DEVELOPMENT OF FRESNEL POWERHOUSE PROTOTYPE WITH THERMAL ENERGY STORAGE CONCENTRATED SOLAR POWER

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Abstract: Our paper evolves the implementation of a prototype to power up a house from solar heat energy for 24x7. We have fabricated a prototype that depicts our idea practically proving that our method is feasible. If this is implemented in large scale then it serves as a power plant. In the concept of Concentrated Solar Power where numerous mirrors are used to concentrate a large area of sunlight onto a small area so as to obtain very high temperatures we use lenses instead of mirrors as when fabricated from different materials under various dimensions they will vary in thermodynamic efficiencies and each of them will produce different peak temperatures. Solar heat can be stored by TES method where solar salt is used as the thermal storage medium and this heat stored will be used to generate electricity by running a steam engine which is coupled to a generator thereby generating electricity for a household. Here we have discussed about the theoretical concepts of CSP and the methods employed by us in the implementation of our prototype. This prototype resembles a power plant in miniature with Fresnel lens for heat source and a heat exchanger with thermal energy storage.

Keywords: Portable Solar Power, CSP, Fresnel Lens, Solar Salt, Thermal energy storage, and Solar Heat Collector.

I. IINTRODUCTION

Today the major problem faced by our state is the demand for electricity. Considering the impact on environment and availability of fossil fuel resources, people and industries are swayed towards renewable energy sources. Recent studies show that public is using less energy overall and making more use of renewable energy resources in developed countries like United States of America, United Arab Emirates and Australia. Even in India consumers are moving towards Renewable Energy due to the power crisis. Conventional energy sources will be depleted in due course of time. Hence future energy demand can be met only by non-conventional energy sources. Considering the solar source we can obtain energy from both light and heat. However we cannot obtain energy for 24 hours by just using photovoltaic cells. Even though we use battery backup it has to be charged to provide uninterrupted power supply. But solar heat can be stored and used to generate electricity for 24 hours. This is the concept of Concentrated Solar Power. In this method either mirrors or lenses can be used to focus the solar heat onto a single area where a heat engine can be placed, usually we use steam engines or stirling engines. Solar collectors are used to collect the solar heat and there are various types in them namely power tower, dish stirling, parabolic trough and Fresnel reflectors. These methods are implemented in various parts of the world and they produce energy in terms of MW.

We concentrate in designing a compact CSP system which can meet the power demand of a single household. For this we chose Fresnel lens. Fresnel lens can be classified as spot and linear Fresnel lens. Linear Fresnel lens provide a linear beam and hence suitable for water heating applications[1]. As the Fresnel lens will be exposed to sunlight during the daytime the material selection[2] is important for fabricating the lens. Various materials are used as heat transfer fluid. Oil is used but it is not safe whereas other materials are expensive. Hence we use eutectic salt mixture[3] which can be used to store the solar heat. Various eutectic salts can be obtained from various combinations of salt and they have different melting and freezing point[4]. The boiler material should be chosen such as it is not corroded by the salt we use[5]. The efficiency of this power plant mainly depends on the specific heat of the eutectic salt mixture[6].

II. METHODOLOGY

A. Concentrated Solar Power

An array of mirrors or lenses when used to concentrate sunlight (solar thermal energy) onto a small area more heat will be produced which can be used as a heat source in a normal conventional power plant. As told earlier in the introduction part electrical power is produced when the concentrated light is converted to heat, which drives a heat engine connected to an electrical power generator. The solar concentrators used in CSP systems can often be used to provide industrial process heating or cooling, such as in solar air-conditioning. Concentrating technologies exist in four common forms, namely parabolic trough, dish Stirling, concentrating linear Fresnel reflector, and solar power tower.

B. Linear Fresnel Lens

Fresnel lens is designed in such a way that the fabrication of lenses with short focal length is simplified when compared to a conventional lens and also the mass and volume of material required will be less than that required by a lens of latter type. In ancient times they were used in light houses. The Fresnel lens reduces the amount of material required compared to a conventional lens as it divides the lens into a set of concentric annular sections. An ideal Fresnel lens would have infinite number of such sections. In each section, the overall thickness is decreased compared to an equivalent conventional lens and it is manufactured by computer-controlled milling equipment (CNC).

