Thermal Analysis and Modelling of Non–Tracking Parabolic Solar Concentrator with Waste Heat Recovery

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Abstract—*It is not practically possible to get an ideal reflecting material (100% reflectivity) for the construction of solar power concentrator. Even at most, a material having a reflectivity of 0.85 can be used but it is very costly. Using readily available economic material like Aluminium, 50-60% of the incident solar radiation can be harnessed at the focus and 40% of the radiation is being wasted. In order to ensure the harnessing of maximum of the incident solar power it becomes necessary to recover the absorbed heat by applying various methods.*

This paper presents the modeling, design and development of an economical and compact non-tracking parabolic solar power concentrator which could be used for various purposes. The paper also suggests two methods for waste heat recovery based on the thermal analysis carried out on the proposed parabolic solar power concentrator.

Keywords: *Parabolic Solar Reflector, Non Tracking etc*

1. INTRODUCTION

The world is dependent upon energy. People's energy use directly correlates to their grade of healthcare, life expectancy and education. These factors determine the quality of human life. Thus the quality of human life is determined by the type of energy used. Solar is a promising renewable energy source. There are several important reasons for considering solar energy as energy source to meet the needs of developing countries. First, most of the countries called developing are in or adjacent to the tropics and have good solar radiation available. Secondly, energy is a critical need of these countries but they do not have widely distributed readily available supplies of conventional energy resources. Thirdly, most of the developing countries are characterized with arid climates, dispersed and inaccessible populations and a lack of investment capital and are thus faced with practically insuperable obstacles to the provision of energy by conventional means, for example, by electrification. In contrast to this, solar energy is readily available and is already distributed to the potential users. Electricity allows people access to refrigeration for food and medicine, energy for cooking and cleaning water, and allows people to read and study at night when there is little work that can be done outside. A small amount of electricity can dramatically change the life of a person who has had none. It is estimated that the power requirement for basic healthy functioning in rural communities is about 0.08 kWh/day/person. This is less than 1% of an average person's usage in the United States, yet many people cannot afford or do not have access to even this small amount. Many under-developed areas around the world receive large amounts of sunlight. Northern Africa and Central Asia receive as much as 7.5 kWh/m^2/day. There is great opportunity to use solar power to provide basic energy needs in these regions. The two most prominent solar energy technologies are photovoltaic (PV) and concentrated solar power (CSP). PV systems are beneficial because they can be scaled to any size, but they are costly and solely produce electricity. CSP systems can provide electricity as well as thermal power. This thermal power can be efficiently used for cooking, water distillation and absorption refrigeration cycles. The maximum development of these systems was not until 1970 due to the global oil crisis, leading to the search for alternative sources of energy such as wind, bio-fuels, solar energy, etc. There is a whole range of technological options designed to take advantage of the solar energy but only a few are popularly known, for example, the solar systems for hot water or photovoltaic systems to produce electricity. However, there are other technologies that are mature enough to be commercialized on a large scale that are unknown by most people. An example of these is the design featuring the semi-cylindrical parabolic solar concentrator. Parabolic solar concentrators are suitable for use in a wide variety of industrial processes which use thermal energy, such as dairy, processed waste, electricity, etc. An example of the application of these parabolic solar concentrators are the eight so-called solar thermal power plants SEGS-II, III, …, IX built in California, USA, with more of 2.5 million square meters of parabolic solar concentrators.

2. LITERATURE REVIEW

Elaborate investigation on solar polygeneration energy systems are predominantly on Solar Photo Voltaic Cell with Thermal (SPV/T) types. Use of expensive multi-junction SPV cells having efficiency of around 40% becomes cost effective on using a concentrator to reduce the semiconductor cell area through increase of electricity conversion efficiency which works competently if the absorbed heat by the cell plate is dissipated to some working fluid efficiently to maintain a low temperature. In this regard several choices of mono crystalline, polycrystalline, amorphous silicon (c-Si/pc-Si/a-Si) or thin-film solar cells can be incorporated in this principle using air/liquid/evaporative collectors & flat plate (glazed or unglazed) or concentrator (Parabolic Trough/dish type) with natural/forced fluid flow, and stand-alone/building-integrated features. Such an effort was made by Italian Ministry of Environment in cooperation with Israel on Building Integrated Spherical Collector (BISC) device in which it was reported that single concentrating collector produced about 70 W of electricity and 160 W of thermal energy under nominal conditions. Investigations were carried out by Bergene et.al. [1] on finding system efficiency for a physical model of a flat-plate PVT/w collector and De Vries et. El. [2] on the performance of several PVT collector designs.

