Concentrated Solar Power Generation

by

Zhilei Jin

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Graduate Supervisory Committee:

Yu Hui, Chair
Raja Ayyanar
Armando Rodriguez

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ABSTRACT

Solar power generation is the most promising technology to transfer energy consumption reliance from fossil fuel to renewable sources. Concentrated solar power generation is a method to concentrate the sunlight from a bigger area to a smaller area. The collected sunlight is converted more efficiently through two types of technologies: concentrated solar photovoltaics (CSPV) and concentrated solar thermal power (CSTP) generation.

In this thesis, these two technologies were evaluated in terms of system construction, performance characteristics, design considerations, cost benefit analysis and their field experience. The two concentrated solar power generation systems were implemented with similar solar concentrators and solar tracking systems but with different energy collecting and conversion components: the CSPV system uses high efficiency multi-junction solar cell modules, while the CSTP system uses a boiler - turbine-generator setup. The performances are calibrated via the experiments and evaluation analysis.

ACKNOWLEDGMENTS

I would like to express my sincere thanks to my beloved family and friends, especially my advisor, Professor Joseph Yu Hui, for his teaching and help throughout my time in the graduate program at Arizona State University.

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INTRODUCTION

1.1 Renewable Solar Energy Resource Status

The global energy challenge is a critical issue facing the world with the depleting of coal, oil and natural gas and the increasing energy consumption. The world should rely more on green renewable energy sources other than the conventional fossil fuels. Ongoing research tries to find more efficient methods of using renewable energy forms such as sunlight, wind, biomass, tides and geothermal heat.

In general, there are factors to consider for selecting the best energy solution for a specific application, such as the location, the ease of installation, technology reliability, energy output capacity and cost [1]. For example, geothermal heat is location dependent, while wind energy is relatively low cost but unreliable due to intermittent wind condition. Also wind power needs regular mechanical maintenances.

Solar energy is the most abundant renewable energy source which is readily available anywhere the sun shines [2]. Solar energy is easy to collect and use with relatively lower overall cost comparing with the other renewable energy sources. Even though solar energy has benefits of being nonpolluting and minimal environmental impact, it does have limitations such as intermittent energy supply as the sun shines only at daytime, and energy conversion efficiency can be low. Sunlight is also a quite diluted power resource which requires a big collecting area to get a sizeable amount of energy [3].

With the advancement of the modern technologies, there are more effective solutions to utilize solar energy to improve our quality of life and be beneficial to the environment as well [4]. Historically, humans have utilized sunlight for space heating, lighting and generating hot water. Nowadays, utilizing solar energy often means converting the sunlight to electricity directly or indirectly, and then using the generated electrical power immediately or sending it back to the power grid or storing the extra unused electrical power in energy storage systems for future use. Sunlight could be converted into electricity directly using Photovoltaic (PV) materials, or indirectly through solar heat generated that could be used by solar thermal electric power systems, which typically includes a boiler, turbine and generator. Alternatively it also may use the thermoelectric materials to convert solar heat into electricity.

Most people living in the developed countries are already used to the comfortable life made possible by electrical appliances such as refrigerator, air conditioner, telephone, television and computer. There are still millions of people living in electricity-poverty without enough electricity to support their basic needs, such as food, medicine, home heating, cooling etc. Many places where these people live have great potential of solar energy resource. Distributed solar power generation could be a quick alternative way to help these poor people to obtain electricity in an economic and environmental friendly way without the high cost centralized power plants and power distribution system.

The world's power consumption is mainly supported by fossil power, nuclear power and to a much limited degree renewable power. Fossil fuel power generation is the biggest source even far more than nuclear and renewable sources combine together. Fossil fuel is a limited natural resource which would be used up eventually. Mass consumption of fossil fuels has negative environmental impacts such as excessive CO_2 emissions, which brings about climate change and environmental pollution problems.

Solar energy still counts for only a small percentage in the renewable energy sector. Compared with wind power, hydroelectricity, geothermal, biomass and bio-fuel as it represents the earth's largest energy source and has minimum negative environmental impacts. Solar power is compatible for both urban and rural remote areas, as well as good for both residential and utility scale development. Solar energy will become the main energy resource of our planet with advancement in solar technology research to lower cost and improve energy conversion efficiency.

1.2 U.S. Solar Power Development

Solar energy is very abundant in sunny areas, such as the Southwestern United States, Australia, North Africa and the Middle East. Solar energy is economical where there is high Direct Normal Irradiance (DNI) and long annual sunshine exposure (Fig 1.1) [5].

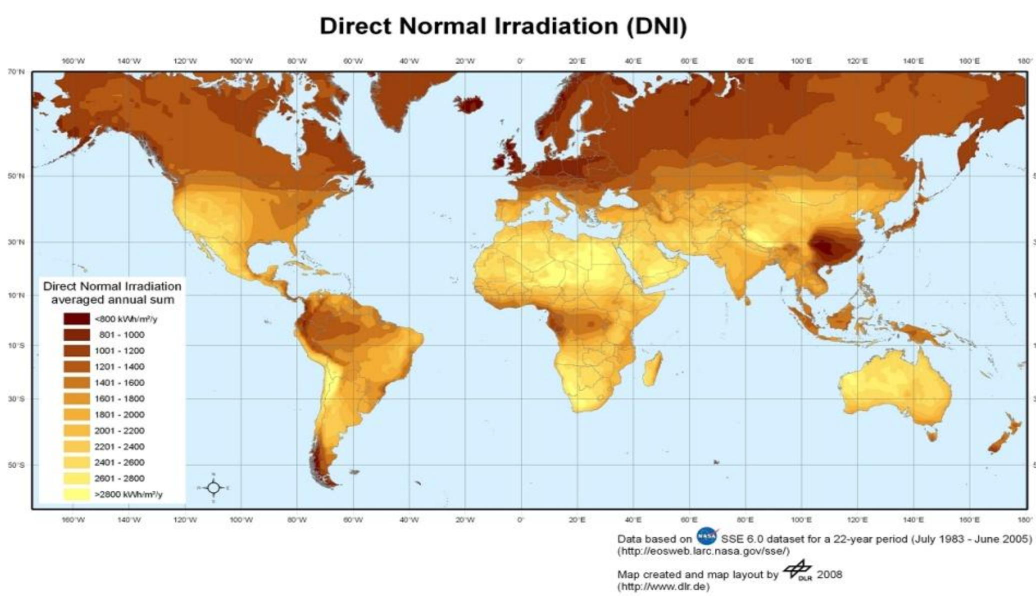

Fig 1.1 Worldwide Direct Normal Irradiation Distribution Map

DNI is the amount of solar radiation received per unit area by a surface that is always held normal to the incident sunlight.

United States (U.S.) indeed can play a key role in the future world energy market with decades of continuing support in the research and development of innovative solar power technologies. Many favorable incentives and policies drive the public to adopt the solar power. U.S. is one big consumer of the traditional fossil fuel energy supplies. U.S. also has great potential of solar radiant resources particularly in the Southwestern U.S. including Texas, New Mexico, Arizona, Nevada, and California with relatively higher annual accumulated sunny hours and higher DNI. Solar resource data is very critical to the solar power project's site selection, projected annual output and its expected performance and the choice of operating technology. These states are the perfect places to implement solar power generation according to the above criteria.

There are many financial incentives for supporting residential, commercial and utility markets to adopt solar power generation across the United States. Solar power generation installation capacity is booming according to the report from Solar Energy Industries Association (SEIA) [7]. Solar power becomes more affordable than ever as continuing improvement of the manufacturing and core technologies in solar radiation collection, semiconductor performance, performance of other system components, and power electronics for energy conversion. The U.S. Energy Information Administration (EIA) issued a report which published the electricity consumption distribution for different energy source [8]. It showed that renewable power counts for only 13% of the U.S. total annual electricity consumption, but coal and natural gas counts for 42% and

25% respectively, while nuclear has an even bigger role than renewable source with about 19%.

There are several reasons for this slow market adoption on utilizing solar energy: sunlight is dilute on earth compared to fuel and nuclear that it is hard to collect and use it very efficiently. Solar energy will be cost-prohibited when compared with the cost of using the traditional resources to get the same amount of power. Solar power generation is expected to gain market acceptance if taking into account of the beneficial and environmental zero carbon emission and the cost free sunlight. The Levelized Cost of Electricity (LCOE) of solar power generation has reached a tipping point to achieve the cost parity of the grid powered by traditional fossil fuel power plant.

1.3 Solar Power Generation Technologies

The concentrated solar power generation technologies could be generically divided into two big categories: Concentrated Solar Photovoltaics (CSPV) and Concentrated Solar Thermal Power (CSTP) generation. We can use the photovoltaic effect to directly convert sunlight into direct current electricity. PV system uses photovoltaic materials to absorb the sunlight which comprises photons with different wavelengths (Fig 1.2). Photons with more than the band gap energy can excite electrons in the photovoltaic material to jump out of the band gap and attain a free electron. Based on Detailed Balance Limit, single junction solar cell has a highest conversion efficiency of 30.8% under one sun radiation. With maximum concentration of sunlight on earth, this efficiency can rise up to 40.8%. It is proven that sunlight concentration could increase solar cell efficiency and reduce cost/efficiency ratio.

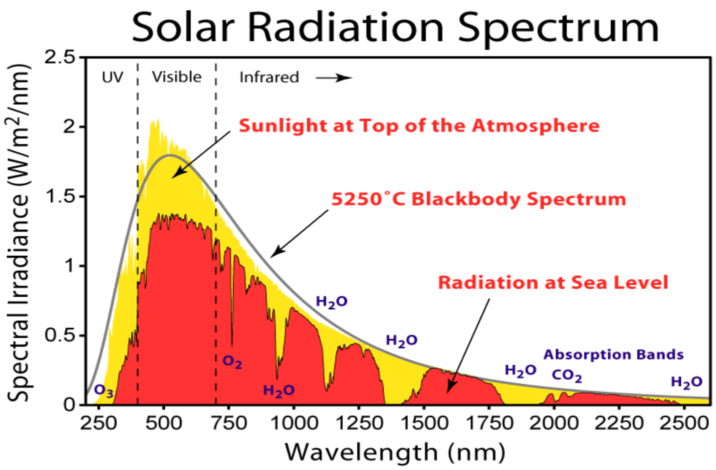

Fig 1.2 Solar Radiation Spectrum

Multijunction solar cell technologies can absorb more photons of different wavelength and perform best with concentrated sunlight. Triple junction solar cells are designed as a three layer sandwich. Spectrum splitting of solar photodiodes is the key to a higher energy output. The top layer, which captures blue photons, uses amorphous silicon (A-SI) with an optical band gap of 1.8 eV (electron volt) for the intrinsic layer. The middle layer is amorphous silicon-germanium (a-SiGe) alloy with about 10-15% Ge, with optical band gap of 1.6 eV, which is ideally suited for absorbing green photons. The bottom layer captures red and infrared photons using a layer of a-SiGe alloy with about 40-50% Ge, with an optical gap of -1.4eV. Light rays not absorbed during the entry would be reflected from the silver /zinc oxide (Ag/ZnO) metal layer and then be absorbed on the way out. Fig 1.3 shows the detailed structure of a common triple junction solar cell.

Multi-junction solar cell architectures are capable of up to 70% theoretical efficiency limit, and up to 50% efficiency in practice. It can convert twice as much of the sunlight converting into electricity than flat panel silicon cells. Currently, there are several suppliers for triple junction solar cells. The most widely used is from Spectrolab - a division of Boeing and a company that set records for the solar cell efficiency. Other companies include Emcore, Azur Space and JDSU [4]. Solar Junction is a new player in this industry and has received a lot of attention for its lattice matched solar cell architecture that provides material band gap tenability to maximize the absorbed sunlight.

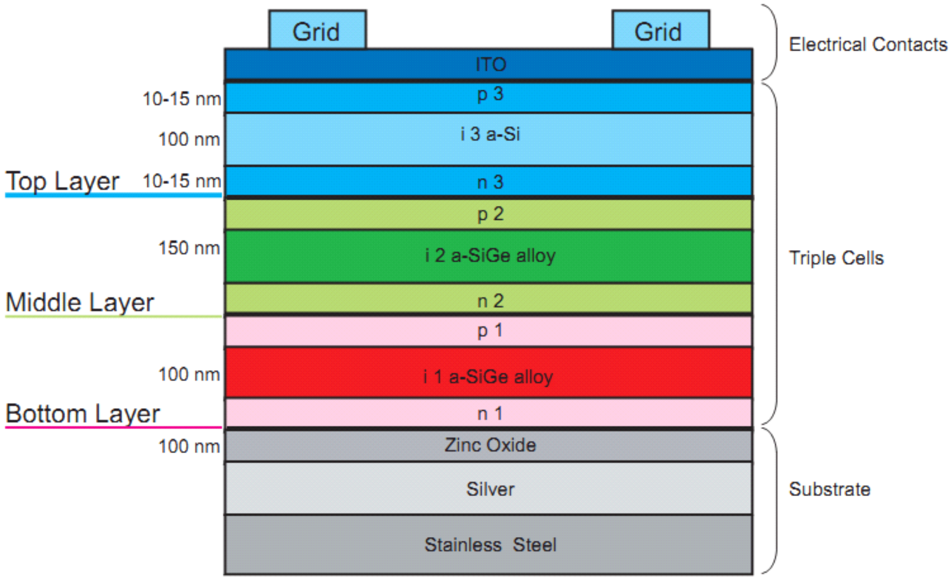

Fig 1.3 Schematic of a Triple Junction Solar Cell

The technology of producing triple-junction cells with more than 40% conversion efficiency under field operating conditions is already mature. Although triple junction cells are more difficult to manufacture than silicon cells and cost much more per unit area, the triple junction solar cells cost much less in terms of per unit power generated through the use of solar concentrators[9,10].

1.4 Concentrated Solar Photovoltaics

Concentrated Solar Photovoltaics (CSPV) system uses concentrator optics to concentrate the sunlight from a bigger area onto a smaller area where the solar cells are located. CSPV usually needs a sun-tracking system to follow sun's position throughout the day. Research on CSPV systems started in the 1970s at the Sandia National Laboratories, but commercial mass production was started only in the past decade. Performance of solar cells increases linearly with the light intensity and output voltage increases the logarithmic ally. Generated power rises linearly with the increasing concentrated radiation level. With high concentration of energy density, there are other challenges such as to overcome solar cells heating up that reduce conversion efficiency.

The CSPV is most efficient in areas such as the Southwestern U.S. region. One benefit from CSPV is that it does not require a lot of water usage, which is in short supply in dry area. Compared to flat-plate collectors, the CSPV systems need direct sunlight, which requires accurate tracking systems. Flat panel PV systems can generate electricity under indirect light and even on cloudy days.

Compared with the non-concentrated PV, the CSPV saves money by using small area of solar cells. The CSPV may reduce overall cost with high energy conversion efficiency. Accumulated installation capacity of CSPV is relatively small compared to other flat panel based PV systems, accounting for only 1 percent of the whole PV market. The world's leading CSPV industry organization predicted that CSPV will grow to 5% - 10 % of the total PV market by 2015.

The CSPV systems can be divided into low concentration LCPV (1-100suns) and high concentration HCPV (100~1000suns) [11]. LCPV systems use relatively lower cost crystalline silicon solar cells and requires only passive cooling to maintain the system's nominal performance. The LCPV systems need only single axis tracking or no tracking at all due to large acceptance angle on silicon solar cell. HCPV systems use high efficiency multijunction solar cells which contain several p-n junctions, with each junction tuned to different wavelength of sunlight. Due to the high solar concentration, HCPV system may require active cooling and high precision dual-axis tracking to make sure it can convert maximum of incident sunlight.

1.5 Concentrated Solar Thermal Power Generation

CSTP system also includes a solar concentrator and a complex sun-tracking system, but uses instead the boiler-steam-turbine-generator setup which utilizes to collect heat energy to drive a heat engine to generate power indirectly. The CSTP and CSPV sometimes are grouped as one general Concentrated Solar Power (CSP).The traditional flat solar panel production cost is dropping and solar cell efficiency has risen to new level. CSP systems are gaining market share particularly for utility scale generation.