In this solar collector the sunlight is focused by a linear Fresnel lens on the receiver in order to heat he working fluid. The lens considered here is a non-imaging Fresnel lens and is shaped in such a way to redirect all solar rays on the absorber[1]. We use hitec salt mixture as our working fluid. The receiver has a metal tube filled with hitec salt mixture. The working fluid flows through the collector absorbing heat energy and is stores in a hot storage tank.

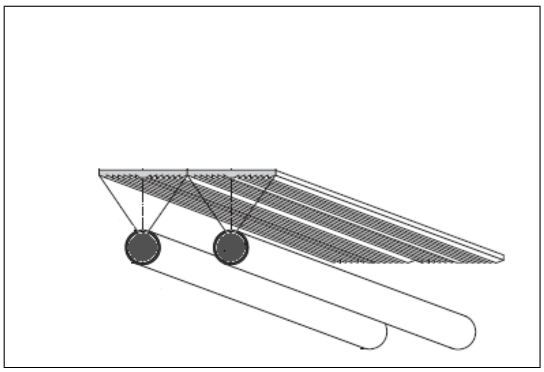

Figure 1: Linear beam focused on tube by Linear Fresnel lens.

1) **Energy from the Sun**
The energy at the sun's surface is calculated as 63,000,000 Watts per meter square. By Inverse Square Law the intensity of the radiation emitted from the sun varies with the squared distance from the source.

Earth-Sun's Distance = 149,500,000 km

The amount of radiation intercepted by the outer limits of the earth's atmosphere can be calculated to be around 1,367 Watts per meter square. On a normal sunny day an average of 500 Watts per metre square energy can be obtained considering the losses.

2) **Energy at the receiver**
The temperature at the focal point of Fresnel lens depends on the following factors :

a) Area of the Lens.
b) Coefficient of Reflections, Absorption and the Spectral transmission bandwidth of lens.
c) Amount of time the object is exposed to sun radiation at focus.
d) Intensity of Sunlight âĂŞ it varies along latitude and longitude.

The amount of heat generated is given by the following equation,

$$\Delta Q = \Delta T \cdot M \cdot S \quad (1)$$

Where, ΔT is the change in temperature at focal point.
M is the mass of the material.
S is the Specific Heat Capacity of the material.
The obtained value will be in terms of Joules which can be converted to Watts based on the change in time.

3) **Temperature dependence of Fresnel lens**
Lenses of concentrating photovoltaic cells in solar panels are exposed to a wide range of temperature. Depending on the orientation and location of the installed solar power plant peak temperature varies from $-10°C$ to $40°C$ in different climatic conditions[14]. Higher temperatures in summer increases temperature of CSP plants pushing it further than its peak limit. Usually lenses which are refractive optical components are affected by a change in temperature in two ways viz, a change of refractive index of the lens due to thermal stress and a deformation of the lens material due to thermal expansion[2].

a) **Change of index of refraction** On measuring the wavelength and temperature dependence of the index of refraction of silicon lens material to an accuracy of 10-4, we came to a conclusion that to this accuracy the temperature dependence of a Fresnel lens is nearly independent of the wavelength and it can be represented in the form of a linear relationship. In a real module the lens cell distance remains fixed and hence a decrease in refractive index along with chromatic aberration of fresnel lens leads to a better focus of blue and ultra violet light leaving the focus in the infrared region. Figure 1 shows the wavelength focused best for a theoretical lens that experiences a change of index of refraction due to thermal expansion but not due to the change of lens geometry. This lens can be designed for specific wavelengths also and hence it can also be used in CPV systems[12]. But in our case of CSP we do not have to concentrate in the wavelength of the light. On the other hand it should be noted that infrared light is responsible for heat and hence it is better if our lens focuses more in the infrared region. However heat produced will experience a minute difference even in the case of such a lens.

