Free Convection Fresnel Lenses Concentrator

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Abstract *— This project involves an evaluation of an improved Fresnel lenses solar energy concentrator. Its innovation consists of preventing forced convection heat losses at the receiver area. Heat losses by convection and by the transmittance and reflectance properties of the solar rays transmission of the material were calculated for the comparison of parabolic and Fresnel lenses solar energy concentrators. The expected efficiency of the Fresnel lenses concentrator within free convection conditions is 93%. An efficiency increment to 95% is noticed for vacuum conditions. Doing the same analysis for the parabolic concentrator the efficiency expectation is 95% within forced convection conditions. The efficiency expectations for both concentrators presents them as competitive choices for energy production.*

Key Terms *— Free and Forced Convection, Reflectance, Thermal Efficiency, Transmittance.*

INTRODUCTION

In a typical sunny day the earth receives an average amount of Direct Normal Irradiance (DNI) of 900 [1]. In year 2009, Abbot [2] said that with this irradiation most of the earth surface could be used to satisfy the current global energy consumption with leftovers.

Professor Carlos Alvarado, Ph. D. P.E. developed a Capstone Design Project with the interest to a further investigation project with the vision to create an efficient solar energy concentrator.

This Investigation has the objective to create an innovative design of solar energy concentrator that can compete with the efficiency of current popular concepts using low cost materials by minimizing the energy losses by forced convection.

CURRENT CONCEPTS FOR SOLAR ENERGY CONCENTRATORS

Solar energy concentrators consist of two main components for the heat flux collection on the receiver. See Figure 1. The losses from the sunlight due transmittance or reflectance of the material as soon as the light makes contact with the concentrator and the losses due convection.

There are seven types [3] of solar concentrators that are known as distinguished designs during the development of this technology. This types are known as:

- Parabolic Concentrator
- Hyperbolic Concentrator
- Fresnel Lens Concentrator
- Compound Parabolic Concentrator (CPC)
- Dielectric Totally Internally Reflecting Concentrator (DTIRC)
- Quantum Dot Concentrator (QDC)

According to the optical principles we can categorize each concentrator in four groups. See Table 1 below [3]:

Table 1
Four Different Groups of Concentrators

Group	Description
Reflector	Upon hitting the concentrator, the sun rays will be reflected to the receiver. Example: Parabolic Trough, Parabolic Dish, CPC Trough, Hyperboloid Concentrator.
Refractor	Upon hitting the concentrator, the sun rays will be refracted to the receiver. Example: Fresnel Lens Concentrator
Hybrid	Upon hitting the concentrator, the sun rays can experience both reflection and refraction before hitting to the receiver. Example: DTIRC, Flat High Concentration Devises
Luminescent	The photons will experience total internal reflection and guided to the receiver. Example: QDC

Each type of solar concentrator present their advantages and disadvantages on their years of effective service. See Table 2 below [4].

Table 2
Summary of the Advantage and Disadvantage of the Concentrators

Type of Concentrator	Advantage	Disadvantage
Parabolic Concentrator	•High concentration	• Requires larger field of view. • Need a good tracking system.
Hyperboloid Concentrator	• Compact	• Need to introduce lens at the entrance aperture to work effectively.
Fresnel Concentrator lens	• Thinner than conventional lens. • Requires less material than conventional lens. • Able to separate the direct and diffuse light - suitable to control the illumination and temperature of a building interior.	• Imperfection on the edges of the facets, causing the rays improperly focused at the receiver.
Compound Parabolic Concentrator	• Higher gain when its field of view is narrow.	• Need a good tracking system.
Dielectric Totally Internally Reflecting Concentrator	• Higher gain than CPC. • Smaller sizes than CPC.	• Cannot efficiently transfer all of the solar energy that it collects into a lower index media.
Flat High Concentration Devices (RR, XX, XR, RX, and RXI)	• Compact. • Very high concentration	• Difficulty to create electrical connection and heat sinking due to the position of the cell. • The cell dimension must be designed to a minimum to reduce shadowing effect.
Quantum Dot Concentrator	•No tracking needed. • Fully utilize both direct and diffuse solar radiation	• Restricted in terms of Development due to the requirements on the luminescent dyes.

PROPOSAL OF IMPROVEMENTS TO SOLAR ENERGY CONCENTRATORS

The idea consist in developing a solar energy concentrator system with a Hybrid type technology based in both types Reflector and Refractor. Using mirrors placed on a structure with an angle to reflect the sunrays to the same area where the receiver is located. See Figure 1. Fresnel Lenses technology will take place with the purpose of refracting the sunrays to direct them to the receiver of reduced area. In order to avoid energy losses forced convection will be eliminated from the receiver area but natural convection will still take place on the investigation. However the manufacturing for the Fresnel lenses solar energy concentrator could also use a vacuum chamber inside the structure to completely eliminate energy losses due convection.