CSTP generally has three different approaches based on the varied solar collector design with varied different system performance and cost. The three approaches are the trough system, solar power tower (or heliostat array) system and dish- heat engine system.

Trough systems:

It uses U-shaped or parabolic reflectors that have pipes running along the top center where the focal point line of the trough shaped parabolic mirror. The reflectors face the sun throughout the whole day with a single axis tracking system, focusing concentrated sunlight onto heat collecting tubes. Heat transferring medium (water or synthetic oil) circulates in the tube so the heat collected could be used to heat up the boiler and steam turbine generation system.

Fig 1.4 A Solar Trough System

Solar Power Tower Systems:

It uses many large mirrors facing the sun with a dual-axis tracking system and reflects sunlight to a central receiver (typically a high tower) where the heat is collected. Collected heat generates electrical power by steam turbine or other heat engines subsystems. CSTP systems could also use an energy storage system to keep power available when the sun is not shining. A typical thermal storage system uses molten salts. The system requires large initial cost for special metal materials and big areas of land. Installed power generation capacity usually is large with multiple million Watts capacity for LCOE to become economical.

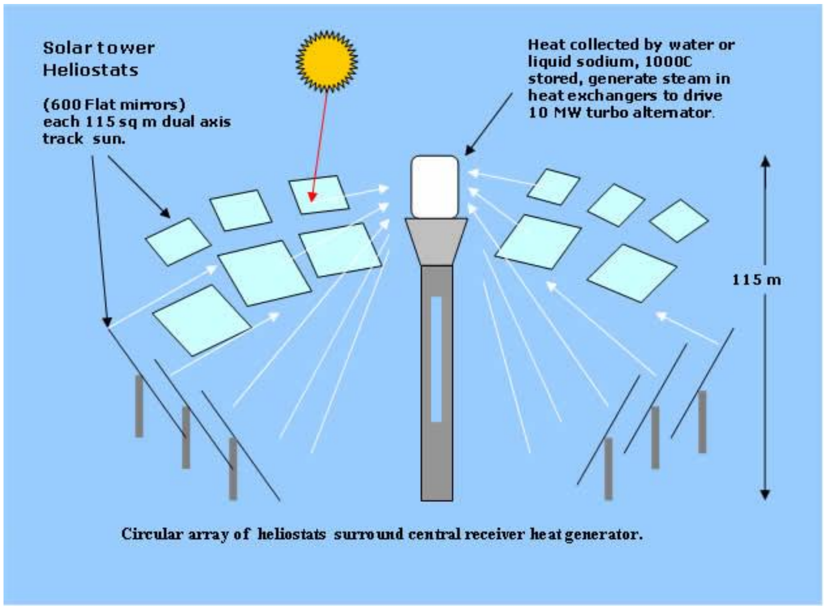

Fig 1.5 A Solar Tower system

Dish-Heat Engine Systems:

It uses dish type mirrors to focus and concentrate the sunlight onto a receiver where a heat engine is placed. The heat engine could be a Stirling engine, a Brayton cycle gas turbine, or a low temperature organic fluid Rankine cycle engine. These heat engines are commercially available on the market.

Fig 1.6 A Dish-Heat Engine System

CSTP generation systems have been deployed and commercialized for decades in the United States. It has advantages such as high system conversion efficiency and reliable power output. It gains acceptances and is appealing to commercial investors. A large CSTP project called “Solana” is being implemented in Phoenix, Arizona. This commercial project has a 280 MW capacity and uses the parabolic trough technology. Two 140 MW steam turbines, 6 hours molten salts thermal energy storage and a natural gas backup system cost a total of 2 billion dollars. It is the largest solar power plant in the world. There are other big CSTP projects across the world, which usually need a large land area similar to the Solana project (1900 acres). The huge initial cost requires innovative financing and government loans.

1.6 Implemented CSPV and CSTP Systems

Both CSPV and CSTP systems are gaining more market share in the utility power generation market. CSPV and CSTP are estimated as the top two solar power technologies in terms of the system efficiency and installation capacity. While lower LCOE of CSTP from relatively mature technology, CSTP has gained more market acceptance as a proven technology with less financial risks. With rapid drop of silicon cell cost, flat panel generation has regained market share recently.

The focus of this thesis is to study the core technologies of the CSPV and CSTP technologies in terms of the optical concentrator design and sun tracking system, heat engine power generation system as well as heat reuse. I focus on designing residential scale CSPV and CSTP generation test units for distributed power generation purpose. A small power output foldable and portable CSPV system was designed, implemented and tested.

I also consider a dish heat engine type CSTP system aimed for residential household use. Electrical power generated by the CSTP system only counts part of the solar energy collected from the sunlight. Extra heat energy will directly be used for heating water and solar air conditioning which will help reduce the domestic electricity consumption on hot water and air conditioning. Most of the extra heat of the thermal power generation can be used. Water usage for a solar thermal power generation system is an important economic factor when most of the installations locations are in sunny, dry climate or desert areas.

1.7 Thesis Layout

This research is based on prior R&D development done at real practical environments. Test data were collected from company field and lab tests. A systematic modeling, analysis, testing, and evaluation of the company's proprietary CSPV and CSTP generation systems were performed to further improve the technology to meet market requirements.

The studies discussed covered the following key aspects:

1. Introduce the special solar concentrator optics design for energy collection part in the CSPV system. (Chapter 2)

2. Implement prototype of a foldable and moveable CSPV system-the Solar Umbrella with concentrator optics, mechanical design and solar tracking control system. (Chapter 3)

3. Implement and test of a residential CSTP system based on a new disk type micro turbine. (Chapter 4)

4. Conclusion and further research topics (Chapter 5)

CHAPTER 2

COCENTRATED SOLAR PHOTOVOLTAICS SYSTEM

2.1 CSPV System Components

CSPV system has the special system design to fulfill the functionality of concentrating sunlight and increasing the overall system conversion efficiency. Here are the CSPV fundamental components which work together for the design objectives:

1) Optical solar concentrator

It includes external reflective concentrator (mirrors) or internal refraction optics (Fresnel lens) or small embedded concentrator optics (micro concentrator) to concentrate sunlight on solar cells surface.

2) Solar cell module

Solar cell module is the key in energy conversion of concentrated sunlight to electricity. In addition, it requires supporting and mounting structures, as well as heat sink to dissipate heat to keep cell temperature down. Sometimes the optical concentrator and solar cells module are combined together as one single module to reduce size, lower cost, and facilitate transport and installation.

3) Solar tracking system

The tracking system can point the optical solar concentrator towards the sun and increase normal incident sunlight intensity. The tracking system could be a single axis or dual axis tracking, increasing the conversion efficiency by 30 percent or more compared with tilted non-tracking flat PV panels. The higher tracking accuracy the solar tracking is, the higher the cost will be.

4) Balance of the system

It includes all the supporting and mounting structures, wiring and any miscellaneous parts, power conditioning equipments (voltage regulator, transformer, and inverter) and power storage devices (batteries). The cost of system not includes transport, installation and maintenance over the CSPV lifetime.

In CSPV system, solar cells are connected in series and parallel circuits to produce higher voltages, currents, and power. CSPV modules consist of solar cells circuits in a protective laminate structure. The solar cells module I-V characteristic curve (Fig 2.1) is important when evaluating the CSPV system. There are 3 key parameters in the I-V curve, short circuit current I_{sc}, open circuit voltage V_{oc} and maximum power point M_{PP}. The I-V curve determines the solar cell conversion efficiency, concentration ratio, temperature and internal serial resistance. Higher temperature results in lower open circuit voltage, higher short circuit current, and overall the maximum power point will shift to a lower power output point. If there are shadings on the solar cells module, the power output will be reduced. A bypass diode is added to cut current flow by a blocked solar panel to avoid the hot spot phenomenon caused by shading.

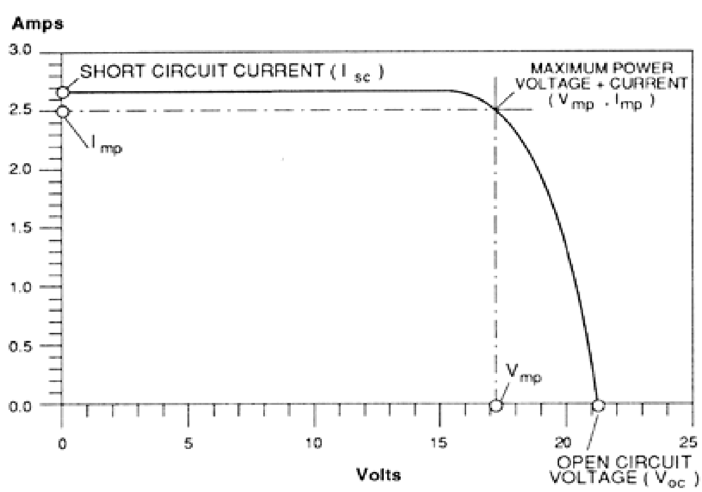

Fig 2.1 Solar Cells Module I-V Characteristics

For solar cells in CSPV systems, conversion efficiency increases with concentrating sunlight ratio. However, this does not mean that electricity production will linearly increase with the light density. Most multijunction solar cells perform best under a certain range of concentration ratio (around 800 suns). The single junction silicon solar cell has shown the same trend performance under varied concentration ratios, while it reaches the highest conversion efficiency at 100 suns concentration. This is because under increased light density, the series resistance will increase and other loss due to the high intensity flux of the new current will become dominant.

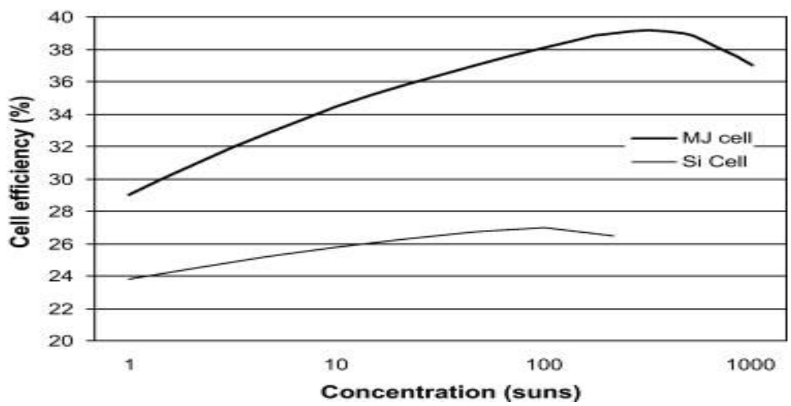

Fig 2.2 Solar Cells Efficiency versus Concentration Ratio

2.2 CSPV Optics Design

The CSPV system could not function with just the high efficiency triple junction solar cells, and it needs also the concentrator optics to collect, concentrate and distribute concentrated sunlight evenly onto the high efficiency solar cells. It is crucial for the CSPV system to have a working concentrator design [12].

First, a conceptual representation of the concentrating process is shown in Fig 2.3, which illustrates the basic principle of concentrating sunlight similar to the magnifying glasses concentrating sunlight to burn holes in the dry leaves. The sunlight is first collected by the concentrator, and then the concentrated sunlight enters onto the receiver where PV material is located.

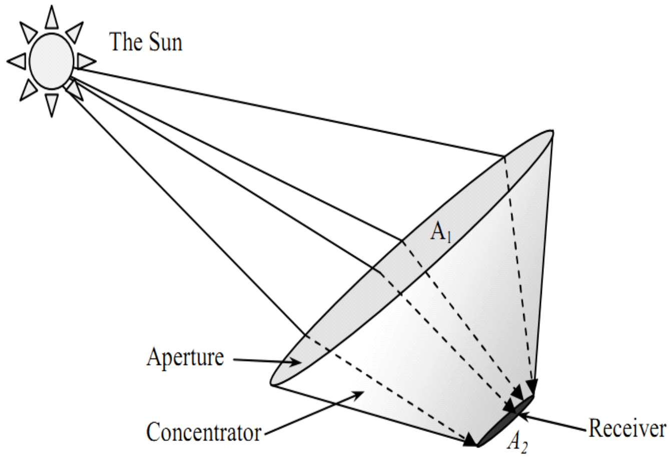

Fig 2.3 Principle of Concentrating Sunlight

The geometrical concentration ratio, Cg of a concentrating system is given by Cg= A_1/A_2, where A_1 is the aperture area of the concentrator and A_2 is the area onto which the radiation is concentrated. There are many types of CSPV systems based on the design differences in concentration optics. If sunlight density is 1 sun at the entrance aperture, then after the concentration, there is a Cg suns ratio at the receiver surface. A few common concentrator designs will be discussed next.

The first type concentrator uses refractive optics such as Fresnel lens or magnifying glasses to concentrate sunlight to a very small area at a concentration ratio of more than hundred; Fresnel lens could have very short optical profile. This could make the structure of concentrator very compact in volume size and weight. This kind of design is very common in the CSPV panel which makes an array out of small Fresnel concentration PV modules. Each small module may have one or several triple junction solar cells. The big panel could produce a large amount of power with higher voltages as the solar cells are connected in series. A higher current is the result of high light intensity or panels connected in parallel.

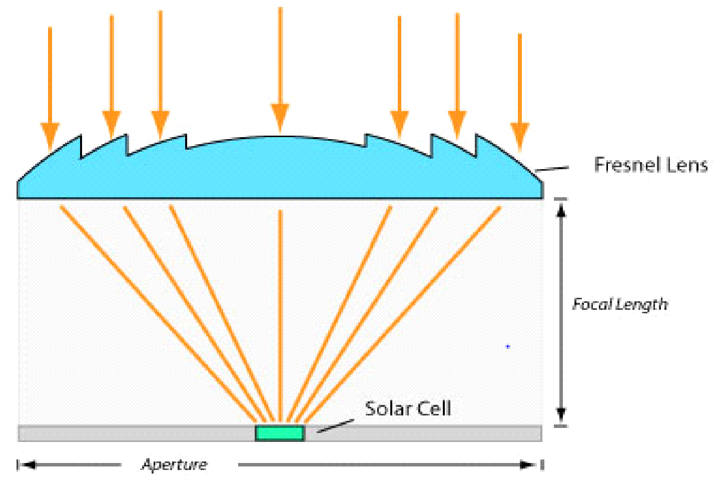

Fig 2.4 Refractive Concentrator

In a system with one Fresnel lens (shown in Fig 2.4), the solar cell might be damaged if unevenly distributed light is concentrated in a small part of the cell which can get super hot. Furthermore, a slight change of the light collection position due to the movement of the Sun will adversely affect the light-gathering efficiency. This kind of refracting system generally uses acrylic Fresnel lenses which may not be optimal. The reason is because acrylic has a short lifespan under sunlight exposure. Lens also introduces chromatic non-uniformity on the solar cell surface. Fresnel lens also can create a round aspect irradiance distribution with a high degree of intensity difference between the central peak value and the nearby annular region. Triple junction solar cells are not able to convert sunlight efficiently when there is a high degree of non-uniform illumination.

One successful commercial product based on Fresnel lens concentrating photovoltaic is made by the company named Concentrix (shown in Fig 2.5). It uses a thin square shaped Fresnel lens to concentrate the sunlight. It has a highly precise solar tracking system working with the concentrator to distribute the light precisely evenly onto the triple junction solar cell.

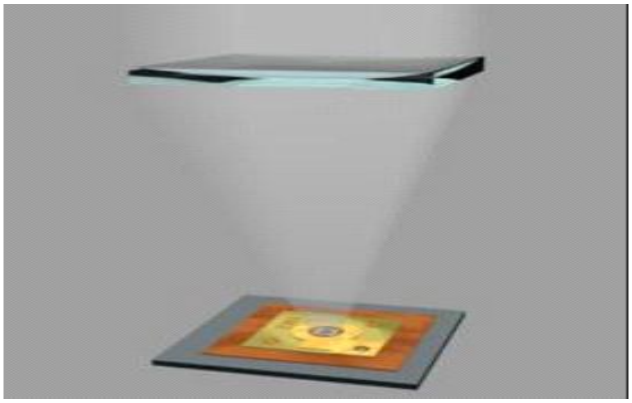

Fig 2.5 Concept of a CSPV Concentrator Module

Another company using Fresnel lens design is Amonix. One issue of this type system is that using lens will cause energy loss after light passed, and it depends on the chosen material's optical characteristics to control the side effect .For example, after the PMMA (polymethyl methacrylate) Fresnel lens has been used for ten years, its optical efficiency will drop from 85% to 81%. One solution is to enhance the Fresnel optical efficiency by better UV durability and lifetime with a less annual degradation.

