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Solar Energy Collection Using an Absorber with a Thermal Compensator

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Abstract: *A fairly steady power output solar-thermal energy collector to produce steam has been fabricated and tested. The basis of this study was the fact that most solar collectors do not give steady energy output due to fluctuations in solar intensity. A Parabolic Dish Solar Collector (PDSC) was constructed and an absorber was positioned at the focus. Water was made to flow through a narrow pipe in and out of the absorber so as to absorb heat energy. The absorber had a temporary thermal storage component consisting of a Phase Change material (PCM) which would gain latent heat of fusion at the melting temperature and then release the same quantity of heat during solidification. This heat storage-recovery mechanism acted as a thermal compensator in the absence of intense radiation. The maximum efficiency of the system with thermal compensator was found to be 44.82% while that of non-compensated system was 11.60%. The thermal compensation effect was tested by simulating a cloudy condition by temporarily obstructing the solar beam and then measuring the energy output. The Solar Energy Device (SED) was found to give stable and reliable power output during the solar harvesting period.*

Keywords: *Parabolic Dish Solar Concentrator (PDSC), Phase Change Material (PCM), Thermal Compensator, Solar Energy Device (SED)*

I. Introduction

The rapidly growing population of the world is overstretching the finite energy resources while replenishment by biomass cycles and fossilization is not near commensurate with the energy demand [1]. More so the continued use of conventional fuels is greatly degrading the environment by CO_2 emission resulting to unsustainable energy balance and accrued economic losses [2]. Governments across the world are legislating policies that encourage the use of green energy with a new focus on renewable energy [3]. In the U.S.A, the world's the leading country in renewable energy production; only 7% of its energy demand is generated from renewable sources with the rest coming from petroleum, natural gas, coal, and nuclear power in the order of decreasing dependency, Fig. 1.

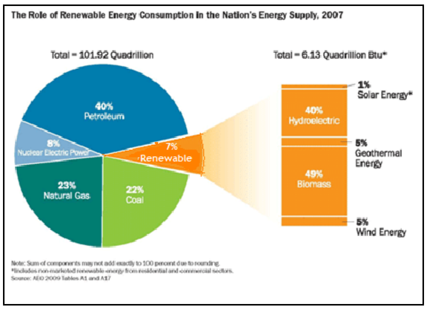

Figure 1: Energy Sources in the U.S.A [Source - Classroom energy 2014]

Even with today's higher energy costs, the nonrenewable energy sources are generally more reliable, affordable and easier to store and transport than renewable energy resources. For renewable energy use to become more widely used, many technical hurdles must be overcome. Most hurdles have to do with the efficiency of tapping renewable energy, as well as producing and distributing renewable energy more reliably and economically [4]. The major reason for the low level of exploitation of solar energy is because solar flux is dispersed in nature, intermittent, unpredictable and only available during the day. The other prohibiting factor is the high capital investment required in construction, and solar tracking cost of solar harvesting devices. For these reasons, a Parabolic Dish Solar Collector (PDSC) with a thermal compensator was designed to harness beam radiation from the sun and produce steam for various applications. Made from locally available materials and with a component of temporary heat storage, the PDSC is relatively cheap to construct and gives steady energy output compatible with conventional energy needs [5], [6]. The temporary thermal storage requires large quantities of matter with high specific heat capacity or high latent heat of fusion, where phase change materials (PCMs) are used. High volumetric heat capacity is desirable because it leads to lower storage system size which reduces the structural costs and enhances energy concentration ratio. A comparison between latent and sensible heat storage shows that when latent heat storage is used, storage densities of 5 to 10 times higher can be achieved [7]. This is because the molten material has more energy per unit mass than the solid material.