SYSTEM CONCEPT DEVELOPMENT

The system is form of a cubical structure in which five of its six faces will have a fixed identical Fresnel lens unit for each side north, south, west, east and top. The face of the cubical structure that does not have a Fresnel lens is in which the structure will rest. Each Fresnel lens has the same properties. See Figure 1 below.

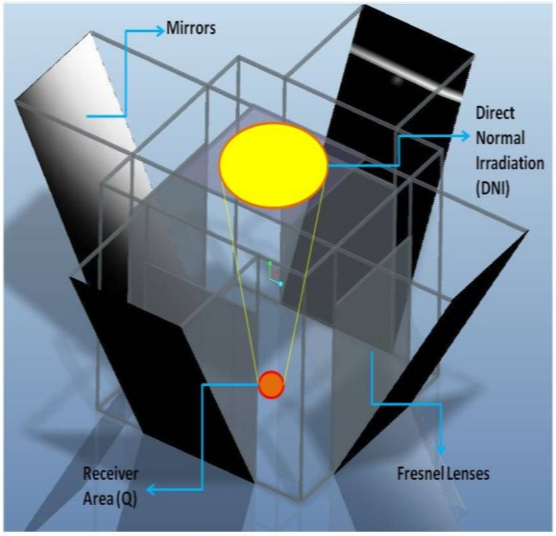

Figure 1
Fixed Cubical Structure

Equations And Mathematical Description

There are two different analysis for the efficiencies of the Fresnel lenses concentrator. The first analysis is based on the efficiency of the receiver where the properties of the element as the absorber of DNI are considered. The device that is used in high temperature solar concentrators for the conversion of concentrated solar radiation to heat is called “receiver”. It is designed to absorb the concentrated solar radiation and to transfer as much energy as possible to a heat transfer fluid. Losses originate from the fact, that the absorbing surface may not be completely black, that it emits thermal radiation to the environment, because it has an elevated temperature, and that convection as well as conduction occur. The heat entrance will be evaluated into a reduced capitation area with no concentration factor assuming that the DNI is orthogonal from the Fresnel lens surface and that the receiver is not protected by a transparent cover the heat entrance from DNI to the receiver can be calculated as (1)

$$Q_{solar} = A_a \cdot I \cdot \eta_{optic} \qquad (1)$$

Where A_a is the aperture area of the Fresnel lens, I is the radiation density of the direct solar radiation or DNI and η_{optic} as the optic efficiency of the concentrator material in terms of reflectance Γ and transmittance τ respectively. The useful heat collected is denoted by the product of (1) and the absorptance properties of the receivers material yields as (2)

$$Q_{absorbed} = \alpha \cdot Q_{solar} \qquad (2)$$

where α is the absortivity coefficient [5] of the receiver material. The heat losses will take place in the reradiating area with emissivity applying the Stefan Boltzmann Law and heat losses due convection as (3) [6].

$$Q_{lost} = A_r \cdot \left[\varepsilon \cdot \sigma \cdot T_r^4 - U(T_r - T_s)\right] \qquad (3)$$

where A_r is the receiver area, ε is the emissivity coefficient [7] of the absorber, σ stands for the Stefan Boltzmann constant, U_L is the convection coefficient [8][9], T_r is the temperature on the receiver and T_s is the temperature on the surroundings. Using (1), (2) and (3) the thermal efficiency for the receiver $\eta_{\mathrm{Re}ceiver}$ is defined by the Carnot efficiency [10] as the ratio of the absorbed heat minus the heat losses and the heat entrance as (4)

$$\eta_{\mathrm{Re}ceived} = \frac{Q_{absorbed} - Q_{lost}}{Q_{solar}} \qquad (4)$$

If a vacuum chamber takes place into the system the energy losses due convection are zero in (3). Therefore the heat losses Q_{lost} [10] will be denoted as (5)

$$Q_{lost} = A_r \cdot \left[\varepsilon \cdot \sigma \cdot T_A^4\right] \qquad (5)$$

However in this investigation DNI its concentrated to the receiver when its covered with fresnel lenses as a transparent cover of PMMA and energy losses occur due the transmittance of the material. As for a parabolic concentrator energy losses from DNI occur due the reflectance properties of the material. Here is where the discussion for the second analysis for efficiency takes place on the concentrator itself where the property of transmittance or reflectance of the material of the concentrator is considered.