b) **Change of lens geometry** In addition to the effects discussed above, thermal expansion of lens material leads to an increase size of the Fresnel lens if the lens if fabricated using a single material. Let us consider a scenario in which the lens as a whole stays centre above the heat exchanger, this moves each Fresnel pitch outward and thus increases the spot size basically by the absolute amount of the lateral thermal expansion. For a fresnel lens of 600mm by 400mm already experiments show that decrease in temperature to be of same order of magnitude as influence of the decrease of index of refraction. In contrast, if the lens is fixed on a glass plate with a small coefficient of thermal expansion a change of temperature results in a deformation of the lens[7]. The results of finite element simulations of the thermal expansion of one pitch of a Fresnel lens structure made of silicone on a glass substrate are shown in the figure 2. This simulation shows the deformation due to an increase in temperature of 20oC for two different pitch angles.

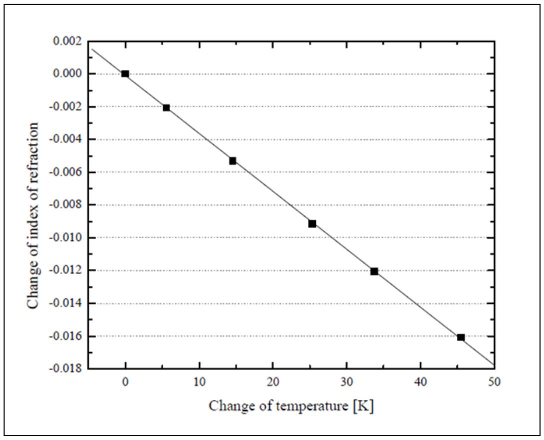

Figure 2: Change in refractive index of lens due to temperature rise

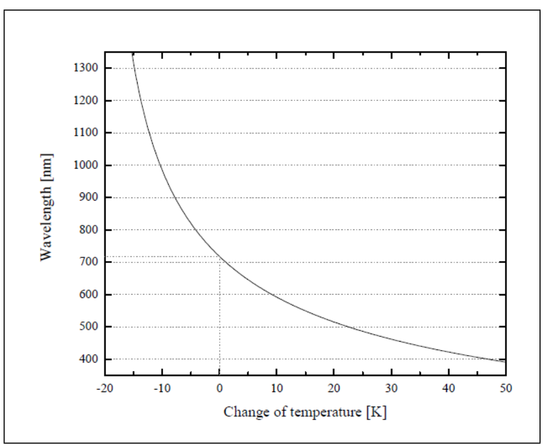

Figure 3: Change in wavelength of lens due to temperature rise

These two factors are a major concern in CPV system[2], but is CPS they are not a big threat to the thermodynamic efficiency of this power plant. Plastic resins such as acrylics and polycarbonates are widely used as materials for Fresnel lenses; among others, for outdoor applications, silicones (silicone rubber, silicone resin, etc.) are promising materials because of their excellent heat resistance, weather resistance, and reliability. Silicones excel over other optical materials such as polycarbonates in transmittance in the short-wavelength region of 250 nm to 350 nm, and are particularly promising materials for applications in electric-power generating systems in which multi junction semiconductors that utilize light in a wide wavelength range from short to long wavelengths are used as cells.

However, since the temperature dependence of the refractive index of silicone materials is generally larger than that of other materials such as acrylic and polycarbonate resins, there has been the problem that the focal length changes with ambient temperature, causing the power generation efficiency to drop. In particular, the problem has been that the change in the focal length is appreciable in the peripheral region of the lens where the angle of incident light deflection (deviation angle) is large. Specifically, a quartz plate, a glass plate, and a resin plate of PMMA, polycarbonate, or the like can be used advantageously.