The second concentrator type is a two-stage concentrator design using Fresnel lens and rod lens. As shown in Fig 2.6, the sunlight was concentrated by Fresnel lens and rod lens. This transmission type of concentrators is more complex than the first type, while it has added benefits with a slight cost increase.

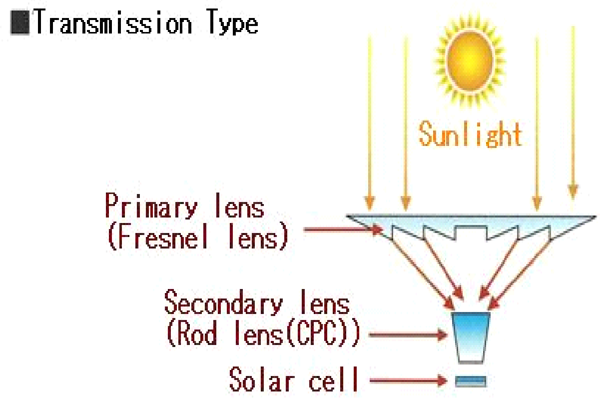

Fig 2.6 Concept of a Concentrator

Compared with the first type, an extra rod lens is added to even out the concentrated light shining on the entire area of the solar cell, thus enabling the whole surface of the cell to be used efficiently. It also provides a wider acceptance angle for the concentrating lights passing from the first stage, requiring a less precise solar tracking system. The Compound Parabolic Concentrator (CPC) optics is used in the rod lens design. As shown in Fig 2.7, there are two parabolic mirrors CA and DB. Both parabolas are cut at B and A respectively, where A is the focal point of parabola CA and B the focal point of the parabola BD. The area CD is the entrance aperture and the flat absorber is AB. This CPC has a better acceptance angle of 2ϴ. The trajectories of the sunlight shining into the CPC are shown in Fig 2.8. It clearly shows a better acceptance angle by using the CPC rod design. For a 3-dimensional “Nonimaging compound parabolic concentrator” the maximum concentration possible is $C = 1/\sin^2\Theta$, where ϴ is the half angle of acceptance of the larger aperture.

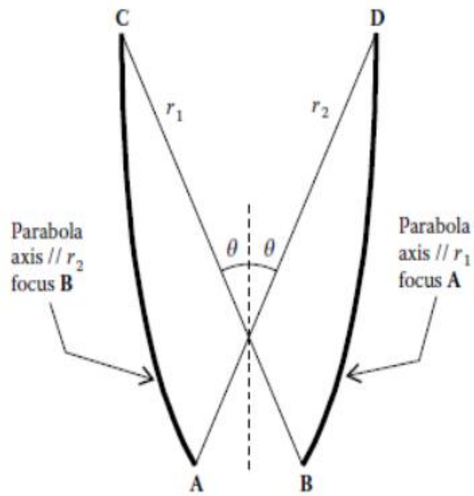

Fig 2.7 Geometry of a CPC

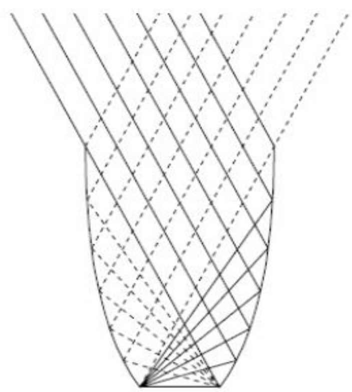

Fig 2.8 Trajectories of the Edge Rays inside a CPC

The third concentrator optics design uses reflective mirrors to concentrate the lights in a multistage way. The first sample of this type reflective mirrors design, shown in Fig 2.9, uses two-stage parabolic mirrors to concentrate sunlight and guide light perpendicular to the solar cells. This design is a simple combination of parabolic reflective mirrors. The other improvement of this design is choosing a different location of the second mirror. The parabolic mirror could be placed before or after the focal point.

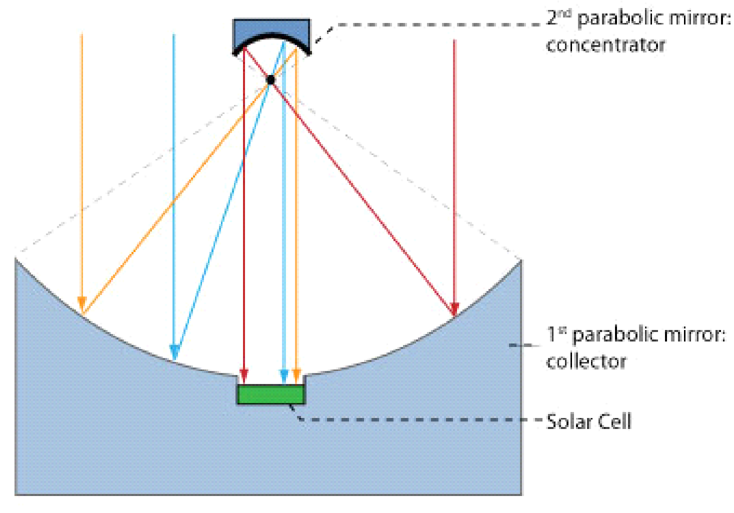

Fig 2.9 Two-Stage Concentrator Using Reflective Mirrors

Another common design named Cassegrain Optic also belongs to the reflective mirror type. As shown in Fig 2.10, the sunlight is first reflected by a primary parabolic mirror and then reflected by a second aspheric mirror down to a rod lens which is made of Compound Parabolic Concentrator with reflective surfaces. The evenly distributed sunlight reaches the solar cell at the bottom of the rod lens. This design is very similar to the Cassegrain reflector telescope shown in Fig 2.11.

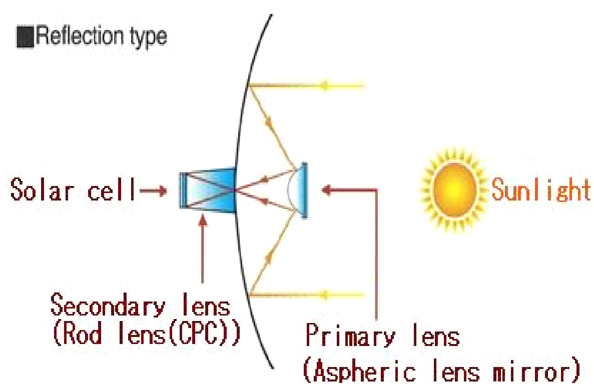

Fig 2.10 Cassegrain Optic Concentrator

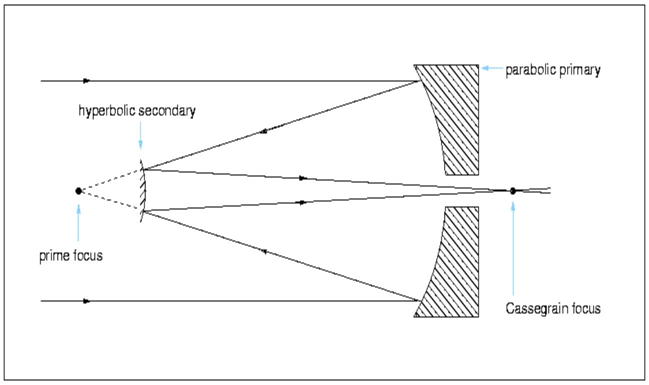

Fig 2.11 Cassegrain Telescope Principle

This Cassegrain optic design has some benefits, such as a two-stage concentration and a wide acceptance angle for the Compound Parabolic Concentrator rod lens. The distance between the two reflective mirrors centers can be very short and has a high concentration ratio as a result of the two-stage concentration; the incidence angle of concentrated light hitting the solar cells could still be so small that there is no need for a very highly precise solar tracking system. A popular CSPV product of this reflection type was made by Solfocus. As shown in Fig 2.12, Solfocus' patented concentrator design uses a parabola glass mirror with a square shape and a secondary aspheric mirror near the focus point of the parabola. The reflected light goes to optical rod, and then light focusing onto a triple junction solar cell. Their design has iterated into a few versions, which keep this patented design as one of the leading CSPV optical designs.

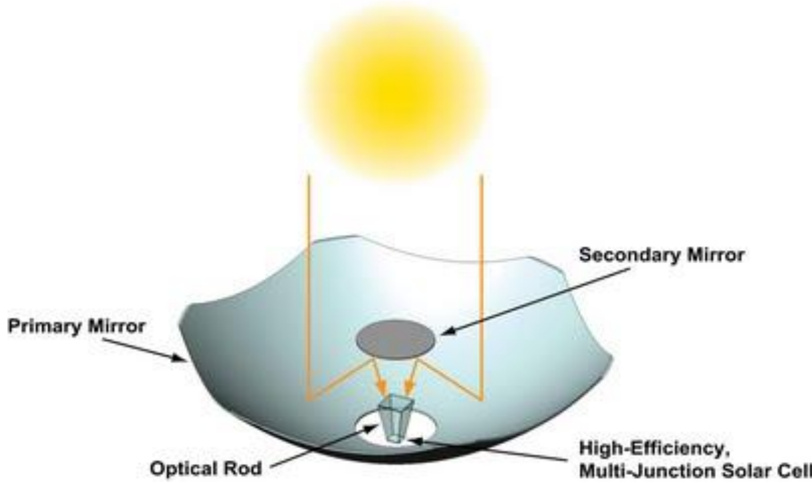

Fig 2.12 Concentrator Design of Solfocus

A Solfocus CSPV panel consists of an array of 560 mirror units, each of which focuses 650 cm^2 of sunlight onto a 1 cm^2 triple junction solar cell at high system conversion efficiency 24%. Fig 2.13 shows what the Solfocus panel product looks like.

Fig 2.13 the CSPV Panel of Solfocus

An uncommon but innovative concentrator design uses light guide optics based on both the reflective and refractive optical properties. The principle of the light-guiding concentrator is shown in Fig 2.14, which is a cut section of a planar concentrator. The parallel sunlight shines onto a planar surface, and the light is absorbed and concentrated into a small area inside the planar structure following the radial lines direction from out layer toward the planar center. The concentrated light will exit from the output aperture, and the solar cells are placed at the output exit. The highly concentrated light will strike onto the multi-junction solar cells and generate electricity. This design has a big benefit as it does not require a significant focal length between the focal point and the PV cell. A company named Morgan Solar has been issued patents on this innovative concentration design.

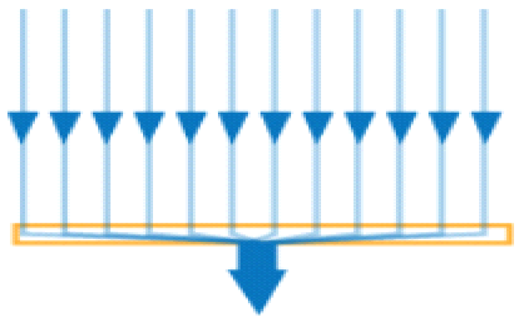

Fig 2.14 Concept of a Light-guiding Concentrator

Morgan Solar's light-guiding optical structure is designed to trap the sunlight striking onto the top of the concentrator (shown in Fig 2.15) with the help of the reflective and refractive characteristics of its optic components, and to transport the lights inside the optic concentrator to its center. The sunlight hits the reflective optical components inside the planar concentrator, and keeps bouncing toward the center of the concentrator, where it will hit the high-efficiency solar cells. Fig 2.16 shows a bundle of parallel light trajectories among the array of circular grooves of the concentrator [13]. The L-shaped reflector has reflective surfaces which reflect the light onto the next L-shaped reflector. The light will keep bouncing between the L-shaped reflectors and the bottom reflector. From the top side of the concentrator, there is an array of the circular groves which are made of the L-shaped reflectors endlessly connected together.

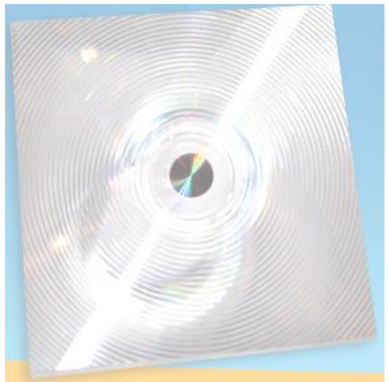

Fig 2.15 Light Guide Optical Concentrator module (from Morgan Solar)

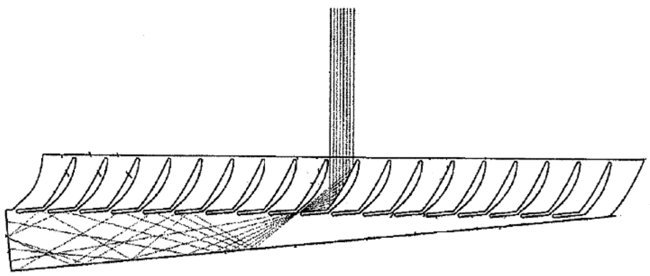

Fig 2.16 Trajectories of Lights Travelling in the Concentrator

Advantages over the other conventional reflective or refractive concentrators includes: a lower optical profile that uses less material, an equivalent or better concentration factor and angular acceptance. The material used is ultra-thin, low cost, lightweight, rugged, and long-lasting. The material selected for the optic parts is made of acrylic and glass, and is therefore less expensive in volume production. It is also designed for high heat, high wind-load, and extreme moisture conditions, leading to a low maintenance cost. It could reach 1000 sun concentration ratio without using bulky structure of the other concentrators. All this would help reduce CSPV system cost and cost per kWh.

Another design uses luminescent solar concentrators. Sunlight is refracted in a luminescent film and then being channeled towards photovoltaic material. As it does not require optical lenses or mirrors, this design works with diffused light and hence does not need solar tracking. This waveguide optics generally uses doped glass sheets or coated with emissive materials. The radiated light is trapped in the waveguide substrate by total internal reflection. The concentration factor usually is low with relatively cheap cost and could increase the PV cell efficiency. There are a few companies developing different film technologies. Covalent uses an organic film, while Prism Solar uses a holographic film (shown in Fig 2.17). Another advantage of this type of design is that it does not need cooling. Most of the luminescent solar concentrators require no tracking just redirecting solar radiation into simple waveguides.

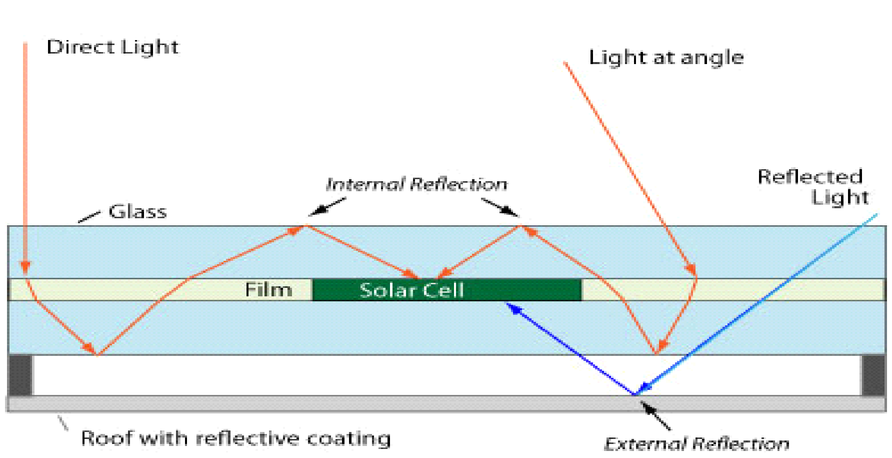

Fig 2.17 Principle of Holographic Film Concentrator

Another type of concentrator designs to achieve high solar flux include the Micro-Optic Slab concentrator, (shown in Fig 2.18)which acts as a hybrid of imaging/nonimaging optical system by combining an imaging lens array with a multimode slab wave-guide. It has three main components: the first is a two-dimensional lens array to collect the incident radiation; the second is a high refractive index slab waveguide placed beneath the array. The top surface of the waveguide is separated from the lenses by a thin, low-index cladding layer. The third component is a mechanism that couples light into the waveguide. This concentrator integrates multiple, focusing apertures with a common, multimode waveguide to direct solar energy to a single solar cell. This system requires new fabrication and molding technologies, as well as a tracking system to achieve the best output power [14].