Parabolic concentrators uses mirrors to reflect the sunlight to a receiver. These mirrors are made with high reflective materials. AccuCoat inc. [11] demonstrates some material reflectivity. For aluminum a reflectivity of 88% to 93% and silver with a reflectivity of 95% to 97%. See Figure 2 and Figure 3 below [11].

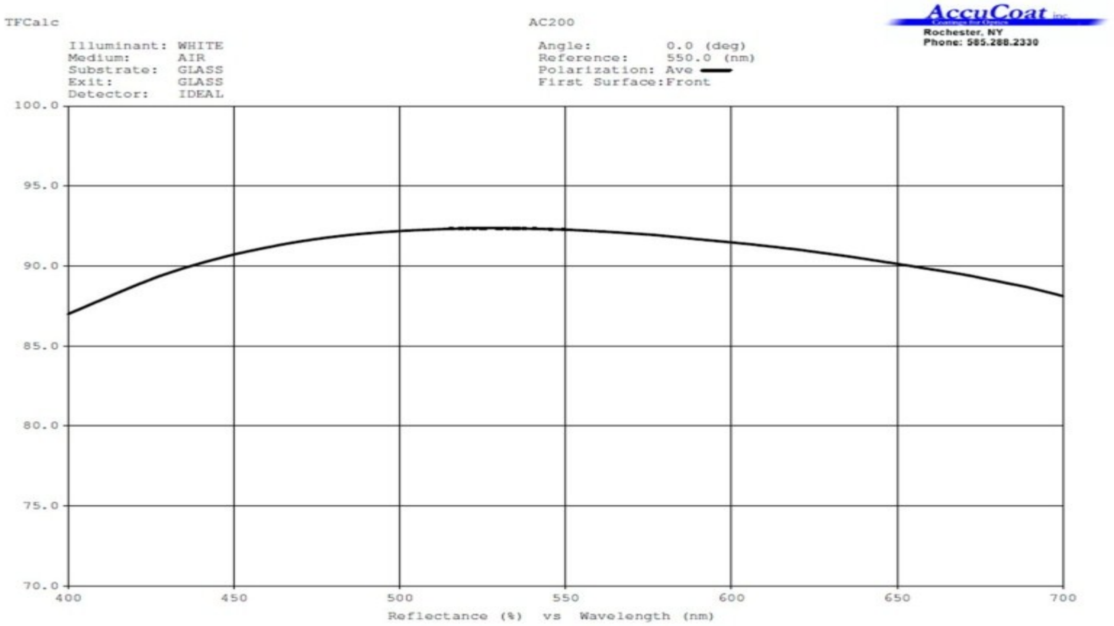

Figure 2
Protected Aluminum Coating Reflectance

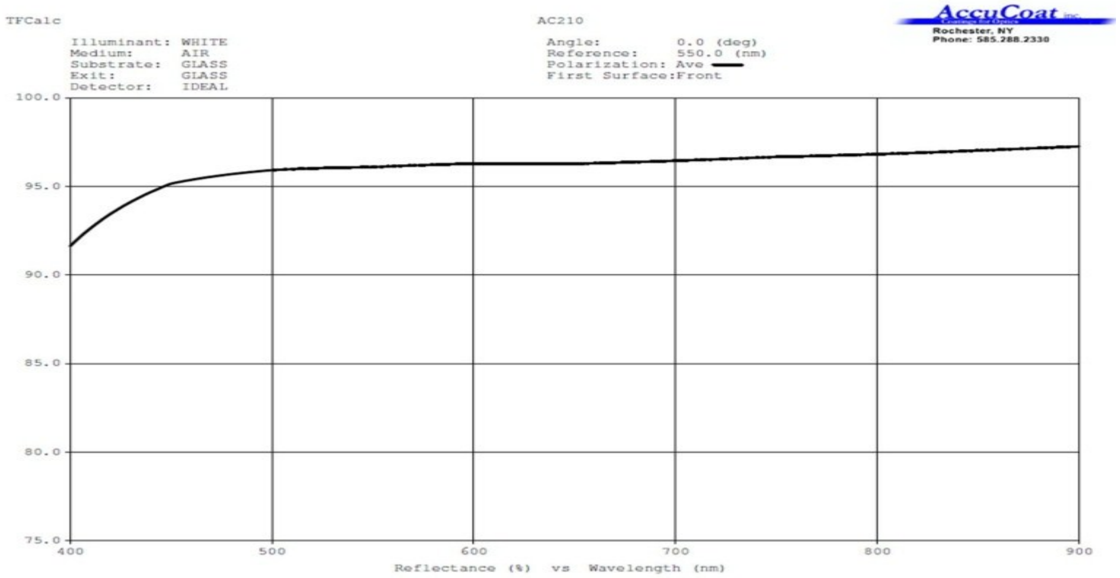

Figure 3
Protected Silver Coating Reflectance

However Fresnel lenses concentrators uses high transmittance materials such as polymer Plexiglass. Also known as Polymethyl Methacrylate or PMMA is a transparent thermoplastic material often used as a light weight alternative to glass. It's also an economical alternative to Polycarbonate when extreme durability is not required. It's low cost, has great clarity. PMMA transmits T up to 93% of light. See Figure 4 below [12].

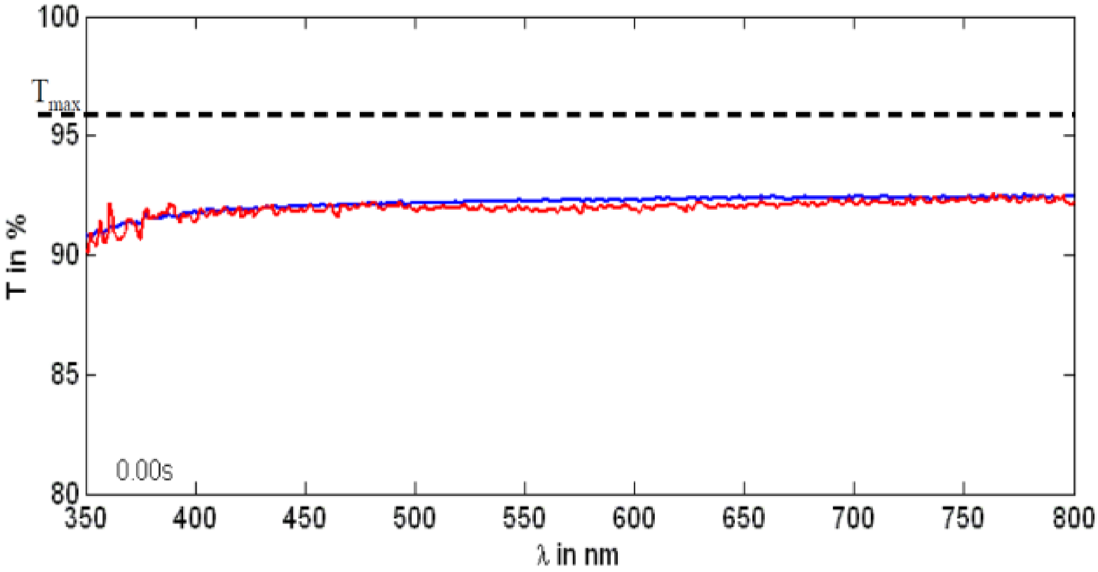

Figure 4
PMMA Transmittance Monitoring

RESULTS

The thermal analysis was executed for the Fresnel lenses concentrator and for the parabolic concentrator as well for comparison purposes. Tables 3 to 5 demonstrates the properties and working conditions for the receiver and for each solar concentrator