c) **Solar Salt Mixture** A non-eutectic salt mixture of 60% sodium nitrate and 40% potassium nitrate is typically utilized in solar thermal power plants and this mixture is commonly called Solar Salt. Solar thermal power plants are a key technology for electricity generation from renewable energy resources. Thermal energy storage (TES) makes it possible to meet the intermediate load profile with dispatchable power, a benefit that has a high value to power utilities. For this temperature range molten salts are attractive candidates because they have advantages in terms of a high heat capacity, high density, high thermal stability, relatively low cost and low vapour pressure. The low vapour pressure results in storage designs without pressurized vessels. One major difficulty with molten salts is unwanted freezing during operation. Freezing must be usually prevented in the piping, the heat exchanger and in the storage tanks using auxiliary heating systems. Hence, salt mixtures with a low melting temperature are developed. At high temperatures, salt stabilities and corrosion aspects play a major role.

The below table[3] presents a systematic list of the melting temperatures of single salts and the minimum melting temperature of salt systems with the cations calcium (Ca), potassium (K), lithium (Li) and sodium (Na) and the anions nitrate (NO3) and nitrite (NO2) using various literature sources. The melting temperatures of the listed single salts range from 220°C (LiNO2) to 561°C (Ca(NO3)2). Salt mixtures, rather than single salts, have the advantage of a lower melting temperature. These mixtures can have similar thermal stability limits as the single salts. Hence, salt mixtures, such as eutectics, can have a wider temperature range compared to single salts[5]. The table shows commonly considered salt systems for solar applications in grey background. These are the binary K,Na//NO3 system with a common anion (containing Solar Salt), the ternary reciprocal systems K,Na//NO3,NO2 (containing a mixture called Hitec) and the two ternary additive systems with a common anion Ca,K,Na//NO3 (HitecXL) and K,Li,Na//NO3. The table clearly shows the tendency of melting temperature depression from the left to right hand side, as well as from the top to the bottom of the table. Hence, it can be expected that systems with a liquids temperature lower than 80°C are feasible. Hitec Salt mixture consisting of

TABLE I
List of solar salts along with their melting point

	NO_2	NO_3	NO_2, NO_3
Single salts and binary systems with common cation			
Ca	398 °C#	561 °C#	393 °C
K	440 °C	334 °C	316-323°C
Li	220 °C	254 °C	196 °C
Na	275 °C	306 °C	226-233 °C
Binary systems with common anion and ternary reciprocal			
Ca,K	185 °C	145-174 °C	130 °C
Ca,Li	205-235 °C	235 °C	178 °C
Ca,Na	200-223 °C	226-230 °C	154 °C
K,Li	98 °C	126 °C	94 °C
K,Na	225 °C	222 °C	142 °C
Li,Na	151 °C	196 °C	126 °C
Ternary additive common anion and quaternary reciprocal			
Ca,K,Li	N/A	117 °C	N/A
Ca,K,Na	N/A	130 °C	N/A
Ca,Li,Na	N/A	170 °C	N/A
K,Li,Na	N/A	119 °C	75 °C
Quaternary additive common anion and quinary reciprocal			
Ca,K,Li,Na	N/A	109 °C	N/A

Sodium Nitrate and Potassium Nitrate was used as the Heat transfer Fluid. There is various eutectic salt mixtures with low melting point[4]. The amount of salt used decides the duration of availability of electricity at midnight. The various Salt mixtures with their melting points are tabulated below[3].

Specific Heat Capacity of Hitec Salt Mixture = 1495 Joules per Kilogram Kelvin[8]

The storage cost is 10.7 dollar per Kilowatt hour and the cost per kg is 0.97 dollar per kilogram[5].