Kribus et al. [3] developed a miniature concentrating PV system that can be installed on any rooftop that can be used in high latitude countries. A standalone solar thermal system comprising of a concentrator made up of low cost thin metallic reflector sheet of moderate reflectance can be visualized as a dual acting system to generate heat both at the focal point of the concentrator & by the reflector sheet itself due to irradiative solar heat absorption. A bench model of a concentrator placed in a housing of heat exchanger pipe assembly having a rear insulation cover with the focal point receiver at the aperture plane was investigated by Dr.S.K Deb & B.C.Sarma[4] to record the temperature augmentation & rear insulation effect. A maximum of 175.6^{0}C for the focal point corresponding 56.40^{0}C for the air & 86.9^{0}C for water against 33^{0}C ambient temperature recorded for a concentrator of 1040.4 mm aperture diameter. Similar study was conducted by Sarma.B.C.et.al [5] to find the collector efficiency of a typical dish concentrator generating hot air from the waste heat recovery where a rise in air temperature by 1.6915 times that of the ambient temperature was recorded experimentally.

In this proposed model, a polygeneration system absorbing solar irradiative heat giving out simultaneous thermal output of hot air, hot water, & steam is being investigated. In this model the effort of formulating collector efficiency & probable scope for serving a multifaceted low to moderate temperature sectors are envisaged. Unlike glazed & unglazed solar air heater, the collector as a meant for, is not necessarily be a flat plate collector with non-tracking mode of orientation. The temperature limitation in a flat plate collector is a compromise of its simplicity in all design aspects inclusive of non-tracking mode. Its popularity for domestic heat at low temperature range and structural compatibility with the building roof etc has made a good potential ground for design improvisation & market penetration.

3. MODEL CONSTRUCTION

The solar concentrator used in this project is a non-tracking parabolic solar reflector. The solar radiation incident on the reflector surface is concentrated at its focus. Steel sheets were used to make the surface of the solar reflector. These sheets are easily available and economical. The frame of the concentrator is made of hollow Aluminium pipes.

Lune method is used to develop the surface of the solar reflector into the required parabolic shape. The method is described below:

1. A sphere may be divided into twelve lunes, one of which is shown in the front view in Fig. 5.1. The semi-circle **qr** is the top view of the centre line of that lune. It is evident that the length of the lune is equal to the length of the arc **qr** and its maximum width is equal to **gh**.
2. We divide the semi-circle into a number of equal parts say eight and we project the division points on the front view to points **1´**, **2´**, etc. Taking **q´** as centre and radii equal to **q´1´**, **q´2´** and **q´3´**, we draw arcs **ab**, **cd** and **ef** which will show the widths of the lune at points **1** and **7**, **2** and **6**, and **3** and **5** respectively.
3. We then draw a line **QR** equal to the length of the arc **qr**. This may be obtained by stepping-off eight divisions, each equal to the chord- length **q1**.
4. After that we draw perpendiculars at each division-point and make **AB** and **MN** equal to **ab** at points **1** and **7**, **CD** and **KL** equal to **cd** at points **2** and **6** etc. Then we draw smooth curves through points **Q**, **A**, **C** etc. The figure thus obtained will be the approximate development of one-twelfth of the surface of the sphere. [8]

