Third LACCEI International Latin American and Caribbean Conference for Engineering and Technology (LACCET'2005)
"Advances in Engineering and Technology: A Global Perspective"*, 8-10 June 2005, Cartagena de Indias, COLOMBIA*

MICRO SOLAR CHIMNEY USING CONCENTRIC VACUUM TUBES

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Abstract
A solar power generator is being designed and constructed at the Ozama Engineering Campus. The system will consist of a solar collector using Concentric Vacuum Tubes (2.2 m2) and a 60-meter tall chimney. The chimney will generate the needed natural draft to move a small axial air turbine (wind mill) that will impulse an electric generator. The turbine will also turn a small air compressor to create a forced convection inside the solar collector and there fore use the whole length of the vacuum tubes with out reaching the stagnation temperature. This paper will present all the work done at our Campus, with local materials and human resources; the theory upon the thermodynamic system that the model will work on; the optimization of its efficiency calculations; the mechanical engineering design procedures, the electronic controls and the computer software interface.

Keywords
Solar Energy, Concentric Vacuum Tubes, Solar Chimney, Solar Convective Tower, Electric Generator Wind Mill.

Introduction

The combination of a solar convective tower (Solar Chimney), a concentric vacuum tube solar collector, a small fan (or blower), and a small power producing expanded are envisioned in this research and development project. The scientific theory, of all these well-developed engineering systems, as the actual construction of this solar electric generator, will be done under the limitations imposed of the underdeveloped world, such as those that can found in the Dominican Republic. Every thing is difficult in the cultures of the underdeveloped worlds. The lack of government funding, lack of understanding of authorities, corruption, lack of incentives to the students, etc; all combine to frustrate any intent of real research and development, in the academic world, in countries that the culture of elementary necessities are always present.

The research project will be built in one of the nine University Campus that form the "Universidad Tecnologica de Santiago (UTESA)", specifically in its newest Campus of "Recinto Ozama" in the Capital of the Dominican Republic. The main building of this Campus has a 5 story high building structure that will be used as support of the 20 to 60 meter high chimney, on a south facing wall. See **Photograph #1** of actual location of solar collector and chimney. The solar collector that will be used is a 15 tubes (1.5 meters in length) array in a stainless steal tank of 30 cm diameter of 1.25 meters long, insulated with styreform. The overall solar collecting area is of 1.5525 m2, made of the 15 CVT 's and a polished back surface reflector.

Photograph #1. Concentric Vacuum Tubes Solar Collector.

The overall experience of the principal investigated can be evaluated since 1982 when he began solar investigations for more then 8 years at a vocational college (IDT-Santo Domingo), (Development of a Solar Air Conditioning System working between 160F and 95F. VII Miami International Conference on Alternative Energy Sources, University of Miami, Dec 9, 1985, Clean Energy Research Institute of the UM), as Director of government Research Center in 1987 (INDOTEC, Book Published, "Programa de Aprovechamiento de la Energía Solar en la República Dominicana", Ohio State University, Editora Taller 1987). At present he is promoting the installations of Solar Water Heaters of the Concentric Vacuum Tubes type in the Dominican Republic.

The objective of this research is to study the possibility of innovation of various removable energy technologies that are accessible, reliable and simple for its implementation; specially, if we take into consideration the fact of the limitations that are encounter in the underdeveloped world environment. With the production in China of the Concentric Vacuum Tubes at a very low economic value, principally due to its high volume of production, the technology of these systems are made affordable to the rest of the world, at reasonable prices. Important is to state and to point out, that this economic attractiveness makes possible a more efficient system at a less cost. The CVT systems work more efficient at higher temperatures, in the order of 30 to 40 % better, then the Flat Plate Solar Collector.

The solar chimney is a technological fact that can be evaluated from the Thermodynamic Theory and a real world installation that can be seen in the experimental prototype built in Manzanares, Spain. This pilot plant consists of a 194.6 m high solar chimney; a mean collector radius of 122 m and an installed aero-generator of 60 kw. Haaf (1983, 1984) gives test results and a theoretical description of the solar tower prototype in Manzanares. Ruprecht et al (2003) gives results from fluid dynamics calculations and turbine design for a 200 Mw solar tower. At present, in Australia their is a program to built a 200 Mw Solar Chimney (http://www.enviromission.com.au) The substitution of photovoltaic electric generation panels with this scenario of solar chimney and solar heating panels is an object to be considered for underdeveloped worlds were the high technology environment involved in the manufacturing of Photovoltaic makes it almost impossible.