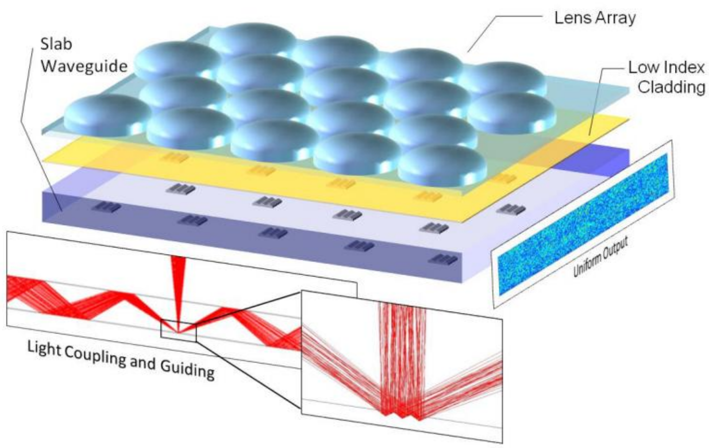

Fig 2.18 Schematic of Micro-Optic Slab Concentrator

A lot of CSPV systems rely on bulky optics such as parabolic dishes or imaging lenses. These elements can produce smaller image of the sun and yield high levels of concentration, but produce non-uniform flux distributions and require very accurate alignment. CSPV has a lot of economic advantages inherited from its PV characteristics and it also offers benefits that normal PV cannot match in economics.

2.3 Economic Analysis of CSPV

Cost of electricity from different energy sources differs dramatically when it includes operation and maintenance cost. The definition of cost has often been dollars per Watt peak ($/Wp). This definition has significant limitations, especially when we try to evaluate investment return without taking into account inflation over the project life time. The more accurate assessment method is Levelized Cost of Electricity adopted by National Renewable Energy Laboratory and Department of Energy. The normal definition of LCOE is given as:

$$\text{LCOE} = TLCC / \left\{ \sum_{n=1}^{N} [Q_n * (1 + sd)^n / (1 + d)^n] \right\}$$

Where TLCC = total life-cycle cost; Q_n = energy output in year *n*; N= analysis period; *sd* =system degradation rate; *d*= annual discount rate.

The LCOE takes into account the electricity generated by the CSPV system over its entire lifetime, not just the peak power produced. The price of coal is increasing while the price of CSPV is decreasing with increased conversion efficiency and a longer lifetime. Therefore the LCOE for the CSPV electricity is decreasing [15].

The CSPV systems usually use little or no water, which is better than the traditional power plant in dry areas. CSPV needs low maintenance and no fuel consumption at all. CSPV uses less semiconductor materials to reduce the system cost and weight. CSPV system is more modularized and easy to scale up and upgradable. CSPV uses less land than PV to generate the same amount of electricity thanks to CSPV increased system efficiency. When considering land permit cost is added into the whole project bill, CSPV is advantageous compared with the flat panel PV. CSPV is still a relatively under-developed technology. There are still significant opportunities for improvements in energy conversion efficiency and system cost reduction that will strengthen CSPV market competitiveness.

Si-based LCPV systems providers like Solaria, Sun Power, Skyline, and others could show great growth in the near future. In the meantime, dozens of companies are working on developing products to participate in the supply chain. For multijunction solar cell used in the HCPV systems, there are a lot of new developments in solar cell research. More companies have shown the potential to make more than 40% efficient solar cells, which will boost supply and drop price for high efficiency solar cell.

New trend of the industry toward standardization could further reduce the cost. Companies servicing the CSPV supply chain are beginning to offer off-the-shelf optics and testing equipment. This standardization could help speed up new product development and reduce the cost. For a successful commercialization of the CSPV technology, it is essential that the design and production work under standards and norms. These will also help increase end-user confidence in the CSPV products.

Efficiency of most triple junction solar maximize at around 450 suns. A trade space exists between the efficiency, absorber area, concentration, operating temperatures, and ultimately cost. There will be new designs for higher temperature tolerance and higher concentration operation. Further advances are additional junctions, better antireflection coatings, and better transparent conducting oxides. It is expected that HCPV cell, module and system efficiency will keep rising toward 50% and very soon (Fig 2.19).

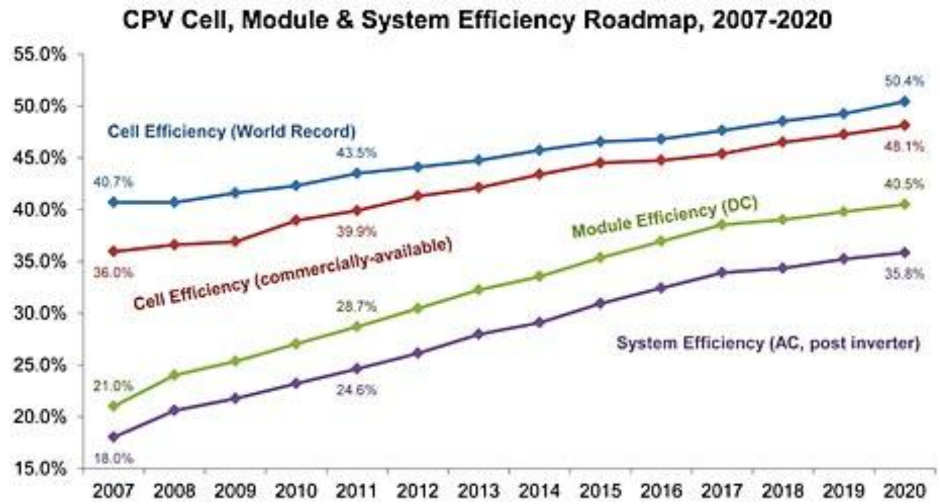

Fig 2.19 CSPV Cell, Module & System Efficiency Roadmap [17]

Unlike silicon industries, different HCPV technology uses different materials and proprietary design and manufacturing technologies, which make HCPV less susceptible to the material prices than the LCPV based on silicon solar cells. LCPV based silicon solar cells have the potential to compete with HCPV technology. However, some silicon based LCPV systems companies are switching to III-V mutlijunction-based HCPV systems resulting in fewer LCPV producers (SunPower, NaREC, BP Solar, Q-cells). An example is Amonix which currently has stopped producing the silicon solar cells module based LCPV [16].

CSPV solar cell cost only account for a small part of the module cost, while the other materials such as aluminum, steel, plastic and optical components are very important. The balance of the system cost normally is more than solar module cost. The CSPV industry is in its infancy in terms of efficiency, automation production and manufacturing volume. A lot of gains can be made in different categories such as the solar cell, balance of system, and initial investment. CSPV systems will start to challenge the flat panel PV market position as soon as CSPV becomes price competitive.

In summary, this chapter went through one important part of a CSPV system namely the solar concentrator optics. Different optics designs were discussed and evaluated. The economic analysis on the new CSPV developing trend also revealed the booming of solar power generation with lower cost and high efficiency new CSPV systems.

CHAPTER 3

A CSPV SYSTEM CALLED THE SOLAR UMBRELLA

3.1 Concentrated Photovoltaics Generation unit

There is a demand for residential, off-grid solar power production system in high direct normal irradiance areas, especially for the underdeveloped areas where the cost for building utility scale electricity grid is so high that a better solution is to generate power locally. The new power system can offer new alternative power solutions for people who travel with Recreational Vehicles (RV), go hiking and camping, drive electrical vehicles with need to charge car batteries. One solution to these needs is an innovative CSPV design called the Solar Umbrella. It uses a light weight foldable and portable reflective parabolic mirror for concentrating solar power onto a receiver module of high efficiency solar cells. The Solar Umbrella could offer direct current (DC) or alternating current (AC) to power electrical appliances. In addition, hot water can be produced via heat exchange for reducing the temperature of the triple junction solar cells during electricity generation.

The Solar Umbrella consists of two or three stages of concentrators, with dual axes sun tracking system, power storage system, photovoltaic inverter and battery charger. The concentrator first stage is a parabolic dish formed by multiple blades made of polycarbonate. The second or third stage concentrators comprise the receiver which adjusts the concentrated lights reflected from the first stage mirror to shine on the triple junction solar cells. The solar tracking system ensures that the parabolic mirror faces the sun for maximum exposure, and the power storage system includes batteries which store unused power during daytime and output power after sunset.

3.2 Solar Umbrella Concentrator Designs

The Solar Umbrella's function is to collect sunlight for generating electricity. A high concentration ratio as much as 1000 times will help the triple junction solar cells work better and output more power. The solar umbrella has 2 different versions, one with 1 meter diameter, and the other 4 meters diameter. The expected power output of 1 meter is 150 Watts using 6 triple junction solar cells, while the 4 meter version is expected to get peak power 3000 Watts using 120 triple junction solar cells. The solar cell type is CTJ receiver assembly from Emcore. The cell has 37% conversion efficiency at 25 degree Celsius ambient temperature under the standard AM1.5 spectrum.

The basic idea of concentrating in the Solar Umbrella (SU) is using a parabolic dish to concentrate sunlight at the first stage, and then use the designed receiver to do the second stage or even third stage concentration. Fig 3.1 shows the schematics of an unfolded and folded solar umbrella. The open umbrella's parabolic mirror could reflect and concentrate sunlight to the focal point of the mirror surface. The folded umbrella could fit into a cylindrical container for easy transportation.

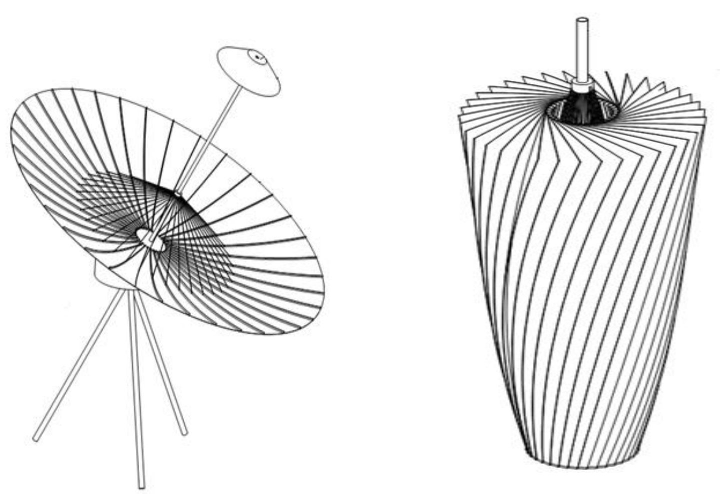

Fig. 3.1 the Concept of Unfolded and Folded SU

The first stage concentrator is the parabolic reflective dish formed by a number of same sized rigid sections of partial parabolic surface with the same focal point up over the centre of the dish. On the principle of optics and geometry, the parabolic mirror dish surface profile satisfies the equation $x^2+y^2=4pz$ in the Cartesian Coordinates (x, y, z) (shown in Fig 3.2). The sunlight comes parallel with the z-axis, and shines onto the surface, then reflects onto a single focal point at (0, 0, p). Since the sun is not exactly a point source, the image of the sun, which is made of the concentrated sunlight at the focal point, is not a single point. The concentration ratio of sunlight on the Earth has a limitation due to both the distance between the Sun and the Earth and their dimensions, and it should be less than 40,000 times.

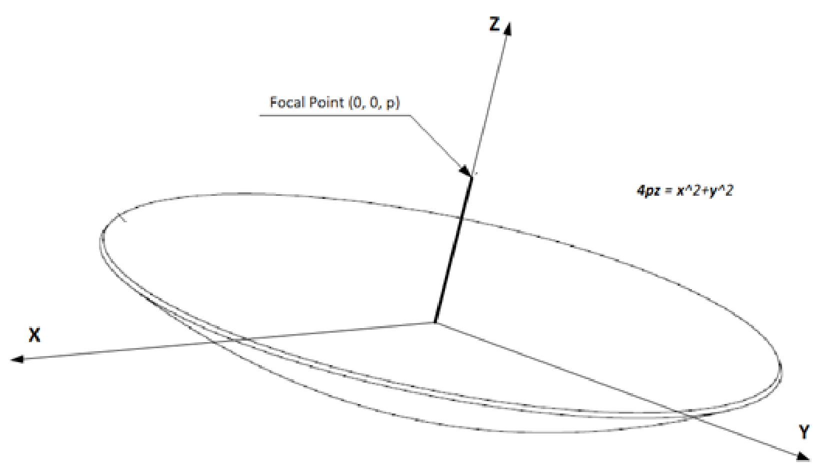

Fig 3.2 Parabola Dish Geometry

The second stage concentration could be fulfilled by the conic shape reflector (shown in Fig 3.3) which stays before the focused light come to the focal point, and finally the concentrated sunlight will hit the solar cells after being adjusted by the second stage concentrator.

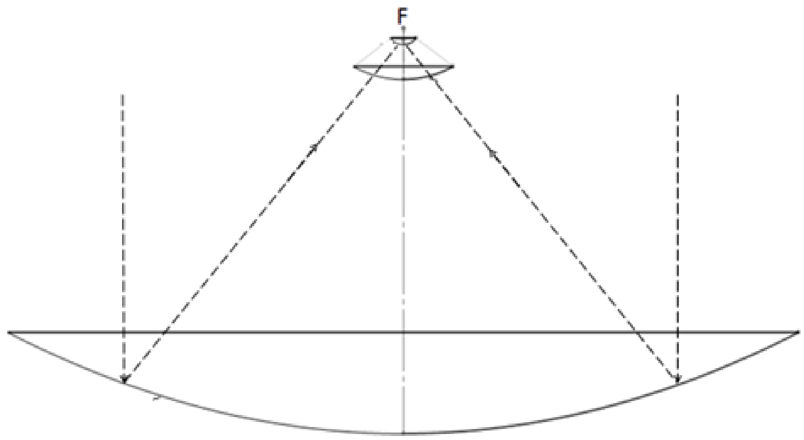

Fig 3.3 Two-Stage Concentrator Concept

The 4-meter dish has a flat reflective receive area of A=πr^2=12.57 square meters as shown in Fig 3.4. The second stage conic receiver has a flat receiving area A_1= πr_1^2=0.20 square meters with a 0.5 meter diameter. The solar cells are arrayed at a flat circular area of $A_2 = \pi r_2^2$=0.012 square meters with 0.125 meter diameter.

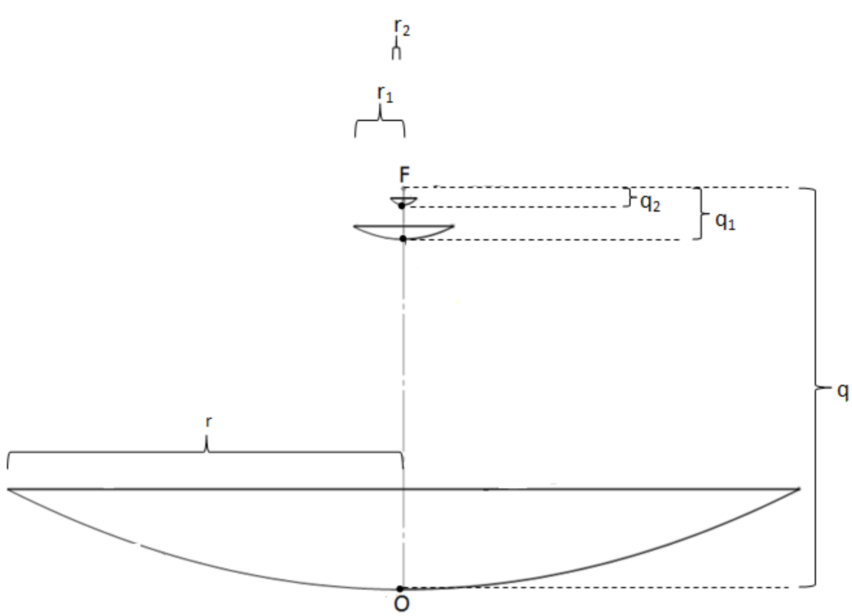

Fig 3.4 Concept Diagram of the Concentrator

It is assumed that all sunlight reflected by the first stage parabolic concentrator A is collected by the second stage concentrator A_1, with all collected light further concentrated onto the solar cells of area A_2. The first stage concentration ratio is $A/A_1=64$, and the second stage concentration ratio is $A_1/A_2=16$, resulting in a combined concentration ratio of 1024=64*16.The conical second stage concentrator makes a shadow onto the first stage concentrator, thereby reducing the amount of light received by each corresponding area A, A_1, A_2. All active reflective areas are reduced proportionally by the holes at the center, resulting in the unchanged concentration ratios.