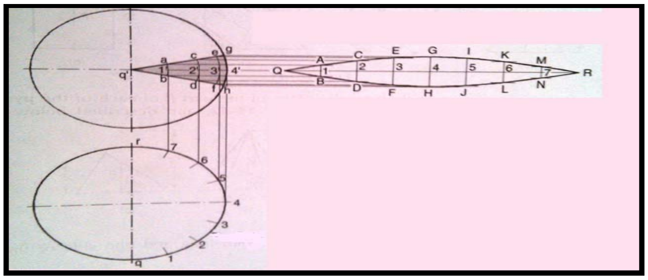

Fig. 1: Lune Method

4. THERMAL ANALYSIS

4.1 Experimental Set up

Fig. 2: Experimental Set up

As seen in the figure above the experimental setup consists of the solar concentrator, a glass plate, an insulator and the support. The concentrator is placed in the sun and then the required thermal analysis is carried out. The incident solar radiation is made up of electromagnetic waves. The glass plate is used so that it traps the radiation once it is reflected by the concentrator. The energy of any electromagnetic radiation is given by

$$E=h\nu$$

$$\text{Or, } E=hc/\lambda$$

where, E=Energy, h=Plank's constant, ν=frequency, λ=wavelength

4.2 Procedure

- Once the setup is installed temperatures of the focus, the reflector surface and the ambient temperature are determined using a TESTO digital thermometer.
- The ambient temperature on any given day remains uniform throughout the duration of the experiment.
- Two thermometers are used to determine the temperatures at the focus and the surface simultaneously.
- Readings are taken after roughly uniform intervals of time.

Fig. 3: Experimental setup for determination of focus temperature

4.3 Result

The following temperatures were obtained during the experiments:

Date: 26/08/14 Time: 12:10-2:00 PM

Serial No	Readings without glass cover and insulation		
	T(Ambient) ˚C	T(Surface) ˚C	T(Focus) ˚C
1	36.3	67.9	159.7
2	36.3	67.3	160.3
3	36.3	66.9	160.2
4	36.3	67.7	160.2
5	36.3	67.4	160.3
6	36.3	67.6	160.1
7	36.3	67.6	160.3
8	36.3	67.6	159.6
9	36.3	67.3	158.6
10	36.3	67.9	160.1

Date: 18/08/14 Time: 12:30-2:25 PM

Serial No	Readings with glass cover and without insulation		
	T(Ambient) ˚C	T(Surface) ˚C	T(Focus) ˚C
1	34.6	64.4	117.7
2	34.6	63.6	107.6
3	34.6	62.9	119.2
4	34.6	63.2	118.1
5	34.6	64.1	117.4
6	34.6	62.3	114.4
7	34.6	62.4	114.5
8	34.6	62.8	115.2
9	34.6	63.2	108.6
10	34.6	62.9	112.9

Date: 30/09/14 Time: 11:10 AM – 01:10 PM

Serial No	Readings without glass cover and with insulation		
	T(Ambient) ˚C	T(Surface) ˚C	T(Focus) ˚C
1	35.4	45.2	116.3

2	36.3	45.8	119.6
3	36.6	51.7	118.4
4	36.5	51.5	122.7
5	36.5	51.9	117.3
6	36.6	52.5	119.4
7	36.6	52.2	119.2
8	36.6	51.7	119.3
9	36.6	51.5	118.2
10	36.6	52.6	120.4

Date: 29/10/14 Time: 12:30-2:35 PM

Serial No	**Readings with glass cover and insulation**		
	T(Ambient) ˚C	**T(Surface) ˚C**	**T(Focus) ˚C**
1	33.4	52.3	108.7
2	33.7	52.5	114.0
3	34.2	63.5	142.0
4	34.2	64.6	143.6
5	34.5	64.7	144.4
6	34.2	64.4	144.8
7	34.2	64.6	144.9
8	34.2	64.3	144.2
9	34.2	64.6	136.5
10	34.2	64.6	140.9

4.4 Inference

- A temperature range of 107.6-160.3°C is obtained at the focus.
- A temperature range of 45.2 -67.9 °C is obtained at the surface.
- Maximum focus temperature: 160.3°C
- Maximum surface temperature : 67.9°C