II. Theory

A small receiver area is necessary in order to achieve a high concentration ratio of any solar energy device (SED).The overall heat capacity of receiver components can only be small owing to the small size of the absorber and hence cannot make up for lost heat during cloud cover. Much in the same way that an electric cooker requires a heavy metallic plate for heat capture and recovery or a flywheel of a motor vehicle engine to give continuity of motion, there is need to have temporary energy storage so as to give a steady and reliable supply during absence of radiation [5]. A medium with high energy storage density is desirable because it leads to lower storage system size, reducing the structural costs and enhancing the energy concentration ratio. Besides the density and the specific heat of the storage material, other properties are important for sensible heat storage which includes: operational temperatures, thermal conductivity and diffusivity, compatibility among materials, chemical and physical stability and cost.

Among the most outstanding thermal storage concepts that are commonly employed in heat storage and recovery systems include: Thermal storage using water tanks, which takes advantage of the high heat capacity of water compared to other sensible heat storage materials [8], thermo-chemical heat [Glaumber's salt] where the heat storage material is a hydrated salt which loses the water of crystallization in a heat-seeking (endothermic) reaction. The same quantity of heat is released when the salt becomes hydrated in a heat-releasing (exothermic) reaction [9]. Phase changing materials (PCM) which make use of the latent heat of fusion/vaporization of salts or metals [10] is also a popular concept. PCMs are latent heat storage materials. As the source temperature rises, the chemical bonds within the PCM break up as the material changes from solid phase to liquid phase. This is a heat-gaining process while the bond formation (liquid phase to solid phase) is a heat-releasing process which provides the heat recovery mechanism of the system.

The ability to store thermal energy is given by:

$$A = \frac{Q_s}{V} = \frac{mC_p\Delta T}{V} = \rho C_p \Delta T \qquad (1)$$

Where m is the mass of storage material in kg, Q_s is thermal energy calculated from the heat capacity, V is the volume in m^3, ρ is the density in kg/m^3.

Thermal energy storage can be classified in terms of the storage mechanism (sensible, latent or chemical) or by storage concept (active or passive). Thermal storage can utilize sensible or latent heat mechanisms or heat coming from chemical reactions. Sensible heat is the means of storing energy by increasing the temperature of a solid or liquid. The latent heat, on the other hand, is the means of storing energy via the heat of transition from a solid to liquid state for melting process or transition from liquid to gas for vaporizing materials. Latent heat storage (LHS) is more attractive than sensible heat storage (SHS) because it is possible to store large amounts of heat with only small temperature changes and therefore has a high storage density. Also the change of phase occurs isothermally and takes some time to complete thus making it possible to smooth temperature variations [11], [12]. LHS therefore has the ability to maintain near isothermal conditions during the heat recovery process. However, many practical problems are encountered with LHS owing to low thermal conductivity and variation in thermo-physical properties under extended cycles of phase transition [12]. The choice of a good PCM depends on technical aspects particular to the solar energy system. However a good PCM should have desirable characteristics. It should have a high latent heat effect i.e. high latent heat of fusion per unit volume such that the required volume of the container to store a given amount of energy is small. The phase change must be reversible over very large number of cycles without degradation, with the melting point being in the desired operating temperature range. High specific heat capacity provides for additional significant sensible heat storage. High thermal conductivity of PCM in both solid and liquid phases makes it effective in charging and discharging of energy. It should have small volume changes upon phase transformation and small vapour pressure at operating temperatures so as to reduce the containment problem. The material must be chemically stable and non-toxic, non-corrosive to the construction materials and of reasonable cost. Physically and chemically stable salts that are cheap and readily available such as NaCl have been used as thermal storage materials though at a reservoir away from the receiver. The compounds have low mass density necessitating big volumes of material which cannot be accommodated at the receiver. A proportion of thermal energy is lost during transportation of the HTF to the reservoir thus compromising efficiency. Furthermore such stable ionic compounds melt at very high temperatures ($NaCl = 802^oC$, $MgCl_2 = 800^oC$) which are unattainable in the moderate temperature concentrators. The 60Sn/40Pb alloy which is a eutectic mixture that melts at 172°C was preferred as it is within attainable moderately high temperature. Although the alloy has a relatively lower specific latent heat of fusion compared to other alternatives cited here, it has the advantage of high mass density and hence can act as a good thermal reservoir. It also has better thermal conductivity which enhances heat transfer. At optimum operating temperature the PCM is in the liquid state and thus preserves the latent heat of fusion and a buffer temperature can be established as the cooling curve of Sn/Pb shows in Fig. 2. This acts as a thermal compensator and when incorporated in the absorber can address the problem of smoothing out energy.