Principal of Operation

The principal of operation of our proposed systems is as can be seen in figure #1. Atmospheric air is forced inside a 4-inch rectangular tube, which serves as a distribution manifold, that introduces this air-flow, via a 3/8 inch cupper tubing, inside the inner glass tube of the **CVT** (Concentric Vacuum tube).

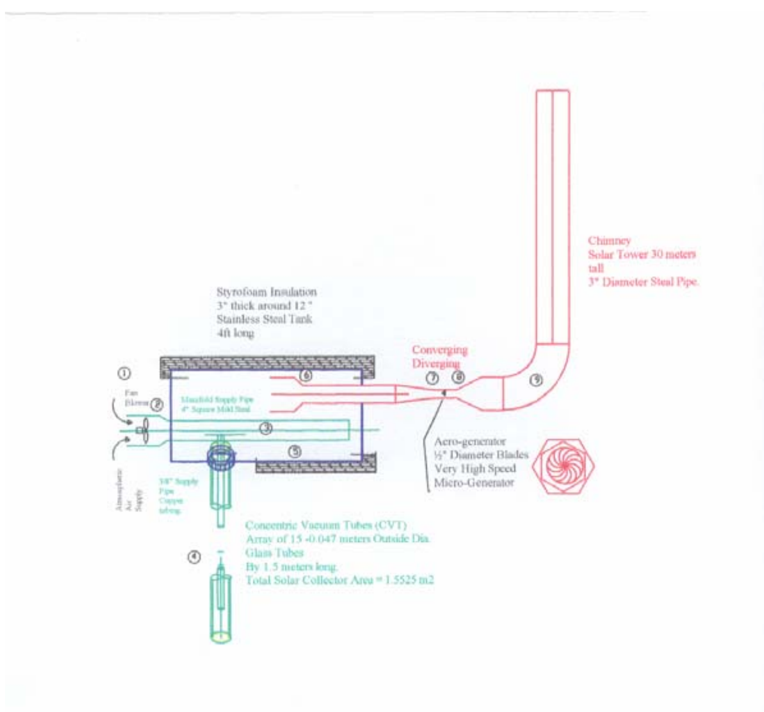

Figure #1. Schematic of proposed solar power generator.

The circulating air is heater inside the chamber formed between the inner glass receiver, impregnate with a selective surface, and the cupper supply tube due to the solar radiation and expelled into the insulated stainless steal 30-cm diameter cylinder tank plenum, at high temperature and slighted increase pressure. As hot air is lighter then cold ambient temperature, a draft lift will be developed that will increase its circulating force through an aero-propelled generator at the entrance of the solar chimney of 20 meters high (first intend). The aero-generator will be enclosed in the throat of a converging-diverging air duct.

Collector

The solar collector is made of an array of 15 CVT with the following dimensions, Heat Transfer characteristics and Thermodynamics parameters: outside diameter 0.047 m (**D**), inside diameter inner tube 0.037mm (**D_r**). Center to center distance of 0.067 m (**d**). Coefficients of transmissibility (τ) and absorptance (α) are 0.92 and 0.90 respectively. The constant loss due to radiation of the hot tubes to the ambient of 0.80 watts/m2 C (**U_c**). A polished S.S. back surface reflector.