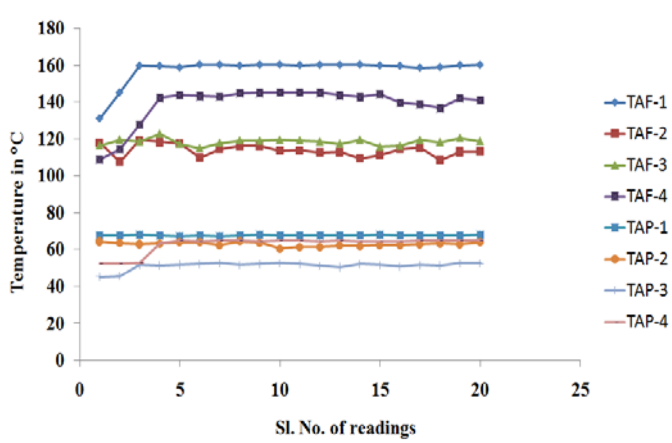

Fig. 4: Graphical representation of temperatures obtained

5. WASTE HEAT RECOVERY

The thermal energy that can be harnessed by a solar reflector depends on the reflectivity of the material used to develop the surface. In an ideal case, the reflector will have a reflectivity of 100%, i.e. the entire energy incident on the plate is concentrated at the focus and the entire incident solar energy can be harnessed. However it is practically impossible to use a material having 100% reflectivity.

This means that the entire incident energy is not accumulated at the focus. A part of the energy is concentrated corresponding to the reflectivity of the surface. The remaining energy is absorbed by the surface and transmitted to the atmosphere. This energy is termed as "Waste Heat" as it is not being used for any application and released into the atmosphere. Waste heat Recovery deals with the recovery of this waste heat and its use in some suitable applications.

In this project, for the purpose of Waste Heat Recovery, the temperature range that can be achieved on the reflector surface was first determined. As seen from the data given in the previous section the temperature range obtained in the reflector surface was 45.2-67.9°C. Subsequently, applications corresponding to this temperature range were searched and the following two applications are suggested:

1. Water pre-heating
2. Solar air heating

Water pre-heating: Normal solar water heaters use the temperature achieved at the focus to heat water. In this project as seen from the thermal analysis results, a temperature range of 107.6-160.3°C was obtained at the focus. This entire temperature range is above the boiling point of water at room temperature. On most days the focus temperature obtained was between 130-150°C. This temperature can be easily used to get steam from water. For this a simple arrangement can be used consisting of a pipe which is placed across the focus. The water going through one end will come out of the other end as steam.

Fig. 5: Aluminium pipe framework

In this arrangement the water which enters the system is at room temperature and the entire heat required to achieve the boiling point temperature is taken from the focus. However if the water before passing through the focus is run across the reflector surface, it will absorb the surface heat before going through the focus. This will increase the temperature of the water and reduce the heat taken from the focus. This in turn will increase the mass flow rate of water passing through the focus.

This arrangement for water pre-heating is present in the model used in this project. As mentioned in the construction of the solar concentrator the frame is made with the help of hollow Aluminium pipes. The pipes are connected to the surface. The water is run through the entire pipe network before it goes through the focus.

Thus this arrangement makes use of the heat that was previously wasted together with the energy that is concentrated at the focus.

Solar Air Heating: Solar air heating systems based on flat plate collectors have been found to be useful in food processing industries for drying of various food products. These industries generally require hot air at low temperature (35-80°C) as process heat for drying of products such as tea leaves/ coffee beans, and also for processing of fruits, spices, cereals, mushroom, papad, vegetables, fish, seafood etc. Hot air is also required in industries such as leather, textiles, chemicals, rubber, paper, pharmaceuticals etc. It is estimated that over 800 million kg. of tea leaves are being produced and dried in Southern states, Himachal Pradesh, West Bengal, Assam and North East States. Another 250 million kilograms of coffee beans are also being produced and dried every year. Millions of tons of food and industrial products are also being dried annually in various industries in the country.

