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# Circular Assembly of Reflector and Absorber for Solar Steam Generation (CARA-SSG)

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**Abstract: This paper deals with harnessing of the solar insolation using a specific variant of the Parabolic Trough Solar Reflector (PTSR) to adapt it for generating steam of particular quality suitable for small scale applications. The major drawbacks of PTSR are that continuous parabolic mirrors are difficult to design and fabricate thereby increasing the first cost. In light of these impediments, the Circular Trough Solar Reflector (CTSR) is a cost effective and viable alternative to PTSR. Acrylic mirrored sheets are used which can be shaped as desired and are fixed on a circular PVC trough. Also it has the ability to continuously track the sun from sunrise to sunset, a feature which is unavailable in PTSR as it leads to shading and blocking which is a non-issue in CTSR. The circular trough is suspended from the central copper tube carrying the water with the aid of cables which provides a 'swing-mechanism', which allows continuous tracking for maximum possible insolation. The trough can be clamped at any point along the circumference by anchoring it to the ground using cables and hooks. In accordance with the afore-mentioned objective, the notable results are net solar energy absorbed by the copper tube (=55412.21 kJ), mass flow rate of steam (= 6.82 kJ/hr) and efficiency of the system (= 36.07%). The efficiency of the system is better than any other form of solar thermal system at this scale and the steam characteristics are suitable for use in household applications, hospitals, agriculture and food processing amongst others.**

**Keywords: Parabolic Trough, Acrylic Mirror Sheet, Solar Tracking, Insolation, Solar Collector, Copper Tube.**

## INTRODUCTION

Energy is the primary and most universal measure of all kinds of work by human beings and nature. Everything that happens in the world is an expression of the flow of energy in one of its forms. Most people use the word 'energy' for input to their bodies or machines and thus think about crude fuels and electric power [1].

Energy is an important input in all sectors of any country's economy. The standard of living of a given country can be directly related to per capita energy consumption. The energy crisis is due to two reasons – Firstly, the population of the world has increased rapidly and secondly, the standard of living of human beings has increased. If we take the annual per capita income of various countries and plot them against per head energy consumption, it will appear that the per capita energy consumption is a measure of the per capita income, and thus, a measure of the prosperity of the nation [1].

The world population at the turn of the year 2011 has reached over 7 billion and with more and more growing economies like India and China, there has been an unprecedented energy demand. Fossil fuel reserves are dwindling worldwide and as they take millions of years to form, they are unable to cope with this ever increasing demand. Thus the need of developing alternative energy solutions is necessary for a sustainable future. The major alternative energy sources are solar energy, hydroelectric energy, nuclear energy, wind energy, geothermal energy, ocean thermoclines and waste heat recovery. At present, hydroelectric and nuclear power seem to be the most promising solutions to the existing crisis. However, the enormous potential of the sun is something which cannot be overlooked.

Numerous techniques have been developed to harness this tremendous power. They can be broadly classified under two headings – solar photovoltaic and solar thermal [2]. Though rapid strikes have been taken towards progress in the field of photovoltaics, it remains a costly affair and is unfeasible for large scale energy generation. On the other hand, solar thermal offers a relatively cheaper and more efficient means of energy generation. This project highlights the use of one particular type of solar thermal mode of harnessing solaparabolic trough system [3].

## METHODOLOGY

"With great power comes great responsibility."

Although it seems that the sun is an infinite source of power, we are yet to develop responsible means to harness it with respect to economy, feasibility and efficiency. This is the main problem which is underlying all endeavors taken up in this field. This effort, though on a much smaller scale, must also address this problem.

The aim of this system is to generate steam of a particular quality suitable for domestic and small scale applications by focusing the solar insolation with the help of a circular trGough reflector onto copper tube carrying water at certain pressure and temperature. To achieve this, following objectives have to be fulfilled –

- Calculation of insolation at the site of system installation.
- Setting a reference quantity and characteristics of steam which is desired to be generated.
- Designing a system capable of meeting the reference output.
- Theoretical calculation of temperature and pressure of the output steam to compare it with the set reference.
- Finally, calculation of the efficiency of the system.

**Design:** A quadrant of a cylindrical pipe of radius 2m, length 1.5m and thickness 4mm is used as the reflector frame upon which continuous acrylic mirror sheet having an area equal to the surface area of the quadrant is fixed. This frame is now suspended from a copper tube of length 2m, whose axis coincides with the axis of the cylindrical pipe, with the help of strong cables to provide it with a 'swing-mechanism' which enables it to swing about the center along the circumference of the cylindrical pipe for continuous solar tracking as shown in Figure 1. This allows all the insolation on the reflector surface to be concentrated along the central line of the tube. The copper tube is supported on two columns on either side having a height of 2m. These columns are of a material strong enough to withstand the complete load of the system. The columns are erected on a concrete base with bearing plates in between aided by angle plates which are clamped to the bearing plates by nuts and bolts. The back of the frame is provided with three hooks and with the use of cables can be used to anchor the trough at any position along the path of rotation of the frame.