The total thermal energy that will be absorbed at the inner glass tube is given by the following equation (J.Kreider, F.Kreith, Solar Energy Handbook, 1981, McGraw-Hill, page. 7-28)

$$q_u = \frac{D_r}{d}\left[\tau\alpha I_{eff} - \pi U_c\left(T_r - T_a\right)\right] \tag{1}$$

Where **q_u** is the heat absorbed per unit area by the inner tube, **T_r** is the temperature at the surface of the tube and **T_a** is the ambient temperature. **I_{eff}** is the solar incidence on the tube that is given by the following equation,

$$I_{eff} = I_{b,c}\left(\cos i_r + \cos i_c \rho\Delta \frac{W}{D_r}\right) + I_{d,c}\left[\pi F_{TS}\left(1 + \rho \bar{F}\right)\right] \tag{2}$$

Where $I_{b,c}$ and $I_{d,c}$ are respectively, the beam and diffuse radiation components intercepted per unit collector aperture area, τ and α are the envelope transmittance and the receiver absorptance, and i_r is the tube incidence angle, which depends on the solar time of the day, and month of the year. Δ is a sum of the shape factor equal to about 0.6 to 0.7 for tubes spaced one diameter apart. F_{TS} is the radiation shape factor from a tube to the sky dome and ρ is the reflectance factor of the reflecting back surface. W and Dr are the geometric dimensions of illuminated strip and outside diameter of the inner tube.

As can be imagined, I_{eff} will depend on several important factors, the globe latitude, time of the day, day of the year, local reflectance and shading of the surrounding, cloud cover and cleanness of the glass collector outer tube. For our case, the local latitude of the city of Santo Domingo is 19.1^o and has a very documented literature on all the statistics of solar incidence, both direct and diffuse for hourly radiation taken on horizontal instruments and published from INDOTEC for the years 1983, 1984 and 1985. (See reference # 1.this book was published during my CEO duties at INDOTEC)

Thermodynamic Analysis of the Solar Collector Tubes

For sake of simplicity, study will be made using in all our analysis a steady flow of a perfect gas through a constant area and frictionless. While the air is circulating in the chamber between the inner glass of the CVT and the metal supply tube, heat is being added due to solar radiation. The appropriate equations are:

Continuity: $$G = \frac{\dot{m}}{A} = \rho V \quad (3)$$

Momentum: $$p + \rho V^2 = constant \quad (4)$$

Energy: $$q_u = h_o - h_i + \frac{V_o^2 - V_i^2}{2} = cp(T_o - T_i) + \frac{V_o^2 - V_i^2}{2} = cp(T_{0o} - T_{0i}) \quad (5)$$

State Equation: $$p = \rho RT \quad (6)$$

Heat Transfer: $$qu = A_{eff} U (T_r - T_f) \quad ♣ \quad (7)$$

With a simple numerical analysis using the computer program of Excel (Microsoft), the 1.5 meter long tube is divider into 1500 small parts. Equivalent to the analysis and study of a control volume made of 1 mm each section. The flow of air between any section, say “n” and “n+1” will absorb heat that is given up by the heat transfer of the collected radiation at the tube wall. At any section of the tube, T_r is the surface temperature of the tube, while T_{n+1} and T_n are the outlet and inlet temperature respectively. With a further simplification between these small sections, we will assume that the average temperature between inlet and outlet temperature of the air is,

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♣ **Coefficient of heat transfer U=h, obtained from** $N_{Nu,b} = 0.023 N_{Nrey,b}^{1.8} N_{Npr,b}^{0.4}$

$$T_m = \frac{T_{n+1} + T_n}{2} \tag{8}$$

Combination of the equations (1), (7) and (8) plus a some algebraic manipulations, we deliver a solution for T_r at any "n" as,

$$T_r^n = \frac{{D_r}/{d} * \tau\alpha I_{eff} + {D_r \pi U_c}/{d} * T_a + h * T_m}{h + {D_r}/{d} * \pi U_c} \tag{10}$$

And with equations (1) and (5),

$$T_{n+1} = T_n + \left[\frac{D_r}{d} A_{eff} \right] \frac{\tau\alpha I_{eff} - \pi U_c \left(T_r^n - T_a \right)}{\dot{m} Cp} \tag{11}$$

This numerical integration is carried out with the following initial conditions,

N	Tn	Tn+1	Tm
0	Ta	T1	Ta
1	T1	T2	(T1+T2)/2
2	T2	T3	(T2+T3)/2

For an effective solar radiation of 400 w/m2, and an ambient temperature of 30 C, a mass flow rate of 0.004 kg_m/sec, a specific heat coefficient of the air (constant) of 1,004.64 J/Kg_m C, a convective heat transfer coefficient between inner glass and air flow of 2.75 w/m2 C, the final conditions of temperature of the air at the segment n=1,500 is of:

Tr = 81.567 C and **Tn = 76.006 C**

Obviously the outlet temperature at the plenum of the collector will be at 76 C, which corresponds to the point #5 in the schematics of figure #1. With a total collector area of 1.5075 m2, the total radiation incident on the collector will be 603 watts. The total energy absorbed by the airflow is 184.85 watts, which gives an efficiency of collection of 30.66 %.

Chimney or Updraft Tower

The chimney converts the heated air flow internal energy into kinetic energy, or what is better known as a convection current of air. The density difference of the air caused by the temperature rise in the solar collector works as a driving force. The lighter column of air in the tower is connected with the surrounding atmosphere at the base inside the collector and at the top of the chimney and therefore producing the desired driving force. Between the collector and the ambient surrounding the installation, a pressure difference is generated that is given by,

$$\Delta P = g\int_0^H (\rho_a - \rho_t)dy \tag{12}$$

where H is the chimney height.

This pressure difference can be divided into two components: a static and a dynamic component. The static pressure difference is the component that is given up at the aero-generator, between points #7 and #8 of figure #1. The dynamic component describes the kinetic energy of the airflow in the chimney. Without an aero-generator a maximum flow speed is obtained and the whole pressure difference is used to accelerate the air.

Using the same numerical analysis that was used in the calculations of the solar collector system of before, with a subdivision of 1 meter and with the inlet temperature of 76 C, diameter of the chimney of 4 inch's, heat transfer coefficient of 1 w/m2C and a mass flow rate of 0.004 kgmass/sec, the pressure differential driving force is of 15.93 kgf/m2 for a 20 meter high chimney.

Aero-Generator Turbine

Conventional analysis of wind axis turbo machinery are simply done with the introduction of an interference factor denominated as "a". For an airflow velocity of V, as the mass of air passes the aero-generator blades, it will reduce its out-going velocity by (1-2·a). While the air is actually in contact with the blades its velocity is set as (1-a). The power that the turbo machine extracts from the airflow is given by:

$$P = N * 2\pi R^2 \rho V^3 a(1-a) \tag{13}$$

where N is the number of blades, R is the radius and ρ is the density of the air. The total energy flux E that is in the upstream of the airflow in the duct is given by the kinetic energy and with an area equal to the area of the blades facing the flow,

$$E = \frac{1}{2}\rho V^3 \pi R^2 \tag{14}$$

If we create a power coefficient Cp as a measure of P/E, the results are equal to $4 \cdot a(1-a)^2$. As can be noticed, the interference factor is a measure of the efficiency of the extracting power from the kinetic energy of the airflow.

The value of "a", has to be obtained using a second relationship that is obtained with a velocity and force diagram on the physical characteristics of the turbo machine. The diagram of figure #2 (♦),

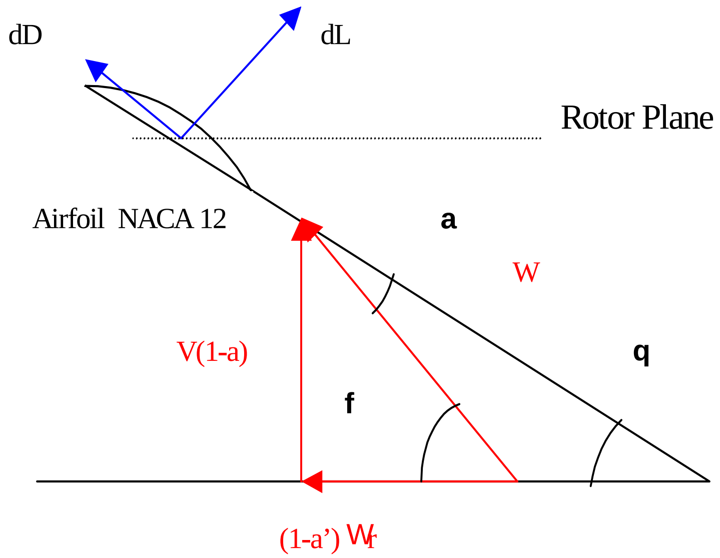

Figure #2. Velocity and Forces acting on a blade of aero-generator.