Consider the three parabolas shown in the above picture with the same focal point F, the radii of parabolas are denoted as r, r_1 and r_2. The vertical displacements: q, q_1, q_2 are measured from the focal point of the big parabola to the center of the three parabolic surfaces O, O_1, O_2. The flat light receive areas of parabolic surfaces are given by A, A_1, A_2. These three parabolas are called co-focal, meaning that the theoretical concentration ratio of the Solar Umbrella would be around 1000 suns assuming negligible optical reflection loss.

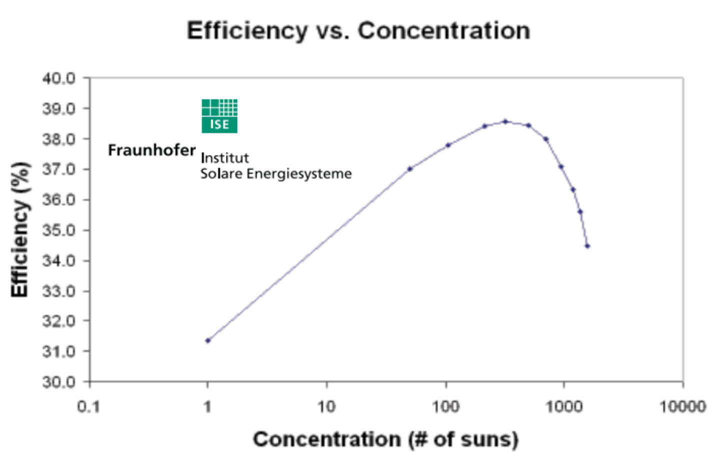

Fig 3.5 Efficiency verse concentration for multi-junction cells

The high concentration ratio will help the triple junction solar cells achieving better conversion efficiency. This has been demonstrated by the Fraunhofer Institute of solare energiesysteme's triple junction solar cells as shown in Fig 3.5 for efficiency versus concentration diagram.

Fig 3.6 it shows that light can be further concentrated by the second surface onto a third surface where the solar cells array is placed. The incident light should be as perpendicular to the solar cells as possible. The third surface can be a spherical surface centered at point F instead of the co-focal parabolic surface. Each cell has its own cone concentrator which captures light from a specific part of the second surface area and adjusts the light onto the solar cell. The cones can be designed in various geometries, including pyramidal section, sectional cone and hyperbolic trumpet cone concentrator (shown in Figure 3.7). The edge of the outside cones could use additional compound parabolic conic shape to capture some stray lights.

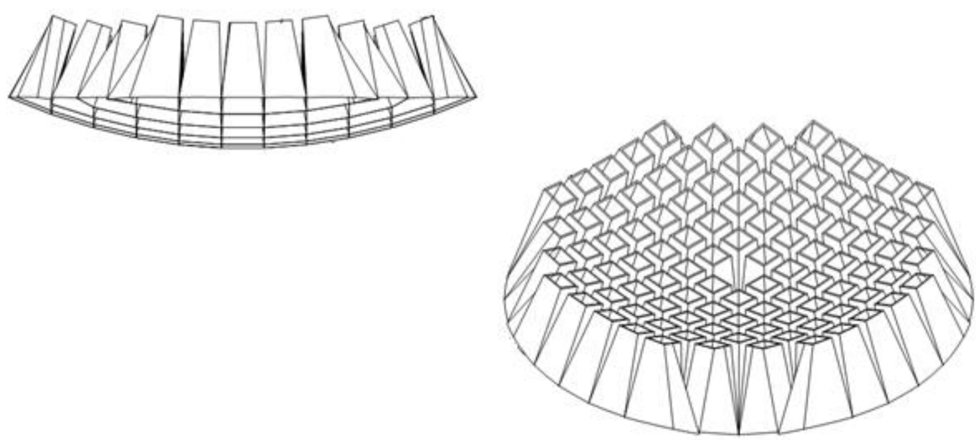

Fig 3.6 Schematics of Concentrator Cones Design (Front and Isometric views)

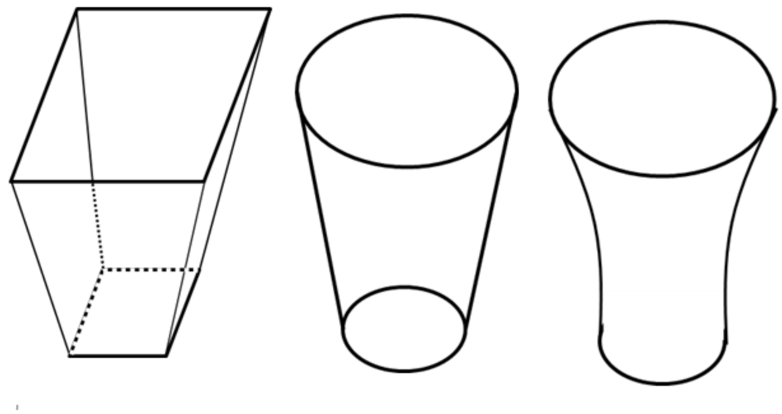

Fig 3.7 Geometries for the Cones

The first reflective parabolic mirror with area A, second stage parabolic mirror with area A_1 and a bottom flat mirror for a Newtonian reflective telescope can help us understand multi-stage light concentration (shown in Fig 3.8). The two parabolas are co-focal on the focal point F. The lights converge when being reflected upward toward the focal point. Light diverges when reflected downward. The combined convergent and divergent mirrors setup helps the telescope structure obtain a magnified light intensity ratio of A/A_1.

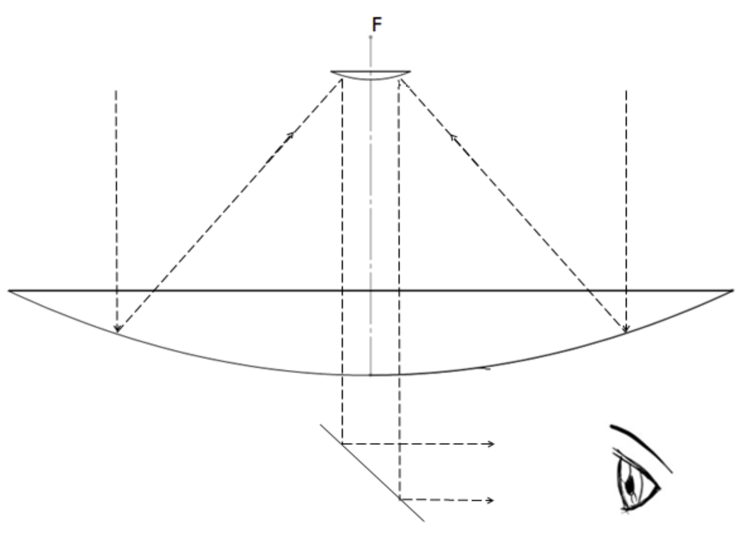

Fig 3.8 Schematic of Newtonian Telescope

The three stage solar concentrator design is the adaption of the Newtonian telescope concept, with a bottom parabolic mirror reflecting sunlight upward, a top parabolic mirror reflecting the focus light downward and a conic concentrator in the center of the first parabola surface. The almost straight concentrated light will go to the array of solar cells at the bottom of the third stage conic concentrator (showed in Fig 3.9).

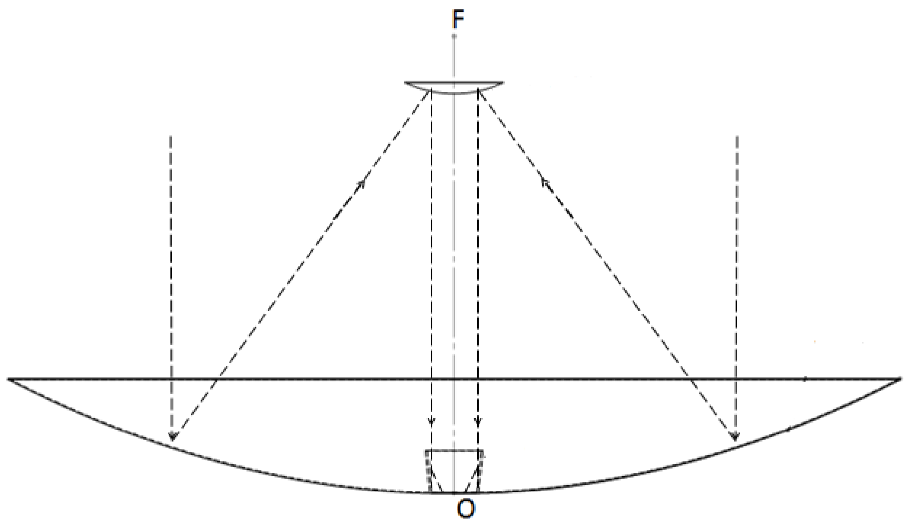

Fig 3.9 Geometry of Three Stages of Solar Concentration

The mathematics of combined focal length of compound lens or mirror telescope is well known. I derived here the optics in this special context of solar PV electricity generation.

A Cartesian coordinate system is used for the derivation (Fig 3.10). The parabola surface center point O is defined as origin (0, 0, 0), the focal point F is at (0, 0, f_1). The focal length of the top mirror is f_2. The top mirror center is placed at (0, 0, f_1–f_2), so that light reflected off the top mirror would travel parallel and straight down. If the top co-focal mirror is moved up by a distance of ε, the focal point of the compound mirrors now shift up from -∞ towards point O. Suppose that new focal point with this shift is at (0, 0, *f*), and the vertical distance between the two parabola surfaces is d. An equation $f = 2d - \frac{f_1 f_2}{\varepsilon}$ is obtained, where $d = f_1 - f_2 + \varepsilon$ .This equation for *f* can be proved for special cases .

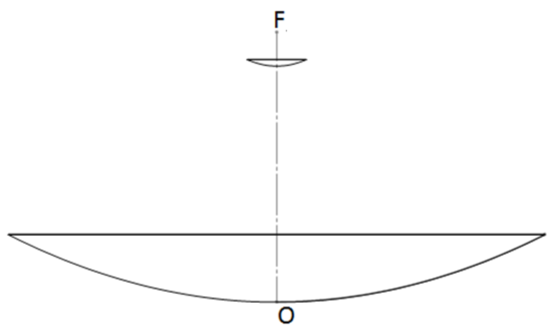

Fig 3.10 Two Co-Focal Parabolas

If $\varepsilon = 0$ as in the case of Newtonian telescope, then it could get that $f = -\infty$. If $d = f_1$, then $\varepsilon = f_2$ and $f = 2d - \frac{f_1 f_2}{\varepsilon} = 2f_1 - \frac{f_1 f_2}{f_2} = f_1$, which indicates that the combined focal length is at the center of the second parabola, now placed at the focal point of the first parabola. Then indicates that as shifting the second mirror up, the focal point *f* has moved from $-\infty$ upward. To obtain a desirable *f* the shift ε needed can be achieved by solving the pair of simultaneous equations $f = 2d - \frac{f_1 f_2}{\varepsilon}$ and $d = f_1 - f_2 + \varepsilon$. In practice for $\varepsilon = 0$, I can place at *O* to concentrate light by means of reflection onto a single chip at (0, 0, 0). Similar arrangement can be made for multiple cells.

The solar umbrella could be folded and unfolded to make it more suitable for portable solar power generation. The design of the folding mechanism for the umbrella is a challenging problem. Many attempts were tried and some were prototyped, and the single axis folding method of blades of umbrella is a choice for its simplicity. The blades are packed in a way that the length of the blades is aligned with the center support and the width of the blades is aligned in a radial direction. The blades rest on different angles of inclination towards the center, and fold toward the center which is similar to the folding of petals of the flower rose.

Figures 3.11 and 3.12 show that the design of the 1 meter prototype solar umbrella of 18 folded blades is arranged into 4 layers. Each blade has the same cuff mechanism holding onto the center platform to allow the blades to move towards the center. The solar receiver is close to the focal point of the opened parabolic mirror made of 18 rigid blades. This four layer folding geometry (shown in Fig 3.13) is the best symmetry discovered yet for the purpose of compact folding. The choice of 18 blades is given by 18=6+6+6, with three concentric layers each with 6 folded blades. The innermost layer of 6 blades could be more compactly folded if it is divided into two layers of 3 blades and then the 3-layer design is evolved into a more compact 4-layer design.

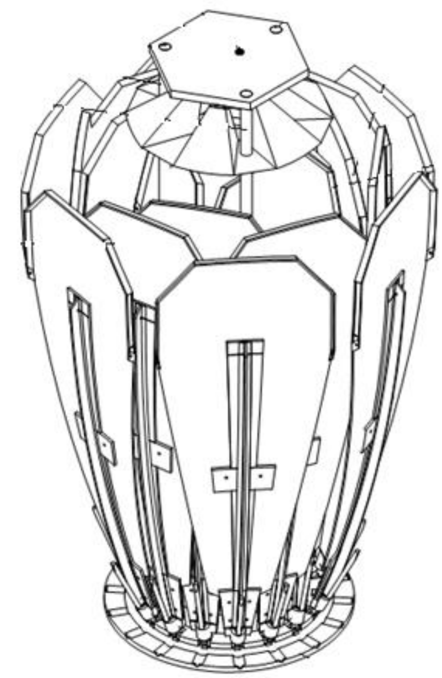

Fig 3.11 the Folded 1 Meter SU Prototype

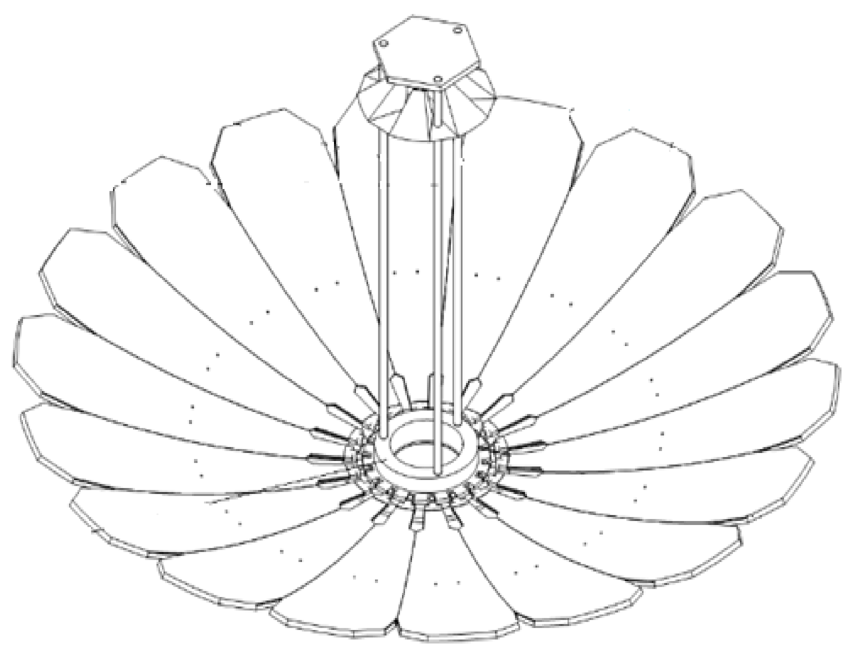

Fig 3.12 Unfolded 1 Meter SU Prototype

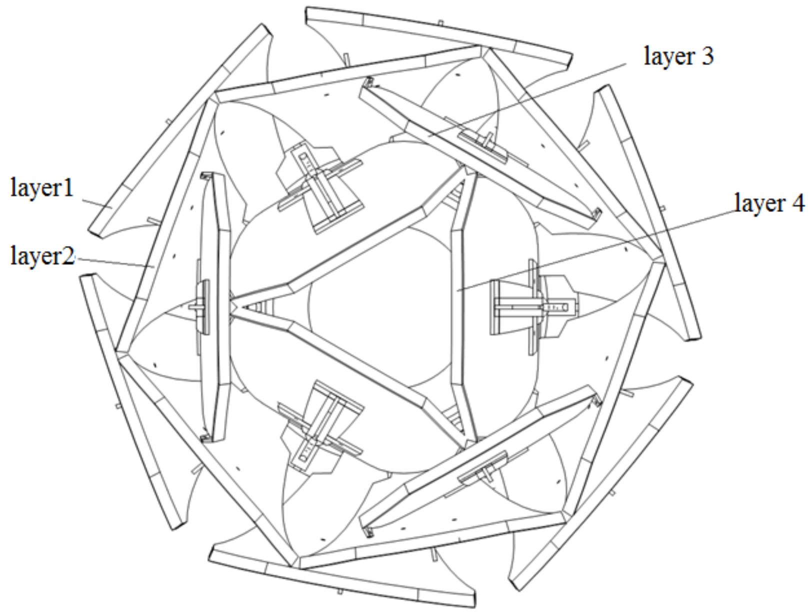

Fig 3.13 Folding Layers Geometry

3.3 CSPV Tracking Systems

As PV cells generate current, solar cells could be modeled as DC current sources. The amount of current a PV panel produces is directly correlated with the intensity of light the PV cell absorbed. For example, the normal to the PV cell is perpendicular to the cell's exposed face (shown in Figure 3.14). When the sunlight is assumed at a constant intensity, the available sunlight to the solar cell for power generation can be calculated: $W = A\lambda \sin(\theta)$, where A represents the limiting conversion factor in the design of the PV cells.