III. MODELLING OF PROPOSED SYSTEM

We have implemented a prototype that is capable of collecting heat and melt salt storing heat energy in it. We fabricated all the components with the help of our technical staffs. The system employs Fresnel lens that concentrate solar energy on a small heat exchanger filled with molten salt. The working fluid was at a temperature around 200-250 degree Celsius. This makes the water to boil and the steam is superheated at this temperature. This steam is then used to run a small steam

TABLE II
The Eutetic salt mixture we used

	NO_2	NO_3	NO_2, NO_3
Single salts and binary systems with common cation			
Ca	398 °C#	561 °C#	393 °C
K	440 °C	334 °C	316-323°C
Li	220 °C	254 °C	196 °C
Na	275 °C	306 °C	226-233 °C
Binary systems with common anion and ternary reciprocal			
Ca,K	185 °C	145-174 °C	130 °C
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Ternary additive common anion and quaternary reciprocal			
Ca,K,Li	N/A	117 °C	N/A
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Ca,Li,Na	N/A	170 °C	N/A
K,Li,Na	N/A	119 °C	75 °C
Quaternary additive common anion and quinary reciprocal			
Ca,K,Li,Na	N/A	109 °C	N/A

engine which is coupled to a DC generator thereby generating current. The construction process is explained below.

For the construction of our prototype we needed to fabricate certain components and had to buy some components online. We ordered steam engine, solar charge controller and DC generator online. Fresnel lens was collected from an old shop. Then we set apart to fabricate the heat exchanger. We collected ideas from various faculties of Mechanical Department and Physics Department. We also used the materials available in our college laboratory for the fabrication.

a) **Design of Heat Exchanger :** At first we came up with the idea of designing a boiler but then as we are also using molten salt to store thermal energy we moved on to heat exchanger. For its fabrication we sought out help from our Mechanical faculty staffs and they guided us. As per their suggestions we bought a metal pipe of small length and filled it with salt and seal at both the ends. Inside this metal tube we placed a small copper container where water will be stored and heated. The metal tube is filled with sodium nitrate and potassium nitrate. As this salt has to be maintained in a liquid state auxiliary heating has to be provided. For this purpose we used an external induction heater. This served our purpose well, it prevented the salt from solidifying and it kept the salt mixture in molten state. In addition to that we gave a coating of thurmalox to the heat exchanger for better collection of solar heat.

b) **Linear Fresnel Lens :** In order to heat the fabricated heat exchanger we need a linear Fresnel lens. We required a linear Fresnel lens of dimensions 1m x 1m and it was available online[16] which costs around 70 $ and it has to be shipped from USA and the shipping costs around 80 $. Hence we dropped the plan of buying it online. We began to search for linear Fresnel lens of desired dimension in Tamil Nadu and at last we got a spot Fresnel lens from a shop. Though in our project we have to use linear Fresnel lens we were able to obtain the desired temperature but the beam was a spot beam. For a small heat exchanger this spot was enough to obtain the desired temperature.

c) **Prime mover and DC generator :** We needed a steam engine or a steam turbine to convert the kinetic energy of steam generated at the boiler into mechanical energy. On surfing the internet we came across liney oscillating steam engine and a steam turbine. As for smaller output steam engines are more efficient than steam turbines we bought the steam engine online[15]. The maximum speed of the steam engine was 1000 rpm. Also we bought a 12V DC Generator which generates 40W at 8000 rpm. It was coupled with the steam engine with gear tooth assembly with gear ratio of 1:8. The heat exchanger and the steam engine was connected using tube which can withstand high temperature and pressure. A resistor and an LED was connected across the generator as a load and we obtained the desired results.

d) **Charge controller :** The output obtained from this DC generator has to be stored in a battery and it has to be inverted to AC. This is done by solar charge controller. We bought a solar charge controller from online[15] and also we bought a 7Ah battery from a local shop. We were not able to charge it continuously due to the uninterrupted steam. But we were able to obtain a minimum output of around 14V. This charge controller is connected to DC generator, a battery and the load.

e) **Working of prototype :** The block diagram of our prototype explains how it operates. The solar heat is collected using a Fresnel lens and this heat is used to heat the molten salt. The hot molten salt is stored in a hot storage tank. This molten salt is then moved to the heat exchanger where it transfers the heat to the water and converting it to steam. The salt's temperature is lowered and then it is stored in a cold storage tank. From the cold storage tank the salt is pumped to the heater where the salt temperature again increases. The steam is used to run a steam turbine and it's coupled to a generator which generates electricity. The block diagram representing our prototype is shown below : After heating the water for about 3-4