respectively. Tables 6 to 10 demonstrates the resultant values for the thermal analysis and the efficiencies. An assumption for the Fresnel lenses concentrator is that only one of the five lenses is considered for the DNI due that the mirrors for the simultaneous solar capitation of the five lenses are not yet installed. No reflectance properties is considered for the PMMA as well as no transmittance for the aluminum and silver coatings.

Table 3
Common Values

Variable	Value	Units	Description
α	0.30		Absortivity Coeff. (Aluminum Polished) [9]
I	900	W/m^2	Direct Normal Irradiation (DNI) [1]
ε	0.77		Emissivity Coeff. (Aluminum Polished) [7]
σ	5.67*10^{-8}	W/m^{2}K^4	Stefan Boltzmann Const. [8]
U_{free}	25	W/m^{2}K	Convection Coeff Free Convection. (Air) [8][9]
U_{forced}	150	W/m^{2}K	Convection Coeff Forced Convection. (Air) [8][9]
T_r	573	K	Receiver Temperature
T_s	300	K	Ambient Temperature

Table 4
Fresnel lens Properties

Variable	Value	Units	Description
A_a	0.79	m^2	Area of aperture
A_r	0.00065	m^2	Area of the receiver
τ	93%		PMMA Transmittance [12]

Table 5
Parabolic Properties

Variable	Value	Units	Description
A_a	5	m^2	Area of aperture
A_r	0.004	m^2	Area of the receiver
Γ_a	88%		Aluminum Reflectance [11]
Γ_s	95%		Silver Reflectance [11]