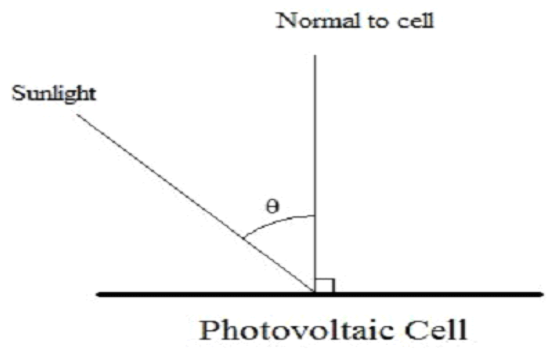

Fig 3.14 Principle of Intensity of Light on PV Cell

Figure 3.15 shows that off axis angle of acceptance affect a maximum power of a triple junction solar cell.

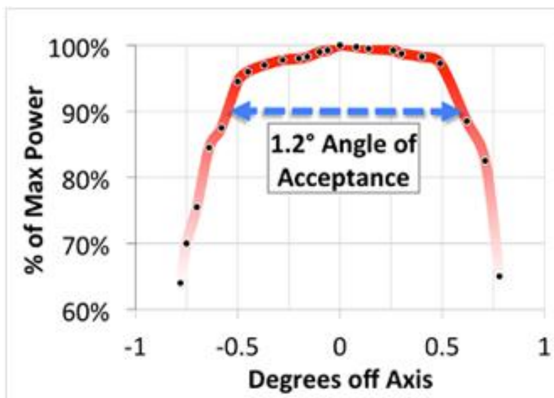

Fig 3.15 Output Max Power versus Angle Degrees off Axis

The solar tracker could be divided into two categories - one is active tracker and the other is passive tracker. Active tracker is directed toward the sun by electrical circuitry in the form of light-sensing photo sensors. Motors and gear trains are then used to direct the tracker as commanded by the photo sensors to the sun's direction. Passive tracker uses mechanisms or materials that respond to heat of the sun, if there is heat imbalance, the mechanism or material will correct the imbalance by facing the panel towards the sun.

For a given concentration ratio, different concentrator optics design will provide different acceptance angles for the PV solar cells. In a typical high concentration system, the tracking accuracy must be in the ± 0.1° range to deliver approximately 90% of the rated power output. In a low concentration system, the tracking accuracy must be in the ± 2.0° range to deliver 90% of the rated power output. As a result, high accuracy tracking systems are typically used in the big PV panel which has a high power output.

3.4 Solar Tracking Systems Review

Single axis trackers

Single axis trackers have one degree of freedom that acts as an axis of rotation. The axis of rotation of single axis trackers is typically aligned along a true North meridian [18]. It is possible to align them in any direction with advanced tracking algorithms [19]. There are several common implementations of single axis trackers [20]. These include Horizontal Single Axis Trackers (HSAT), Vertical Single Axis Trackers (VSAT), Tilted Single Axis Trackers (TSAT) and Polar Aligned Single Axis Trackers (PSAT)[21].

Horizontal single axis tracker (HSAT)

The axis of rotation for horizontal single axis tracker is horizontal with respect to the ground (Fig 3.16). The posts at either end of the rotation axis in a horizontal single axis tracker can be shared between trackers to lower the installation cost.

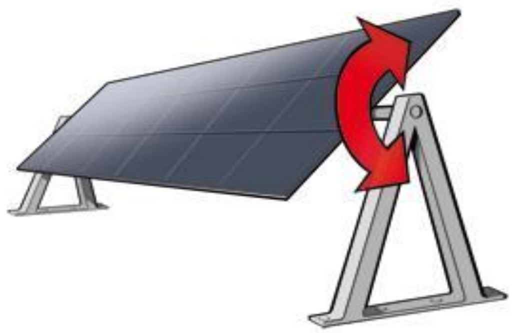

Fig 3.16 Horizontal Single Axis Tracker

Vertical single axis tracker (VSAT)

The rotation axis in vertical single axis trackers is vertical with respect to the ground (Fig 3.17). These trackers rotate from East to West over the course of the day. Such trackers are more effective at high latitudes than horizontal axis trackers.

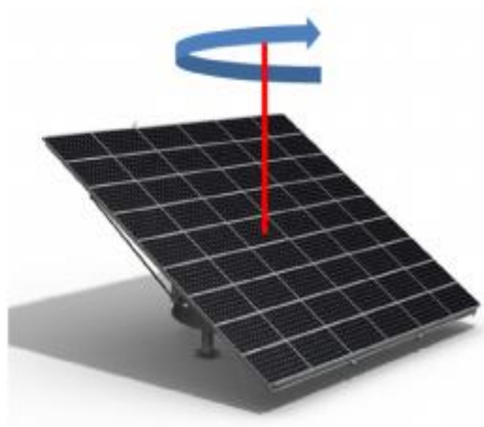

Fig 3.17 Vertical Single Axis Tracker

Tilted Single Axis Tracker (TSAT)

The TSAT axis of rotation is neither horizontal nor vertical with respect to the ground; it is at any angle between horizontal and vertical with the face of the solar panel array oriented parallel to the axis of rotation (Fig 3.18). As the system tracks, it sweeps a cylindrical arc to track the visible motion of the Sun throughout the day. All trackers with axes of rotation between horizontal and vertical are considered tilted single axis trackers. Tracker tilt angles are often limited to reduce the wind profile and decrease the elevated end's height off the ground.

Fig 3.18 Tilted Single Axis Tracker

Dual axis trackers

Dual axis trackers have two degrees of freedom that act as axes of rotation. These axes are typically normal to one another. The axis that is fixed with respect to the ground is considered a primary axis. The axis that is referenced to the primary axis is called a secondary axis. There are several common implementations of dual axis trackers. They are classified by the orientation of their primary axes with respect to the ground. Two common implementations are Tip-Tilt Dual Axis Trackers (TTDAT) and Azimuth-Altitude Dual Axis Trackers (AADAT).

Tip-Tilt Dual Axis Tracker:

A TTDAT tracker has its primary axis horizontal to the ground. The secondary axis is then typically normal to the primary axis (Fig 3.19). The posts at either end of the primary axis of rotation of a TTDAT can be shared between trackers to lower installation costs.

Fig 3.19 Tip-Tilt Dual Axis Tracker

Azimuth-Altitude Dual Axis Tracker:

An AADAT has its primary axis vertical to the ground. The secondary axis is then typically normal to the primary axis (Fig 3.20). The main difference between AADAT and TTDAT is the way the panel rotated for daily tracking. Instead of rotating the array of panel around the top of the pole, AADAT typically uses a ring mounted on the ground with the panel array mounted on a series of rollers. The AADAT could support larger arrays than TTDAT which stand on single loading point of the pole.

Fig 3.20 Azimuth-Altitude Dual Axis Tracker

The dual axis trackers are used not very widely due to the cost and the economic tradeoff behind the technology. Both the single axis and dual axis trackers have disadvantages, such as the adoption of tracking system will incur more upfront cost and the tracking systems components need maintenance. Also the added moving parts will increase system complexity and reliability. Finally compared to permanent mounts, the sun tracking structure is less rigid and more vulnerable to weather-related damage.

3.5 Solar Umbrella Dual Axis Tracking

The Solar Umbrella system needs dual axis tracking based on principle as the azimuth and altitude dual axis tracker. The goal of the tracker for Solar Umbrella is to design an active and dual axis solar tracker with an allowable error of 0.1°.The use of tracking system in the CSPV system greatly improves the power gain from solar radiation [22].

This dual axis tracking system includes the following components:

1. Sun tracking algorithm: the algorithm [23] calculates the azimuth and zenith angles of the sun. The two angles are then used to position the solar panel or concentrator toward the sun. The algorithms are pure based on astronomical references while others use real time light intensity readings. The algorithms also need to compensate the atmospheric refraction.

2. Control unit: the control unit executes the sun tracking algorithm and coordinates the movement of the electrical positioning system. It can be implemented in programmable logic controller (PLC), industrial personal computer, or microcontroller platforms.

3. Electrical positioning systems: the system moves the panel or reflector to face the Sun at the optimum angles. This positioning system utilizes encoders and variable frequency drives or linear actuators to monitor the current position of the panel and move to the desired positions.

4. Drive mechanism and transmission: the drive mechanisms may include linear actuators, linear drives, worm gears, planetary gears, and threaded spindles.

5. Sensing devices: for trackers that use light intensity in the tracking algorithm, pyranometers are needed to read the light intensity. Ambient condition monitoring for pressure, temperature and humidity may also be used to optimize the efficiency and power output.

Since the Solar Umbrella needs to easily set up automatic finding its location and unfold when wind speed is too high. The control platform uses the Global Positioning System chip, electronic compass and anemograph instrument to implement the automatic deployment of the solar umbrella and safety protection features.

The dual axis solar tracker for the solar umbrella is implemented using a special tracking control algorithm that is a hybrid between open loop and closed loop control. Open loop control is needed because the sun can be obscured by clouds, eliminating or distorting the feedback signals. The electrical positioning system needs to actively follow the sun's position even when there is no sun detected during the day. The open loop means that the control unit sends motion control commands to the motor and driving mechanisms to move to the calculated sun's position regardless. The closed loop component requires adjustments, which needs to get the real accurate sun position from the sensors and then predict how to get the best solar radiation then move the motors. This closed loop control adjusting process is imperative to reduce the accumulated error from the driving motor, gears and other mechanisms. The two motors can be operated manually; alternatively I can use photo sensors to detect the sun position, and control the two motors with analog signals. The prototype concept is shown in the Fig 3.21. The parabola dish on top of the support base simulates the unfolded solar umbrella's first stage reflective surface. There is a photo sensor module on the rim of the dish which could tell the sun's position or whether normal to the sun.

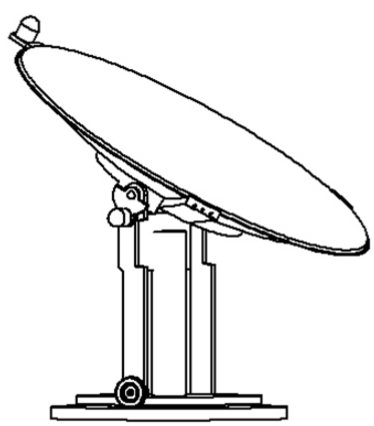

Fig 3.21 Dual Axis Tracking Test Platform

The solar umbrella tracking system used two DC gear motors and microcontroller based printed circuit board platform which could output digital signals and with input digital and analog signals from all the sensors(Fig 3.22). The control algorithm implements the open loop and closed loop system hybrid method to track the sun with high resolution of accuracy.

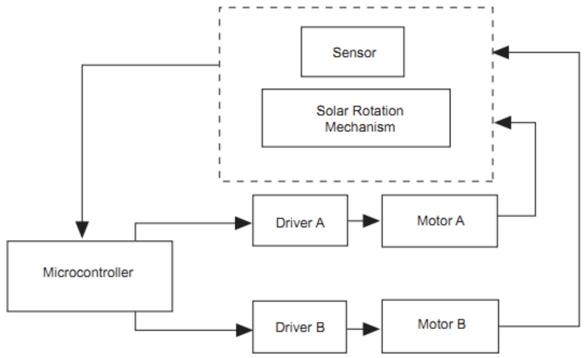

Fig 3.22 Solar Tracking Control Blocks

The tracking system positioning control algorithm is implemented on the microcontroller platform with communication with GPS chip to get time and location information and compass chip to get the dish orientation angle information to automatically calculate the solar position using the algorithm provided by NREL. The diagram of the system logic is showed in Fig 3.23.

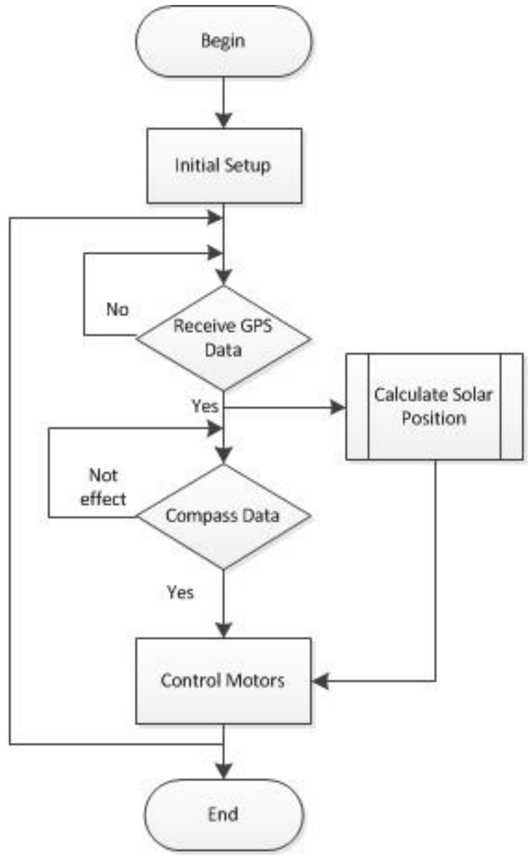

Fig 3.23 Diagram of the SU positioning system

The tracking system control unit will implement other special functions into the microcontroller which was chose from open source Arduino. Safety issues mandate the umbrella to unfold itself in high wind. It also needs to monitor the solar cell temperature to adjust the speed of coolant circling.

CHAPTER 4

A CONCENTRATED SOLAR THERMAL POWER SYSTEM

4.1 The CSTP System Components

I studied a concentrated solar thermal power generation system, which includes the following components connected based on the energy flow in the system (shown in Fig 4.1):

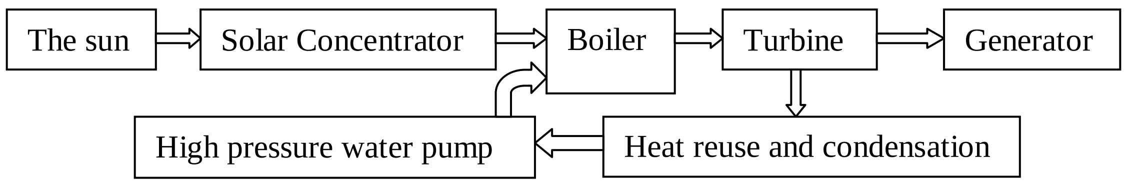

Fig 4.1 the Designed CSTP Structure

1. Optical solar concentrator could be made by glass or metal with reflective surfaces in a parabolic dish shape. The concentrator dish can be a reflective film backed by polycarbonate or carbon fiber composite material.
2. The solar thermal boiler for collecting heat energy from concentrated sunlight heat or from a backup natural gas furnace fire and it will heat up water to high pressure, high temperature steam.
3. The disk type micro turbine converts the heat of high pressure and temperature steam into kinetic energy.
4. The wasted heat reuse and steam condensation is can be used for water heating or solar air conditioning applications to increase the whole system energy using efficiency.
5. The AC generator converts the kinetic energy of the rotating turbine into AC current, which is grid-tied to the generating of the power grid.