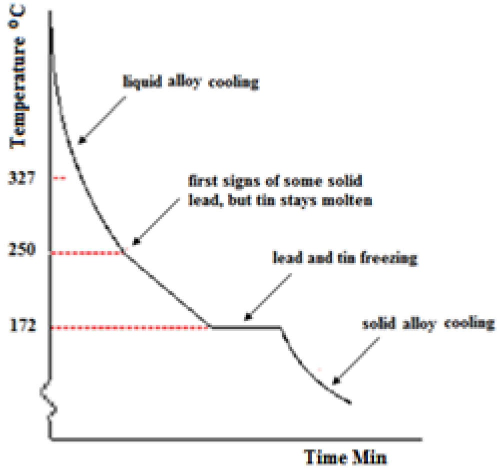

Figure 2: Cooling curve of 60Sn40Pb alloy [Source -www.chemguide.co.uk]

Steam generating Parabolic Dish Receivers (PDRs) have the challenge of transporting thermal energy to the converter or storage medium without much loss [13]. Every energy transformation is accompanied by some energy loss and hence the need to harvest solar energy through the most direct end use process. Fig. 3 shows a possible energy transformation process. Recent PDR systems for generating electricity install the steam turbine generator at the central receiver. This in turn requires a large absorber area to accommodate the generator components hence reducing the concentration ratio. A high density thermal storage medium at the receiver can smooth out energy output while solving the problem of heat loss during transportation.

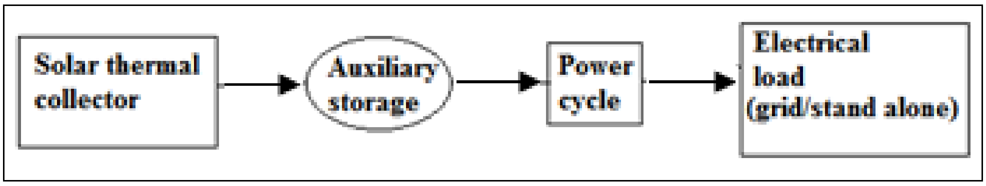

Figure 3: Schematic diagram representing solar energy transformation

In a study done by Kawira on solar energy output of Parabolic Trough Solar Collector (PTSC), the results showed unsteady energy output [13]. It also showed that on a clear day, even though the energy output curve is expected to be smooth the results indicated erratic variation probably caused by intermittent cloudy conditions and draughts. This problem can be solved by incorporating temporary heat storage at the absorber to serve as a thermal compensator.

The desirable characteristics of a good PCM were considered when selecting the Sn/Pb alloy with the outstanding ones being the fact that the alloy has appreciably high latent heat effect (23 x 10^3J/kg) with its melting point being in the desired operating temperature (172 °C), the alloy has high thermal conductivity in both solid and liquid phases, high mass density (8520 kg/m^3) and it is of reasonable cost [7].

III. Materials and Methods

3.1 A. Fabrication of Thermal Compensating Receiver

A steel globe was salvaged from an obsolete refrigerator compressor unit. This served as the blackened bulb absorber housing the PCM. The PCM surrounded a copper tube coiled to increase thermal contact. The inlet tube was insulated from the outlet steam pipe with glass wool to prevent heat exchange (Fig. 4). The pipes were encased in a larger diameter pipe which was the central antenna supporting the receiver.

The fabricated collector and receiver parameters were:

Aperture area = 5.538 m^2

Receiver area	=	0.0616 m^2
Aperture depth	=	0.625 m
Focal length	=	0.9 m
Diameter of inlet pipe	=	0.005 m
Diameter of outlet pipe	=	0.005 m
Concentration ratio	=	89.9
Mass of PCM	=	2.650 kg

Fig. 4 shows schematic diagram of the receiver components while Fig. 5 and Fig. 6 show the interior fabrication of the absorber and complete PDSC respectively.

