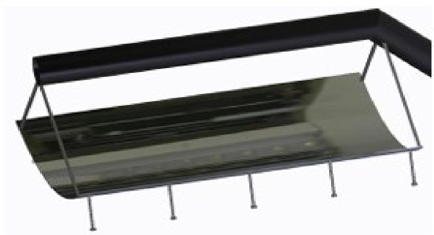


Figure 26: Concept drawing of a parabolic concentrating collector

Total plant design

The total plant (Figure 27) shows one possible solution for a solar dryer for cocoa beans using heated air and forced air flow.

Figure 27: Solar dryer concept drawing

Overall, it is a practical, efficient and affordable drying system, which should lead to better efficiency and an improvement of the production output.
The Rotor-Stator unit (Figure 28) fulfills the needs boundary conditions in any way even though it is not optimized or acoustically proven. It is one possible solution.

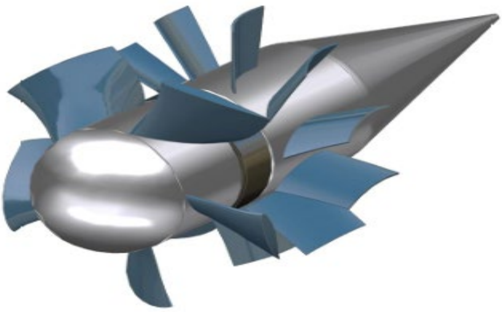


Figure 28: Concept Drawing of the Rotor-Stator-unit

Based on the scale of planted cocoa and financial capacity, smallholders can invest in a suitable size of solar drier. Smallholders ferment and dry the cocoa beans that they produced pods by themselves can invest the smallest drier with $2.34m^2$ drying bed and 100 kg/batch.
Smallholders cultivate cocoa trees and buy pods from neighboring farmers should build a $4m^2$ drying bed solar drier with capacity of 200 kg fermented cocoa beans in one batch. The $9m^2$ drying bed solar driers (450 kg/batch) can satisfy commercial buyers/companies who have more cocoa beans for drying.
Using solar driers will help to shorten the time of drying, to reduce loss of cocoa and labour, and to improve the flavour and quality of cocoa. That helps to increase income of smallholders. This also demonstrates the important role of research and technology transfer in agricultural activities.

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