Setting food outside to dry takes longer time, up to a week for some types of produce. And it never dries out as well as we would like for longer-term preservation. Fruit acids want to reabsorb moisture, and produce rehydrates at night when the sun is out of sight. That is not even considering the effects of rain and daytime humidity. Moreover, the longer it takes to dry our food, the more nutrients leach away from it. Drying is a process which deals with the removal of water or moisture through evaporation from a solid or a semi solid material. During the drying of a wet material, two processes are taken place. First the heat energy is transferred from the surrounding to the material to evaporate the moisture from the outer surface creating a moisture gradient close to the surface. Once the surface moisture is removed from the material, the second process begins and internal moisture is transferred to the surface via diffusion and is removed due to the first process. The rate of the drying process is governed by the rates of these two processes. The removal of moisture from the surface of the material depends on the external factors such as temperature, relative humidity, surface area of the material, pressure and the internal transfer of moisture depend on the internal factors of the material such as physical nature of the material, temperature and the moisture content and its gradient. It is widely being employed to improve the shelf life of organic materials such as food items by reducing the moisture content up to which the microorganisms cannot survive. Drying of grains such as paddy will improve the shelf life and hence longer storage periods can be achieved.

The following table shows the drying air temperature of some common food products [9]:

Sl. No.	Product	Moisture Percent		Drying Air Temperature
		Initial	Final	
1	Bananas	80	15	70
2	Garlic	80	4	55
3	Onions	80-85	8	50
4	Rice	25	12	43
5	Tea	75	5	50
6	Wheat	18-20	11-14	43-82

Similar application can be undertaken with the help of the parabolic solar power concentrator. The air can be passed through the Aluminium pipes or heating. As seen from the thermal analysis the surface temperature range (45.2-67.9°C) corresponds mostly to the required temperature range.

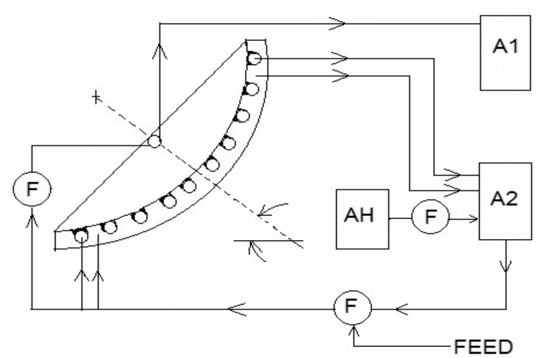

Fig. 6 (A): Block Diagram (1)

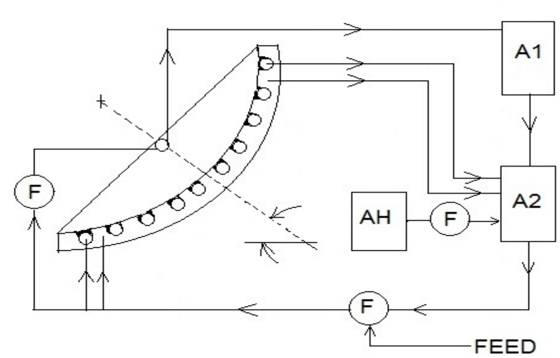

Fig. 6 (B): Block Diagram (2)

A1 and A2: Applications
AH: Auxiliary Heater
F: Fan

The rate drying of food products will depend on the moisture content of the air. The moisture content of the air heated by the surface heat will decrease and then it can be used for drying purposes.

The diagrams below are some suggestive block diagrams showing how solar concentrators can be used for drying purpose.

The air can be fed through the pipes forming the frame and touching the reflecting sheets. Thus it takes up a large portion of the heat absorbed by the sheets and gets heated up to a higher temperature. Further the heated air can then be passed through the focus of the concentrator where owing to the very high temperature it can be heated to a much high temperature if needed. Otherwise the waste heat can be directly used for heating and the energy at the focus can be used for other purpose.

6. CONCLUSION

This project deals with the thermal analysis of an economically viable non-tracking parabolic solar power concentrator. The prototype is made of cheap and easily available material. Experimental determination of temperature profiles so far has shown a focus temperature range of 107.6°C to 160.3°C and surface temperature range of 45.2°C to 67.9°C. Two applications suggested for waste heat recovery are water preheating and solar air heating for drying of food products. The temperatures that have been achieved with this prototype have been limited by the errors in the construction of the parabolic reflector surface. A qualitative analysis of the solar concentrator system has been carried out with suggestions for waste heat recovery. The project has proven helpful in providing a better understanding of a solar concentrator system.

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