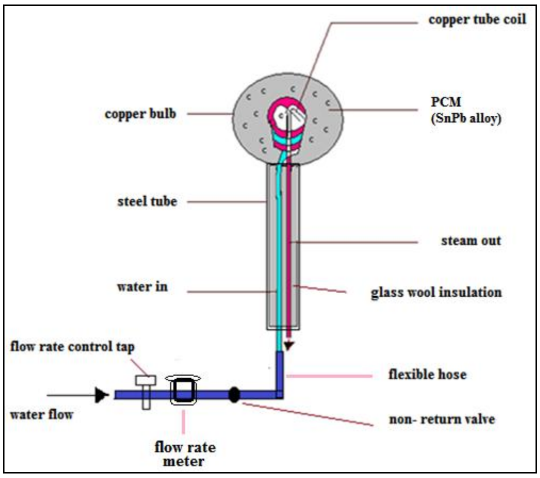

Figure 4: Components of the compensating absorber

Figure 5: Coiled copper tube inside the absorber

Figure 6: The complete PDSC assembly

3.2 Mass Flow Rate and Heat Transfer

The HTF was delivered from a high tank reservoir and made to flow by gravity at a controlled rate so as to enter the high temperature absorber. The mass flow rate, $\dot{m}$ in kg/s was measured using a flow rate meter. Provided there was no leakage in the flow pipes, the volume of water entering the absorber unit was equal to the volume leaving the hot receiver per unit time. The rate of flow was controlled using a tap to ensure the right amount of water attained the desired temperature. A non- return valve was fixed in the inlet pipe to prevent counter flow of high pressure steam from the hot receiver. The inlet temperature of water, T_1 and outlet temperature, T_2 were measured using two thermocouple thermometer probes at the inlet and the outlet proper mix points. Fig. 7 shows the outlet temperature of HTF at various times of the day for the absorber with thermal compensator.

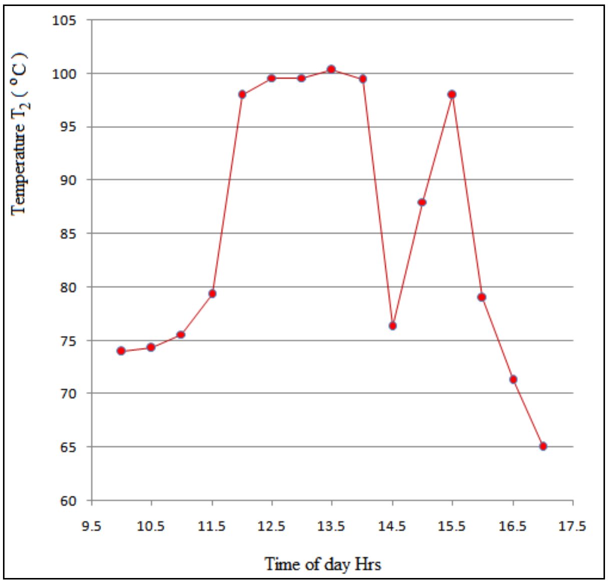

Figure 7: Output temperature variation of HTF

Under steady state condition, the temperature rise of water was used to determine the heat transferred to the water using the equation 2 of heat gain:

$$\dot{Q} = \dot{m}c_p (T_2 - T_1) \qquad (2)$$

Where, $\dot{m}$ is mass flow rate of heat transfer fluid, c_p is the heat capacity of water at constant pressure, $(T_2 - T_1)$ is the temperature gradient with T_1 the inlet temperature and T_2 as the outlet temperature of the heat transfer liquid [2] and $\dot{Q}$ is the rate of heat delivery by receiver which is the power output.

The total heat intercepted by the dish was calculated using effective dish aperture area A_a and the prevailing solar constant G_s [11]. The effective aperture area was determined with consideration of reflectance of the aluminium foil.

$$A_{ae} = A_a r \qquad (3)$$

Where A_a and r are aperture area and reflectance respectively, A_{ae} is the effective aperture area.