4.2 CSTP System Modeling

The solar energy to electric energy conversion efficiency can be calculated from losses due to the optical reflectors, thermodynamic engine, and the AC generator. It can start from a certain amount of solar energy shining onto the concentrator. Power is reduced after each light reflection, and finally light hit on the surface of the boiler. Light is then transferred into heat to cold water in the boiler. It has heat loss by convection, radiation and transportation. The steam comes through pipes to the steam turbine. Part of the energy is converted to useful kinetic energy to the generator. The AC generator converts the kinetic energy into an electric current, with conversion loss from internal resistance and friction.

Steam exiting from the turbine may be used to heat water prior to its entry to the boiler, or used for other purposes such as absorption chilling and household heating. The steam eventually condenses and is collected in a reservoir of water. The Rankine cycle of water then repeats again: water pumping, heating to form high pressure and temperature steam, work producing through a turbine, and condensation.

Optical Solar Collector

The accuracy of the parabolic mirror profile determines how well the focusing the dish could achieve. To concentrate the sunlight perfectly- wavelength is ranging from 400 to 700 nanometers (nm), the reflector surface must be corrected within about 20 nm. I also consider reflectance and emittance of the reflecting materials.

The method used in this research to test the accuracy of the parabolic dish is laser rays tracing. I set up the reflective dish indoor with multiple point laser pointing vertically downward rays to the dish from ceiling height to examine how accurate the reflected laser light may be focused at the focal point. Two types of solar concentrator optics were tested: a customized reflective sheet with polycarbonate support made by chemical vapor deposition on the front surface, and commercial solar concentrator polished film on aluminum support made by 3M. I also measured the reflection of the material. The data collected from the transmission and reflectance measurements indicated a significant amount of light was absorbed close to 60% at wavelength 400nm.The second sample showed the reflectance meet what was claimed in the product brochure.

Disk Type Micro Turbine

Micro turbine is a new method to allow distributed power generation at homes. Micro turbines generate KiloWatts of power output instead of MegaWatts of power for utilities. Micro turbine has the advantages of less moving parts, compact size, lightweight, good efficiency, low electricity cost, and less maintenances. The micro turbine can be gas turbines or steam turbines using air or water as the heat transfer medium.

One example of utility scale turbine is the Combined Heat and Power (CHP) style turbine built by Capstone Turbine Corporation. Capstone Turbines could use alternative fuels to provide power and heat in remote areas. These smaller turbines have a lot of uses in military field including Unmanned Aerial Vehicles (UAV), missiles, and remote control aircraft.

For smaller turbines called nanoturbine can be very small in dimensions. One small turbine is built at MIT by Professor Alan H. Epstein. Nanoturbines aimed for small wattage power output based on the manufacturing technology called Micro Electro

Mechanical Systems (MEMS). The goal is to reach to around 10 Watts or less of power to support personal daily power needs

In this thesis I focused on the disc type micro turbine. One very common disc type micro steam turbine is the Tesla turbine invented by Nikola Tesla in 1913. The Tesla turbine combines a stack of smooth round disks, with nozzles blowing a high speed steam/gas to the edges of the disks. The gas drags the disk by means of viscosity and the adhesion of the gas with disk surface. The gas exhaust exits from the center of the disk. At low Reynolds number (R_e=Initial force/Viscous force), the boundary layer effect is most effective for momentum transfer of the Tesla turbine. This Tesla turbine is an efficient self-starting prime mover for power generation

There are three basic types of turbines: impulse turbine, reaction turbine, and lift turbine. Here is a diagram to show the difference function principle of the first two main types of turbine (showed in Fig 4.2)

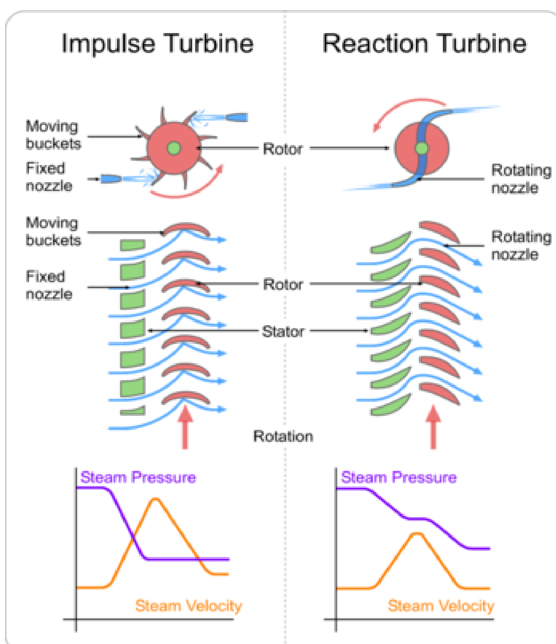

Fig 4.2 Turbine Function Principle Diagram

The main distinction between impulse and reaction turbine is the manner in which the steam is expanded as it passes through the turbine. For the impulse turbine, the hot and high pressure gas expands when passing over the turbine blades. The speed up gas imparts momentum to turbine blades by means of impact. In reaction turbines, the steam is continually expanding as it flows over the blades. The blades are lifted and rotates similar to the differentiate pressures on opposite surface a turbine blade. The De Laval turbine is an impulse turbine with a single blade wheel. The Charles Parsons turbine is one typical example of the reaction turbine.

Tesla turbine is a radial turbine in which the flow of the working fluid is radial to the shaft. The disk type micro turbine is invented with the objective to best utilize the pressure energy of high temperature, high pressure superheated steam or gas. The turbine converts high pressure steam to mechanical torque. A hot gas is expanding through the spiral shape micro-tunnel to drive the turbine rotating at a certain speed range. The gas performs work through adiabatic expansion. The prototype disc steam turbine is made of stainless steel by Electro Discharge Cutting Machine (EDM) technologies.

The figure 4.3 shows a long spiral channel for gas flow. The gas flows from the center in the spiral micro-tunnel of the turbine, and expands through the long channel, finally reach the exit. The hot and high pressure gas drives the turbine to rotate. The gas will gradually drop its high pressure and expands adiabatically with lowered temperature.

For the linear spiral micro tunnel shown in Fig 4.3, It has $r(\theta) = 10 + 2.5\theta/\pi$ for the ten turns made for $0 < \theta < 20\pi$. At the inlet of the spiral, it has $r(0) = 10$mm. At the outlet with $r(20\pi) = 60$mm, the length of the infinitesimal length of the spiral dL($dL = r(\theta)d\theta$) has expanded by a factor of more than 6, close to the factor of 10 increase in volume for the gas as pressure is reduced from 20 atmospheres to 1 atmosphere.

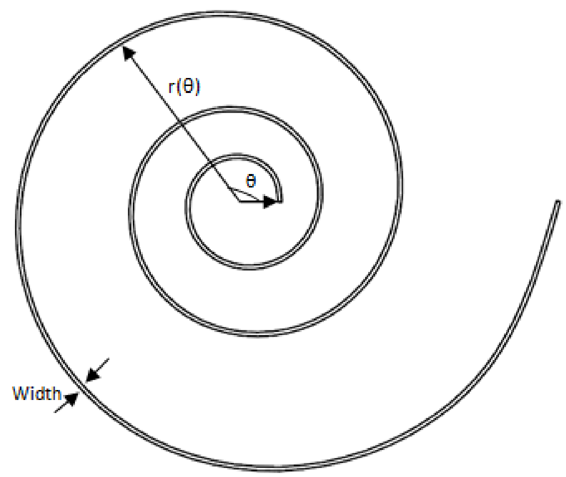

Fig 4.3 Spiral Shape Micro Tunnel

The turbine consists of layers of stainless steel discs, top and bottom caps. There are spiral shape micro tunnels cut off on each disk layer. The top cap has a steam inlet in its center, while the bottom cap has an extended shaft hooked to the driving shaft of generator. The disk type micro turbine could use a combined burning furnace and the sunlight concentrator to heat up water in the two stages boiler and get the high pressure superheated steam. The disk type turbine converts thermal energy in pressured steam into useful mechanical work.

I examined the thermodynamics of the expanding gas in the spiral tunnel. As the gas spirals outward, gas molecules are forced to change course defined by the boundaries of the spiral. The outward spiraling flow of gas has a feature suitable for the adiabatic expansion of the gas. Assume that the infinitesimal length dl of steam at radius $r(\theta)$ contained inside the infinitesimal angle $d\theta$. It can be calculated that $dl = \sqrt{(r(\theta))^2 + (dr(\theta)/d\theta)^2}d\theta$. As the gas travels outwards on the spiral with increasing θ, it expands in volume as pressure is reduced. For this linear spiral, the function $r(\theta)$ and its first derivative $dr(\theta)/d\theta$ are positive functions of θ. Therefore, dl increases as θ increases. The gas expands within the expanding dl as it spirals outwards.

The gas volume expands as it moves through the spiral (As PV^{γ} =Constant, where $\gamma = \frac{7}{5} or \frac{5}{3}$ for air/steam or mono-atomic gas respectively). I express volume as function of pressure (for initial and final values subscripted by 1 and 2), it has $V_2 = V_1 (\frac{P_1}{P_2})^{1/\gamma}$.

Consider gas counter clockwise flowing in the spiral, turbine which is turning in a clockwise direction. As the turbine turns faster, the gas as seen outside the turbine is spinning at a slower angular velocity as canceled by the turbine spinning .In essence, the spinning turbine causes the gas exit and shortens the distance traveled by the gas.

4.3 Analysis of Micro Disc Turbine

It can use a Rankine cycle for the disk turbine which using circling water to transfer energy from a high temperature heat source.

The Rankine cycle has five progressive stages in this design:

1. Cool water is pumped at high pressure into a boiler;
2. The water is heated and evaporated at high temperature, becoming saturated steam;
3. The steam is further heated to become superheated;
4. The high pressure steam is admitted the steam turbine through its center entrance where steam spirals through to its low pressure end.

5. The steam condenses, and the cool water recycles through the pump.

Electricity is extracted from the generator which is directly coupled to the shaft of the turbine. The Rankine cycle is shown in Fig 4.4.

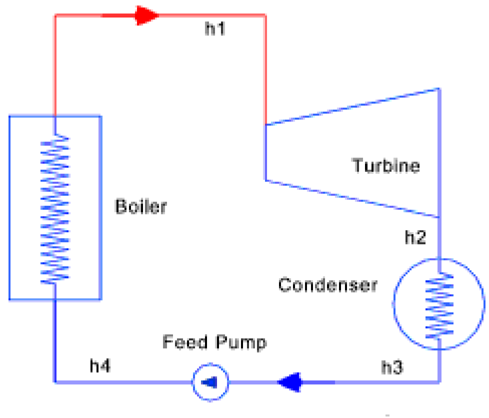

Fig 4.4 Rankine Cycle Stages

Work generated equals to the energy entering the turbine as steam (with enthalpy h1) minus the energy leaving the turbine as steam (with enthalpy h2) after expansion. Heat transfer from the furnace (or the solar thermal concentrator collector) will be the difference in the enthalpy of the steam leaving the boiler and the water entering the boiler (h1-h3).The ratio of output work/input by heat transfer is the thermal efficiency of the Rankine cycle, with Rankine thermal efficiency = (h1-h2)/ (h1-h3).

The momentum transferred to the disk with the interactions between the spiral walls and the steam molecules as the steam passing the long resistive tunnel. The turbine rotates in the reverse direction to the steam exiting direction from the turbine. For Tesla turbine, the boundary layer effect is more efficient at low flow pressure and momentum transfer. Our turbine works better under slow pressure reduction at a low rotational speed than conventional turbines.

The Navier Stokes equation can be used to explain the motion dynamics happened to the steam flowing in the steam turbine. The assumption of an incompressible gas with Newtonian flow (fluid density ρ and dynamic viscosity μ are constant), with a velocity field $\bar{V} = (u_r, u_\theta, u_z)$ was made, where $(r, \theta, z)$is the cylindrical coordinate direction.

Vector form: $\rho \frac{D\vec{V}}{Dt} = -\nabla P + \rho\vec{g} + \mu\nabla^2\vec{V}$

Where $\rho\vec{g}$ standing for the body force such as gravity or centrifugal force. This is a statement of the conservation of momentum in a fluid applying the Newton's second low to a continuum.

The incompressible continuity equation:

$$\frac{1}{r}\frac{\partial(\gamma u_r)}{\partial r} + \frac{1}{r}\frac{\partial(u_\theta)}{\partial\theta} + \frac{1}{r}\frac{\partial(u_z)}{\partial z} = 0$$

r-component:

$$\rho\left(\frac{\partial u_r}{\partial t} + u_r\frac{\partial u_r}{\partial r} + \frac{u_\theta}{r}\frac{\partial u_r}{\partial\theta} - \frac{{u_\theta}^2}{r} + u_z\frac{\partial u_r}{\partial z}\right)$$

$$= -\frac{\partial P}{\partial r} + \rho g_r + \mu[\frac{1}{r}\frac{\partial}{\partial r}(r\frac{\partial u_r}{\partial r}) - \frac{u_r}{r^2} + \frac{1}{r^2}\frac{\partial^2 u_r}{\partial\theta^2} - \frac{2}{r^2}\frac{\partial u_\theta}{\partial\theta} + \frac{\partial^2 u_r}{\partial z^2}]$$

θ-component:

$$\rho\left(\frac{\partial u_\theta}{\partial t} + u_r\frac{\partial u_\theta}{\partial r} + \frac{u_\theta}{r}\frac{\partial u_\theta}{\partial\theta} - \frac{u_r u_\theta}{r} + u_z\frac{\partial u_\theta}{\partial z}\right)$$

$$= -\frac{1}{r}\frac{\partial P}{\partial\theta} + \rho g_\theta + \mu[\frac{1}{r}\frac{\partial}{\partial r}(r\frac{\partial u_\theta}{\partial r}) - \frac{u_\theta}{r^2} + \frac{1}{r^2}\frac{\partial^2 u_\theta}{\partial\theta^2} - \frac{2}{r^2}\frac{\partial u_\gamma}{\partial\theta} + \frac{\partial^2 u_\theta}{\partial z^2}]$$

z-component:

$$\rho\left(\frac{\partial u_z}{\partial t} + u_r\frac{\partial u_z}{\partial r} + \frac{u_\theta}{r}\frac{\partial u_z}{\partial\theta} + u_z\frac{\partial u_z}{\partial z}\right)$$

$$= -\frac{\partial P}{\partial z} + \rho g_z + \mu[\frac{1}{r}\frac{\partial}{\partial r}(r\frac{\partial u_z}{\partial r}) + \frac{1}{r^2}\frac{\partial^2 u_z}{\partial\theta^2} + \frac{\partial^2 u_z}{\partial z^2}]$$

Where gravity components $are\ (g_r, g_{\theta}, g_z)$.

The energy input to our turbine is about 10Kw solar energy contained in the heat of the superheated steam generated by 2cc of water per second. The total enthalpy of steam at 20 atmospheric pressure and 800 degrees Kelvin is about 3.5KJ /cc of water. The 2cc volume of water could generate around 400 cc superheated steam with total enthalpy of 7 KJ. It is expected exiting gas with a temperature around 400 degrees Kelvin at 1 atmosphere in pressure.