gives the relations for the drag and lift forces on the blades of the aero-generator. The extracted power is given by,

$$P = \rho \frac{N\Omega}{2} \int_0^R crW^2 (C_L \sin\phi - C_D \cos\phi) dr \qquad (15)$$

where Ω is the angular velocity of the propeller, c is the cord size, W is the relative velocity of the airflow to the blade, C_L and C_D are the lift and drag coefficients; which are obtained from empirical airfoil data. The angles α, θ, ϕ are the angle of attack, airfoil angle of inclination and are related by, $\alpha = \theta - \phi$.

♦ See reference "Kreider and Kreith, Solar Energy Handbook", McGraw-Hill,, 1981 page 23-9.

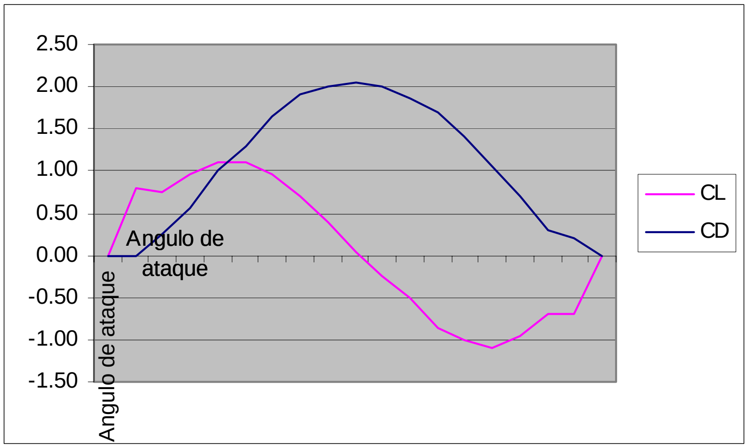

Figure # 3. Airfoil correlations for NACA 0012, Lift and Drag coefficients.[⊕]

Using equations (13) and (15), and with the same techniques stated before and with the auxiliary of Excel (Microsoft), plus a trail and error; by choosing values of "a" and "a' ", and the data of figure #3 for the empirical correlations of the NACA 0012 airfoil, results are obtained for a 1 inch diameter blade, N=22, a=0.3, a'=.55, c=0.3 mm, blade angle=20.55, angular speed= 16,000 rad/sec equal to 152,788 RPM.

Construction and Field Installation

At present all the theory and calculations needed to design our working system has been developed. At our own shops, of the University, we are mechanically building all the piping and installing the Vacuum Tubes Solar Collector. To create the effect of the airflow converting tower, we will used a 4" PVC pipe of 15 meters that forms part of the existing building structure for rain drainage at the roof, plus the addition of 15 meters more to get our 30 meters in height. In Photograph #2, can be seen this pipe.

In Photograph #3, can be seen the construction phase of the 4" mild steel square manifold that will distribute the forced air into the heating chamber between the inner glass absorbing tube and the cupper supply tube.

[⊕] J.H. Strickland (1975) "The Darrieus Turbine: A Performance Prediction Model Using Multiple Streamtubes" SAND75-0431

Photograph #2 15 meter 4 inch pipe used as solar chimney

Photograph #3. Construction phase of the 4” mild steel square manifold. As can seen a cupper tubing fitting is installed to support supply pipe inside vacuum tubes.

Conclusions

The desire to develop the culture of R&D in the Dominican Republic is one of the important motives of the University “UTESA” in the pursuer of this scientific investigation. Also it is important that our students of mechanical and electrical engineering see via “hands on” the developments of the new technologies. It will be the responsibility of all last year students to create innovations on this system, both on the actual physical construction as well in the theory behind the idea. It has been programmed that by the months of June, July and August, the experiment will be working and experimental data plus analysis of the results will be published in the semi annual scientific magazine of our University, “Ciencia y Tecnología”.

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