In the prototype dish the effective aperture area was calculated as the product of aperture area and reflectance of the reflective material.

$$A_a = 7.07 \text{ m}^2 \text{ x } 0.78 = 5.538 \text{ m}^2$$

Where 0.78 is the reflectance of the aluminium foil

The solar energy intercepted by the aperture per unit time was given by:

$$\dot{Q}_s = G_{sc} A_a \cos \theta_i \qquad (4)$$

Where, G_{sc} is the prevailing solar intensity and θ_i is the angle of incidence. For the perpendicular aperture, $\cos \theta_i = 1$. A_a is a design parameter and was calculated from the diameter of the spherical receiver using equation 5:

$$A_a = \pi r^2 \qquad (5)$$

The solar intensity at the location of solar harvest was measured using solar power meter in W/m^2.

3.3 Testing of the Compensating Receiver

To perform steady state receiver testing: a receiver without thermal storage (non-compensating receiver) was designed so as to compare its energy output characteristics with that of the compensating device.

The testing was done under similar conditions of collector and absorber geometrical parameters. Water was connected to flow by gravity from a high tank into the system at a controlled steady rate. The rate of flow of HTF and solar power intercepted needed not be the same in both cases because the objective was to observe buffering effect in the absence of intense radiation. The inlet temperature T_1 and outlet temperature T_2 of HTF was measured at the proper mix points in the pipes using two thermocouple thermometers. Calculation was done to determine the quantity of heat transferred into the water using the equation of heat gain (equation 2).

Solar intensity was measured using solar power meter fixed outside the aperture but perpendicular to the aperture plane and parallel to the antenna supporting the receiver. This would measure the prevailing solar beam radiation intercepted by the dish at various times of the day. Simulation of cloudy condition or period of low solar intensity was done by disorienting the dish aperture away from the solar beam. Data was collected for the power output while steady flow of HTF was maintained. The data was computed for both compensating and non-compensating devices and the cooling curves for both devices plotted (Fig. 8).

IV. Results and Discussions

The performance of PDSC with thermal storage was determined on a typical sunny day and data used to plot energy output curve in comparison with solar energy captured. Data was collected on different days using the compensated and non-compensated device. Fig. 8 shows the performance of compensated absorber with HTF flow rate of 0.46g/s

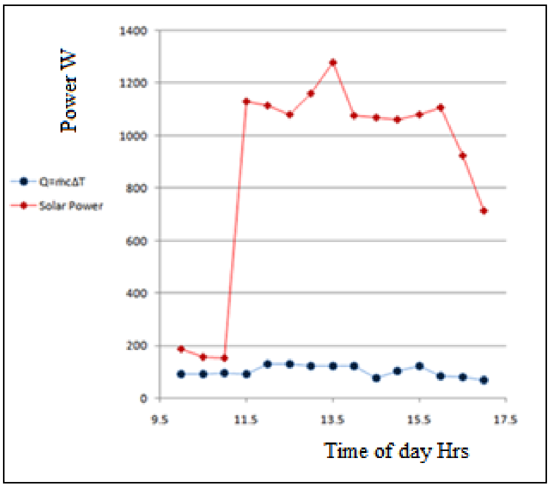

Figure 8: Performance curve of compensated Absorber

The energy output of compensated receiver showed a steadier output while the non-compensated one showed tendency of fluctuations. Fig. 9 shows performance of non-compensated absorber with HTF flow rate of 0.667g/s

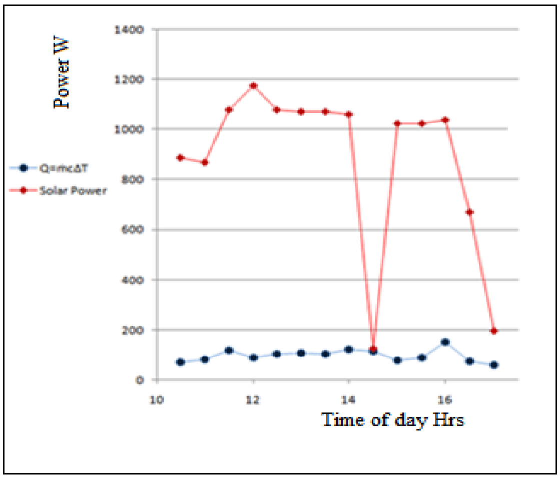

Figure 9: Performance of Non-Compensated Absorber

The cooling curves of both compensated and non-compensated devices in simulated cloudy conditions were also compared (Fig. 10). The flow rate of HTF through the non-compensated receiver was 0.667g/s and the flow rate through the compensated receiver was 0.83g/s.