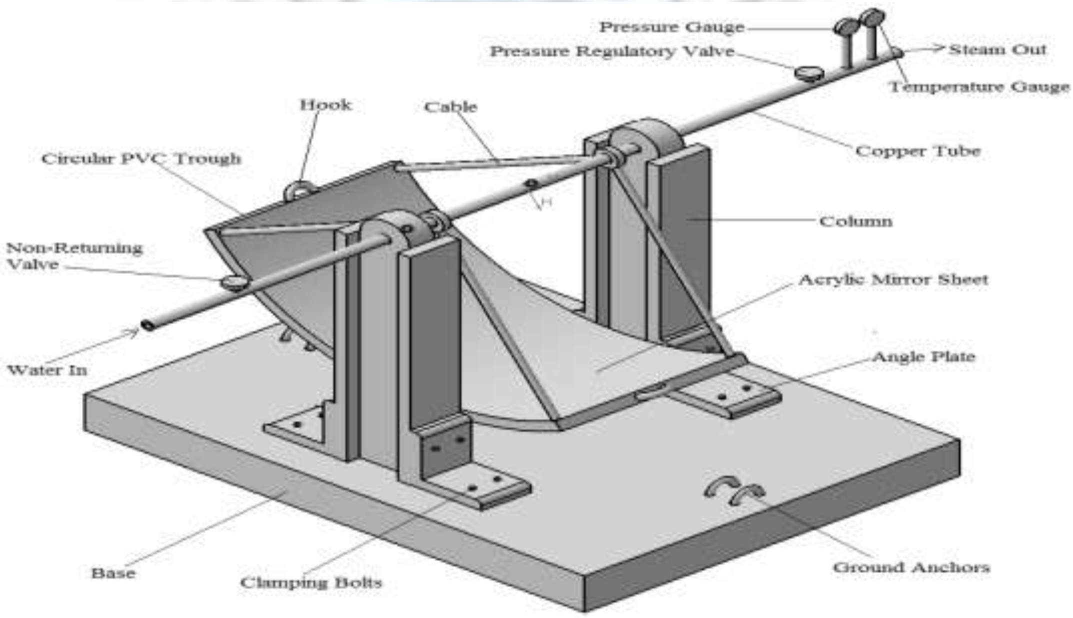


Figure 1 - CATIA V5R18 Model of CARA-SS

**Working:** Pre-heated water at 60˚C and atmospheric pressure enters the copper tube using a pump. Flow rate is maintained with the help of non-returning valve. Insolation on the reflector is concentrated on the copper tube which in turn converts it into heat raising the temperature of the water flowing inside it. On sufficient heating, it gets converted into steam whose outlet pressure is measured with the help of a pressure gauge and it is kept at that pressure with the aid of a pressure regulatory valve. The temperature gauges are also fixed on the inlet and outlet of the setup. The outlet steam then flows into a steam collector. Depending upon the steam characteristics, its uses are determined.

## MATERIALS

Taking into account the properties of various materials, the following are selected for CARA-SSG:

- **Circular Trough or Frame –** PVC sheet is used, which is cut in the form of a circular quadrant. Polyvinyl chloride (PVC) is used here because of its light weight, high durability, easy workability & formability and low cost. It can be made softer and more flexible by the addition of plasticizers, the most widely used being phthalates [4]. In this form, it is used in clothing and upholstery, electrical cable insulation, inflatable products and many applications in which it replaces rubber [5].

- **Acrylic Mirror Sheet –** Instead of using highly finished parabolic mirrors which are very heavy and costly, a better alternative in the form of acrylic sheet is used. The setting up of parabolic/flat mirrors on the frame, makes the design very complicated and is extremely time consuming. The acrylic sheet used here is of high quality (95% reflectivity of a highly finished mirror). Acrylic sheets are very tough and they have a protective back coating which protects it against scratching during fabrication and working. Mirror grade acrylic sheets are 100 times stronger than the glass fabrication, but when doped with polycarbonates, its weight reduces significantly and it becomes 200 times stronger than glass. Practically, the average weight of a mirror grade acrylic sheet is upto half of the weight of an average glass panel[6].

- **Copper Tube –** K type copper tubes are used for providing a passage to the flowing water, so that the water gets converted to steam inside it through the process of solar heating. Copper tubing is most often used for supply of hot and cold water, and as refrigerant line in HVAC systems. Copper offers a high level of resistance to corrosion. Rigid copper is a popular choice for water lines. It is joined using a sweat, compression or crimped/pressed connection. Copper tubes have one of the highest tolerances amongst other metals and consistent dimensions throughout the tube length. These tubes are compatible to transfer heat in a wide variety of conditions. Moreover, there's a high availability of seamless drawn copper tubes in half hard temper and a variety of diameter and wall thickness combinations [7] [8].