Table 6
Heat Entrance, Heat Absorbed and Heat Losses @ Free and Forced Convection and Vacuum for PMMA Fresnel Lenses

Variable	Value	Units	Description
Q_{solar}	661	W	Fresnel lens heat entrance @ free convection
$Q_{absorbed}$	198	W	Fresnel lens heat absorbed @ free convection
$Q_{lost,forced\_conv}$	47	W	Fresnel lens heat losses @ forced convection
$Q_{lost,free\_conv}$	7	W	Fresnel lens heat losses @ free convection
$Q_{lost,vacuum}$	3	W	Fresnel lens heat lost @ vacuum

Table 7
Heat Entrance, Heat Absorbed and Heat Losses @ Forced Convection for Parabolic Aluminum

Variable	Value	Units	Description
Q_{solar}	3960	W	Parabolic heat entrance
$Q_{absorbed}$	1188	W	Fresnel lens heat absorbed
$Q_{lost,forced}$	161	W	Fresnel lens heat losses @ forced convection

Table 8
Heat Entrance, Heat Absorbed and Heat Losses @ Forced Convection for Parabolic Silver

Variable	Value	Units	Description
Q_{solar}	4275	W	Parabolic heat entrance @ free convection
$Q_{absorbed}$	1283	W	Fresnel lens heat absorbed @ free convection
$Q_{lost,forced}$	173	W	Fresnel lens heat losses @ forced convection

Table 9
Thermal Efficiencies for Fresnel Lens

Variable	%	Description
$\eta_{abs,forced\_PMMA}$	23	Fresnel lens absorber efficiency @ forced convection
$\eta_{abs,free\_PMMA}$	29	Fresnel lens absorber efficiency @ free convection
$\eta_{abs\_vac\_PMMA}$	30	Fresnel lens absorber efficiency @ vacuum

Table 10
Thermal Efficiencies for Parabolic Aluminum and Silver

Variable	%	Description
$\eta_{abs,forced\_alum}$	23	Parabolic absorber efficiency @ forced convection
$\eta_{abs,forced\_silver}$	29	Parabolic absorber efficiency @ forced convection

WORK FOLLOW-UP

- Correctly calibrate the solar tracker and the linear actuators.
- Finish installation of thermocouples in the area of the entrance to the temperature readings.
- Installation of four mirrors for the collection of samples from the side lenses.
- Take real-time sampling and develop analysis and conclusion and of samples taken.
- Continue the research for efficiency increment on solar energy concentrators and their mechanisms.

REFERENCES

[1] Benitez, P., et al., "High Performance Fresnel-based Photovoltaic Concentrators", *Optics Express A40,* Vol. 18, April, 26th 2010, pp 8

[2] Abbott, D., *"Keeping the Energy Debate Clean: How Do We Supply the World's Energy Needs?".* In Proceedings of the IEEE, Vol. 98, 2009, pp 42

[3] Muhammad, S., et. al., "Solar Concentrators", *International Journal of Applied Sciences (IJAS),* Vol. 1, 2010, pp 4

[4] Madhugiri, G., et. al., "High Solar Energy Concentrators With a Fresnel Lens: A Review", *International Journal of Modern Engineering Research (IJMER)*, Vol. 2, June 2012, pp 1382

[5] Absorbed Solar Radiation, 2013 May 8, http://www.engineeringtoolbox.com/solar-radiation-absorbed-materials-d_1568.html,

[6] Pitz, R., "High Temperature Solar Concentrators", *Solar Energy Conversion and Photoenergy Systems,* Encyclopedia of Life Support Systems (EOLSS), 2007, pp 6

[7] Emissivity Coefficient of Some common Material, 2013 May 8, http://www.engineeringtoolbox.com/emissivity-coefficients-d_447.html

[8] Incopera, Frank P., et. al., "Fundamental of Heat and Mass Transfer", 6th Edition, pp. 8-9

[9] Water and Air Flowmeters, 2013 May 8, http://www.engineeringtoolbox.com/convective-heat-transfer-d_430.html

[10] Rabl, A., "Comparison of Solar Concentrators", Solar Energy Group, Argonne National Laboratory, December 1975, pp 3-4

[11] Metal & Dielectric Mirror Coatings, AccuCoat, inc., 2013 May 8, http://www.accucoatinc.com/mirrored.html

[12] Kaless, A., et. al., "Entspiegelung von PMMA durch einen Plasma-Ionenprozess", Fraunhofer Institut Angewandte Optik und Feinmechanik, March 2005, pp 9