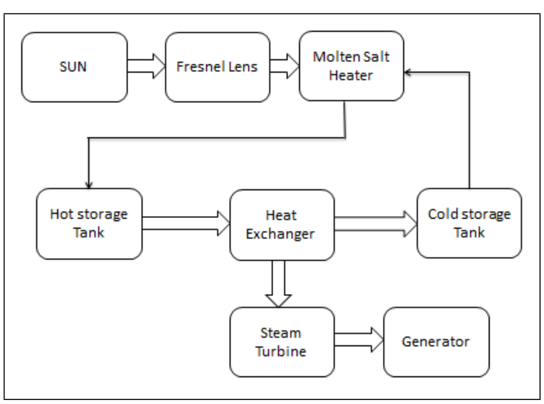

Figure 4: Block diagram representing our prototype.

hours using the Fresnel lens we were able to produce steam at high pressure. This steam was fed to the inlet valve of the steam engine. Initially the steam engine ran at a very high speed due to high pressure steam. But the speed continued to drop as the steam pressure decreased. Multimeter was used to check the output from the DC generator. We also cross checked it by connecting an LED in series with a resistor across the output terminal of DC generator.

The total cost of our project is about Rs.9,000. We are able to generate 40 Watts. And that doesn't mean that this method is expensive. If we had a better heat exchanger and a better steam engine (1 HP) we could have generated a lot more than this. But due to cost considerations we just built it as a prototype. Here we have experimentally proved that with our method generation of electricity is possible. Our complete prototype looks as below. The

Figure 5: Our complete prototype

heat can be transferred either by direct method or indirect method. Auxiliary heating can be used to avoid freezing of the salt mixture. Even our project can be implemented in a large scale using an array of Fresnel lens as shown below.

IV. RESULT AND DISCUSSION

The output obtained was measured using a multimeter and they are shown below for reference. The maximum voltage that we obtained was 14.55 V. Even though the generator's rating is 12 V due to very high speed we were able to obtain such a high voltage. As the steam pressure decreased the voltage value dropped to 10.26 V. This voltage is enough to charge the battery using the charge controller.

Installing PV Cells in our house for 1 KVA costs around Rs.1,00,000. But we estimate that our project costs only around Rs.40,000 to generate 1 KVA. And PV Cells are not reliable and if any faults occur, replacement cost will be higher. But in our case the steam engines and heat exchanger proves to be reliable when fabricated by expertise. Care must be taken when selecting the material for heat exchanger as it should not be corroded by the salt which we use. Further auxiliary heating should be provided to prevent the solidification of the salt. Trackers can be used to improve the collection of solar heat. Fresnel lens must be clean regularly for better thermodynamic efficiency. Trackers can be avoided in the case of curved linear Fresnel lens. This will also reduce the capital cost however fabrication of such lens is a tedious process.

Figure 6: Multimeter reading displays the maximum and minimum voltage.

V. CONCLUSION

This paper presents a new methodology to harness and store the solar energy to produce electricity. The prototype developed by our team has proved to be feasible and hence this can be implemented in a large scale to generate more power. As it involves less capital cost and less area when compared to photovoltaic method it can be implemented at homes for their own domestic use. Future work involves the design of a small scale Fresnel Solar power plant with molten salt which can meet a load of 1KW i.e., to meet the demand of a single household.

VI. FUTURE WORK

This paper presents a new methodology to harness the solar energy and produce electricity. The prototype developed by our team has proved to be feasible and hence this can be implemented in a large scale to generate more power. As it involves less capital cost and less area when compared to photovoltaic method it can be implemented at homes for their own domestic use. Future work involves the design of a small scale Fresnel Solar power plant with molten salt which can generate 5KW i.e., to meet the demand of a single household.

We have filed a patent in the name of our HOD and we will submit our technical data to the Patent society in the forthcoming months. After that we have planned to claim money from DRDO to implement this project in real time. Details of the patent for our project under Intellectual Property India.

VII. ACKNOWLEDGMENT

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