4.4 Disk Micro Turbine Prototyping and Test

CAD modeling and simulations are made to validate the turbine design. The first stage of design concept was to build a straight radially expanding circular tunnel as shown in Fig (4.5.a).This concept is a variation from the Hero turbine. The other concept tested included a 3 spiral shape axisymmetric tunnels with a circular cross section cutting off area formed by two disks stacked together (shown in Fig. 4.5.b).The air comes into the center chamber and exits through the 3 tunnels simultaneously. Another design showed in Fig 4.5.b, which aimed to increase the impedance of the gas tunnel by using contraction nozzle with variable cross section areas for the whole spiral length is shown in Fig (4.5.c). These designs were built using a 3D printer using for PVC plastic material. These prototype turbine designs were tested using high pressure compressed nitrogen gas, and then connected to a DC motor to generate the electricity. The test results showed that the rotating speed of the turbine is relatively higher than the expected design rotation speed which is around 3000 rpm. The power output from the DC motor is positively proportional to both the input nitrogen gas flow rate and pressure.

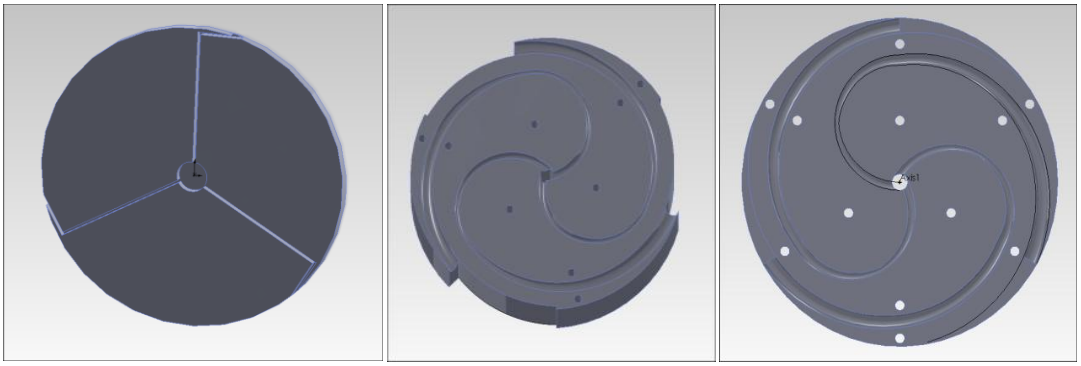

Fig 4.5, Turbine Concept CAD designs (from left to right 4.5.a, 4.5.b, and 4.5.c)

To reduce the high rotation speed, methods were used to slow down the rotation speed and increase kinetic to electrical conversion efficiency. Figure 4.6.a demonstrated the design of 3 turn spirals through the disk. The thickness of the designed disks is increased from 6mm (Fig. 4.6.a) to 12.7mm (Fig. 4.6.b, Fig. 4.6.c).The design of Figure 4.6.b also has a decreased width of the cross section area of 0.5mm width. The latest design is shown in Figure 4.6.c, which has only one spiral but with 10 turns.

The test of the turbine is built on a special test setup which has the turbine axle aligned with the generator shaft. The testing steps are as follows: prepared first the DC motor, I then applied the gas to measure the speed of the turbine using a tachometer and last measured the voltage at the motor terminals for various resistor loads.

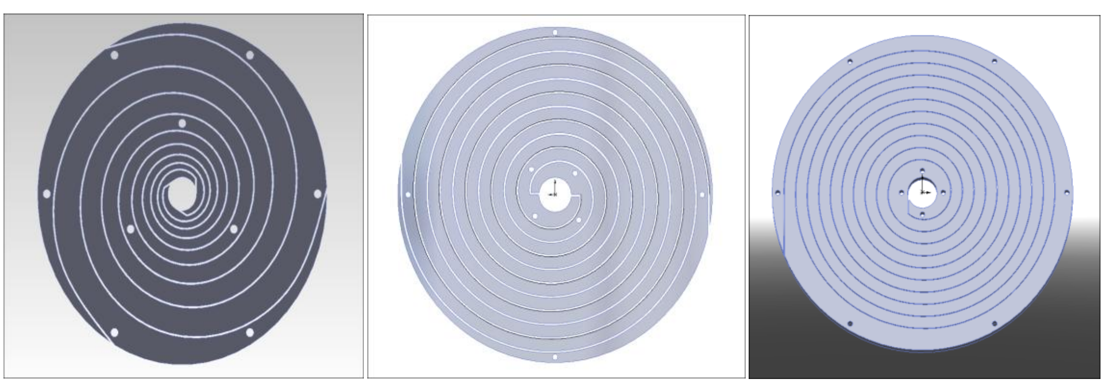

Fig 4.6 the Disk Turbine Evolved Designs (from left 4.6.a, 4.6.b and 4.6.c)

Fig 4.7 showed the setup for the testing of disk type turbine designed based on the concept of Fig 4.3. Gas comes in from the right side, and the generator is shown on the left side, in the middle is the testing turbine built by our 3D printer. The turbine uses a tube to guide the gas into the turbine within a shaft to drive the generator set. The turbine includes two disks stacked up. The exits are on opposite side of the disks. The gas is injected through a nozzle into a female cavity of the turbine. Some gas leaks occur which functions as a gas bearing.

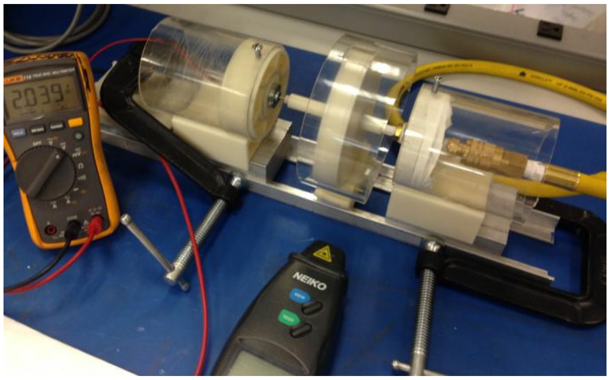

Fig 4.7 Disk Type Micro Turbine Testing Setup

The turbine has only been tested using the compressed nitrogen gas. The boiler has already been built, but the stainless tube superheating coil has experienced some metallic flaking issue when intense heat wave applied. The DC motor internal resistance is tested 23.4 Ohms. The formed gas bearing leakage was so hard to control as if the seal gap is too tight that there was high friction force. The friction force tended to be small when rotate at higher flow rate with high rotating turbine speed. I tested the DC motor terminal voltage for open circuit situation and also with a value of 100, 50, 10, 5, 1 Ohms respectively resistance added between the terminals. The testing compressed nitrogen gas pressure is stable at 300 PSI with varied gas flow rate from 2.5 to 7.5 CFM (cubic food per minute).Fig 4.8 shows the turbine ration speeds versus varied input gas flow rate to the turbine under open circuit and with different resistance situations. Fig 4.9 shows the voltages generated at the load with varied gas flow rate under the similar different loads situation above mentioned.

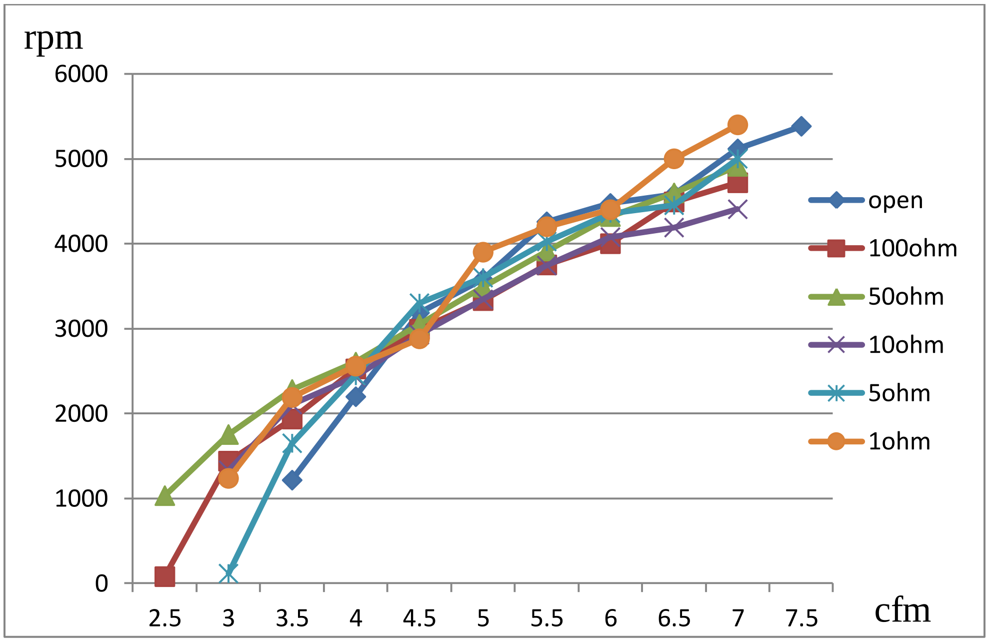

Fig 4.8 Rotation Speeds versus Varied Gas Flow Rate

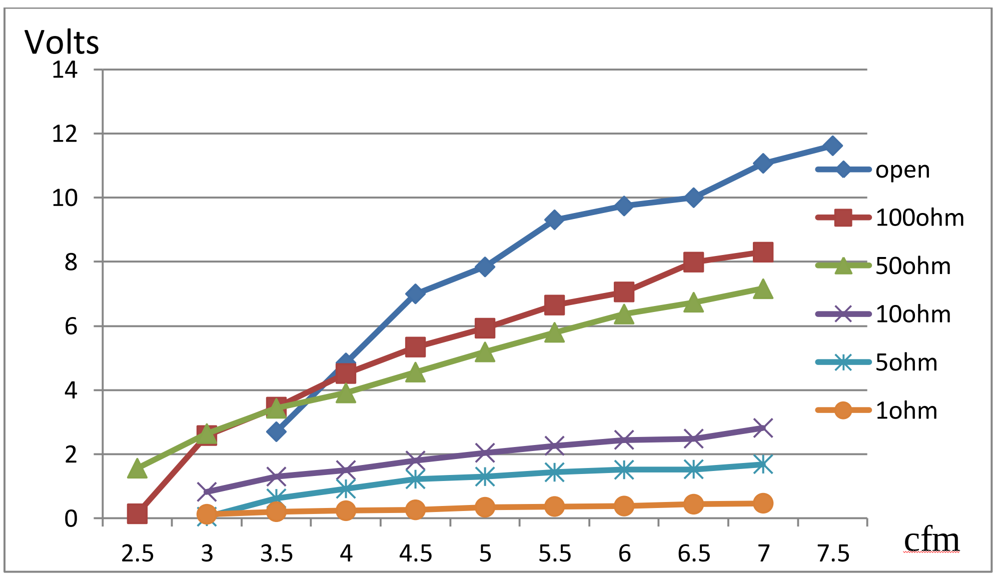

Fig 4.10 Voltages versus Varied Gas Flow Rate

Consider different load resistance and the DC motor internal resistance together, I can calculate the overall system equivalent resistance with varied load conditions. Fig 4.10 showed the power generated from the turbine DC motor system with each load situation under varied input gas flow rate.

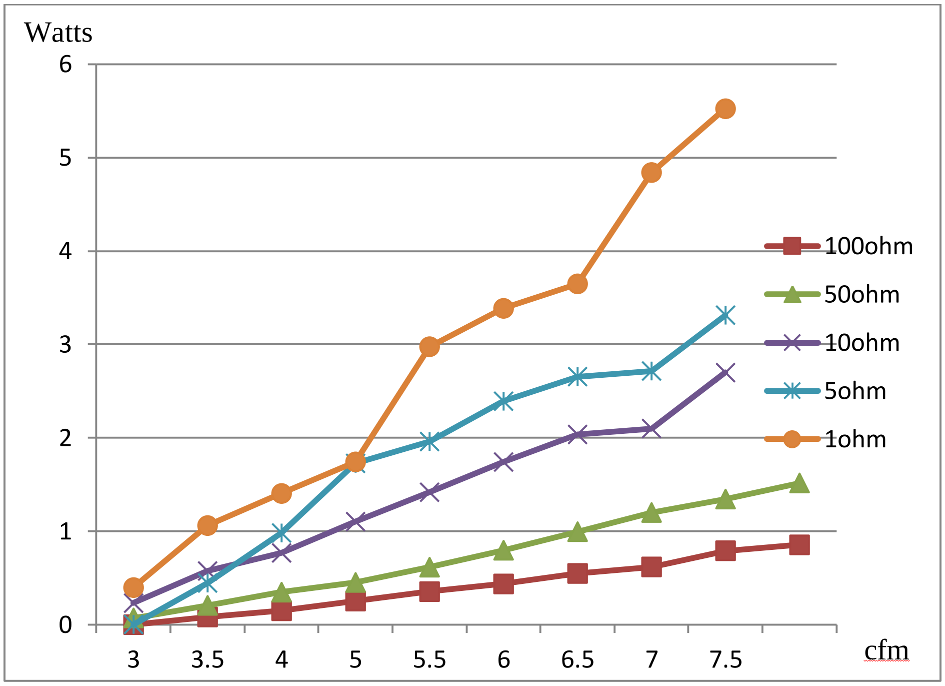

Fig 4.10 Power versus Varied Gas Flow Rate

Software tools are available for computational fluid dynamic analysis of the steam flow in the designed turbine. The turbine tests and simulations have validated the methods of using narrow width, long spiral length and many turns to improve the micro tunnel impedance on the rotation speed reduction. But further extensive tests need to be done on the steam turbine built by stainless steel using the superheated steam.

In summary, an experimental design of a CSTP system was implemented based on parabolic solar concentrator, boiler, disk type turbine and generator platform which has been tested and evaluated in different testing situations. The small bladeless turbine has been tested and proved it can perform designed objectives. There will be more continue simulation and testing involved with the new turbine to further improve the energy conversion efficiency.

CHAPTER 5

CONCLUSION

In this research, the solar energy research meaningful point is discussed. I discussed the most promising technology-concentrating solar power generation which includes CSPV and CSTP. The two testing concentrated solar power generation systems are implemented and validated in different situations.

The CSPV system includes two important parts: one is the concentrator optics, and the other is solar tracking system. Various types of solar concentrator designs are reviewed in terms of their performance and characteristics. The very common concentrator optic is refractive (e.g. Fresnel lens) and reflective (e.g. Parabola dish) optics .The innovative design using light guide optic provided a new solution for the concentrator design.

The Solar Umbrella system is a portable and light-weight CSPV aims for some distributed solar power generation applications. It uses two stages concentration optical systems. The first stage is formed by 18 blades of reflecting parabolic mirror, while the second stage is a reflecting cone to further concentrate and also evenly adjust the concentrated sunlight shining onto solar cells. The Solar Umbrella uses a dual axis tracking system to attain higher power output. The solar umbrella uses the azimuth and elevation dual axis tracking and its hybrid digital control system uses both open loop and closed loop system. The tests and data collected from the implemented Solar Umbrellas system has proven the design objects.

Future work of the Solar Umbrella would be the power inversion and power storage system. The power inversion includes the DC-AC inverter design. The power storage means using (e.g. lithium-ion) batteries to store the electrical power generated by the CSPV system. Also the charging and monitoring of battery system to extend the life of battery could get the best performance of the battery system.

The implemented CSTP system is a boiler, turbine and generator type. A typical disk type micro turbine was designed and tested to convert the high pressure and temperature gas from the boiler. The CSTP system was based on using solar energy to heat up a heat medium (water) to transfer the energy to a heat engine (turbine), and then transfer the heat engine mechanical output to drive a generator to get power output.

CSTP is similar to CSPV as it needs similar solar concentrating optics and dual axis solar tracking system. But the CSTP has an advantage compared with the CSPV, as it collects the energy in the form of heat which is easy to recollect the waste heat which could be used for other purpose. This feature will help CSTP system reaches to a higher overall system energy conversion efficiency than CSPV which relying most on solar cell modules conversion efficiency. The designed micro turbine based energy system has proved the design objectives. The discussion on the CSTP systems provided the core technology and trending researching topics in the concentrated solar power generation field.

There will be further computational fluid dynamic (CFD) research using commercial CFD simulates software to test the turbine performance under varied high pressure and high temperature situations. Also the turbine will be tested on different heat mediums as well. There should be more extensive optimization in mechanical design, materials selection, and manufacturing process for the CSTP system.

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