- **Pressure and Temperature Gauges** – Pressure gauges and temperature gauges are used at specific places which serves the purpose of pressure and temperature measurement. The pressure gauges will have dual graduations with psi and graduation in feet of water per meters of water, with an error limit of 1-1.5%. Bi-metallic temperature gauges are also installed for temperature measurement. These have a quick reacting bimetallic coil which helps in accurate temperature readings [9].

- **Valves –** There are two types of valves which are to be used in the setup, namely pressure regulatory valve and non-returning valve. These are used to regulate the pressure of the flowing water inside the setup (tubes). There is additional feature of thermal expansion bypass in the regulatory valves [10]. Non-returning valves in the form of ball valves, butterfly valves, plug valves etc. are used [11].

- **Column –** The columns used in this setup are of ISLB-150 type (I-section). This type of column is used because of its appropriate weight per meter length (14.2 kg/m) [12]. The specific use of I-section type bars is due to the reason that, the vertical element called the web resists the shear forces while the flanges resist most of the bending moment experienced by the beam. ISLB stands for Indian Standard Long Beams. 150 is the depth of the section in millimeters. The flange width is 80 mm, flange thickness is 6.8 mm and thickness of web is 4.8mm [12]. These dimensions are according to the proper strength considerations for the required load carrying purposes.

- **Cables –**Stationary steel ropes are used in the setup, which act as suspension cables for the trough [13]. The endurance of these wire rope steel cables is very high and is of light weight which serves the design purpose of the above setup. They also impose less resistance to rotation and are highly cost effective.

- **Bearing plates** – Steel bearing plates are used in the setup for giving a platform support to the vertical columns. Bearing plates are used to transfer the column forces to the concrete base.

- **Angle plates –** High quality grain cast iron (FG220) angle plates are used in the setup. These angle plates ensure rigidity and stress relieved by artificial seasoning.

- **Pump –** Multi-staged horizontal pressure booster pumps are used for maintaining the proper mass flow rate of water. These are economical and easily available in the market.

- **Miscellaneous –** The other parts that are to be used to complete the construction are, clamps, nuts, bolts, male and female hoses etc.

## RESULTS

### Solar Energy Incident

**Specified Data:**
Length of Circular Trough, L = 1.5 m
Inner Radius of Circular Trough, $R_i$ = 2 m
Thickness of Circular Trough, t = 4 mm
Outer Radius of Circular Trough, $R_o$ = 2.004 m
Length of Copper Tube = 2 m

Inner Diameter of Copper Tube, $d_i$ = 16 mm
Outer Diameter of Copper Tube, $d_o$ = 20 mm
Insolation in BIT Patna = 4 kWh/$m^2$
Reflectivity of highly finished mirror = 0.90
Absorptivity of Copper Tube = 0.95

**Calculations:**

Surface Area of Trough, $$A = \frac{\pi R_i L}{2} = 4.71\ m^2 \quad (1)$$

Reflectivity of Acrylic Sheet = 95% of the reflectivity of highly finished mirror = 0.86
Total solar energy reflected by trough in 1 hr $= 0.86 \times 4.71 \times 4 \times 60 \times 60 = 58328.64$ kJ
Total solar energy absorbed by the tube in 1 hr $= 0.95 \times 58328.64 = 55412.21$ kJ

**Steam Characteristics**

**Specified Data:**

Temperature of preheated water at tube inlet, $T_{in}$ = 60˚C
Temperature of superheated steam at tube outlet, $T_{sup}$ = 250˚C
Pressure of superheated steam at tube outlet, $P_{sup}$ = 10 bar
Specific heat of steam, $c_{p_s}$ = 2.20 kJ/kg˚C
Enthalpy of steam at 180˚C, $h_g$ = 2776.20 kJ/kg
Temperature of saturated water at 10 bar, $T_s$ = 180˚C
Specific heat of water, $c_{p_w}$ = 4.18 kJ/kg˚C
Density of Water, $\rho_w$ = 1000 kg/$m^3$
Density of Steam at 10 bar and 250˚C, $\rho_s$ = 4.75 kg/$m^3$
Inner Diameter of Copper Tube, $d_i$ = 16 mm

**Calculations:**

Heat required in raising the water to saturation temperature at 10 bar,
$$h_w = c_{p_w}(T_s - T_{in}) \quad (2)$$
$$= 4.18 \times (180 - 60) = 501.6\ kJ/kg$$
Latent heat of vaporization, $h_l = 2260$ kJ/kg
Enthalpy for superheated steam,
$$h_{sup} = h_g + c_{p_s}(T_{sup} - T_s) \quad (3)$$
$$= 2930.40\ kJ/kg$$

Net amount of heat required to be supplied, $$q_t = h_w + h_l + h_{sup} \quad (4)$$
$$= 5692\ kJ/kg$$

Mass flow rate of water, $$\dot{m}_w = \frac{\text{Total energy absorbed by the tube}}{\text{Net amount of heat required to be supplied per kg}} \quad (5)$$
$$= \frac{55412.21}{5692}$$
$$= 9.74\ kg/hr$$
Considering 30% losses,
Mass flow rate of steam,
$$\dot{m} = 0.70 \times 9.74 = 6.82\ kg/hr$$
Area of flow of water,
$$A = \frac{\pi}{4} \times d_i^2 \quad (6)$$
$$= 2.011 \times 10^{-4} m^2$$
$$\dot{m}_w = \rho_w \times A \times v_w \quad (7)$$
or, Velocity of Inlet Water,
$$v_w = \frac{\dot{m}_w}{\rho_w \times A} = \frac{9.74 \times 100}{1000 \times 2.011 \times 10^{-4} \times 3600}$$
$$= 1.34\ cm/s$$

Velocity of Outlet Steam,

$$v_s = \frac{\dot{m}}{\rho_s \times A} \quad (8)$$

$$= \frac{6.82}{4.75 \times 2.011 \times 10^{-4} \times 3600}$$

$$= 1.98 \text{ m/s}$$

**Efficiency of CARA-SSG**

Since the output steam is not being used to produce any mechanical work, the work output, W can be calculated by equating it to the heat content of the output steam. Therefore,

$$\eta_{thermal} = \frac{W}{Q_{in}} \quad (9)$$

$$W = \dot{m} \times h_{sup} \quad (10)$$

$$= 6.82 \times 2930.40 = 19985.33 \text{ kJ/hr}$$

$$Q_{in} = 55412.21 \text{ kJ/hr}$$

$$\text{or, } \eta_{thermal} = \frac{19985.33}{55412.21} = 0.3607 \text{ or } 36.07\%$$

## DISCUSSION

CTSR is a variant of the parabolic trough system. In this model, following improvements have been made to make CTSR a cost effective and viable system to meet the energy demands of domestic and small scale enterprises:

- Instead of parabolic geometry of the frame, a circular geometry is used which affords simpler design and ease of fabrication.
- Compared to other types of solar collectors like CLFR and heliostats, CTSR captures a larger solar incidence with equivalent receptive area.
- Unlike solar collector arrangements for large scale power generation, CTSR avoids any form of shading and blocking as the units are arranged in series [14].
- Higher temperatures are reached for equal insolation as compared to other types of collectors.
- The two greatest drawbacks of parabolic trough system were the design and fabrication of continuous parabolic mirrors and the steel structure on which the entire mirror is supported which has to be continuously aligned with the path of the sun using an electronic tracking device. This makes the whole affair heavily stressed, capital intensive and complex to operate & maintain.
- CTSR takes care of these problems partly due to the ingenuity of the design and also because of its small scale approach. Firstly, the problem of the heavy and expensive parabolic mirrors is dealt with by replacing them with low cost, light weight and more durable acrylic mirror sheets. Though they have a reflectivity of about 95% of the parabolic mirrors, it is well compensated by its other advantages, especially, for a small scale system. Secondly, the complex tracking system is replaced by a much simpler method which can track the sun's path from sunrise to sunset. This is achieved by a swing-set mechanism.

The theorized results are in direct concordance with the improvements mentioned above.

**Applications**

The steam characteristics indicate that the applications of the steam generated by the system are akin to low pressure steam applications. Thus, the steam generated can be used in various applications ranging from sterilization in hospitals, microbiology laboratories to preserving food in food processing units. It can also be used in agriculture for soil sterilization and improving soil health. Steam is also a very effective lifting gas as it is not flammable unlike hydrogen and is cheap and abundant unlike helium. It has also domestic uses such as solar cooking, heating swimming pools, steam cleaning of fabrics & carpets and 'steam showers'.

## CONCLUSION

Considering its small scale purpose, CARA-SSG surpasses any other solar devices used for steam generation. The disadvantages of PTSR and irregularities of Scheffler concentrator are easily dealt with because of its simple construction, ease of fabrication, high durability, light weight, compactness and low cost. It affords much simpler tracking for the entire path of the sun from sunrise to sunset which is not possible in any other solar collectors like CLFR and PTSR due to high shading and blocking. The efficiency of the CARA-SSG is about 36% which is far more than any such system involving fossil fuels which have a mere efficiency of 19%. Moreover, the large scale version of the system can be easily realized by just connecting similar setups in series.

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