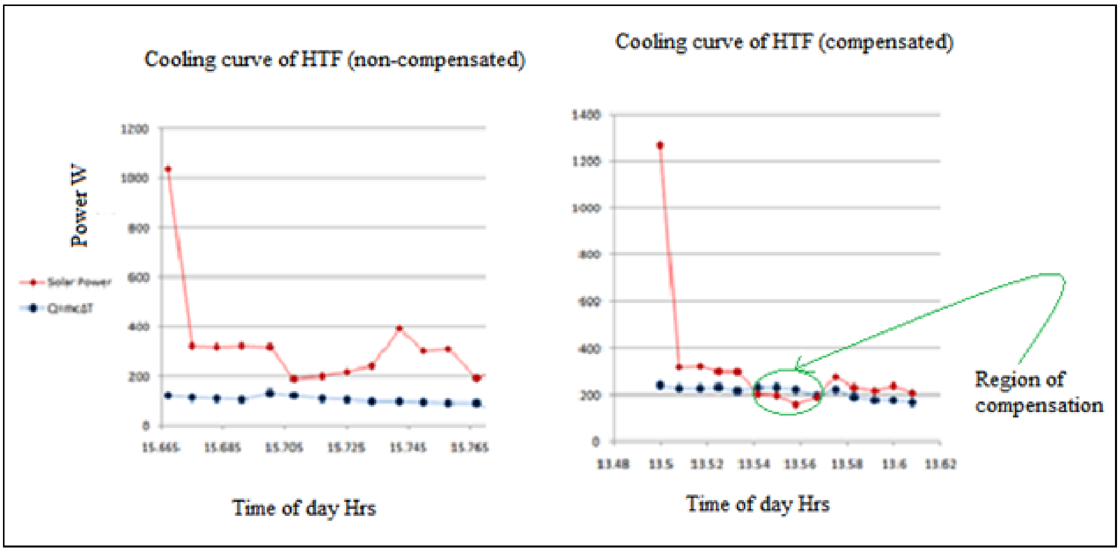

Figure 10: Comparing cooling curves of compensated and non-compensated absorbers

The cooling curve of the compensated receiver showed steadier energy output. At some point (circled region) the graph (Fig. 9) shows greater energy output than the energy intercepted – this evidenced energy recovery from latent and sensible heat storage of the storage medium.

Table 2: Comparison of Efficiencies

Efficiency of Compensating PDSC		Efficiency of Non-compensating PDSC	
Minimum	Maximum	Minimum	Maximum
3.44%	44.82%	2.05%3	11.6%

V. Conclusion

The study in this paper was meant to seek a way of stabilizing energy output of thermal SEDs so as to make them compatible with conventional energy sources. The problem of erratic power output of PDSC, PTSC and other solar harvesters can be reduced by using an absorber with thermal compensator. The compensated absorber showed steadier energy output in prevailing erratic weather and simulated weather conditions. There was appreciable increase in efficiency (max. = 44.82%) of the PDSC when thermal storage medium was employed as compared to maximum of 11.60% without storage medium. However, better buffering could have been achieved if suitable PCM of lower melting point was used in the moderate temperature PDSC. Better thermal contact could have been ensured by using thin metal casing for the absorber. In the prototype PDSC the PCM was placed between the absorber wall and the HTF. During the heat recovery process the PCM was more likely to discharge a greater fraction of heat exteriorly than interiorly. The coiled copper tube should have taken the outer part nearest the absorber wall rather than the interior for better heat transfer. The PDSC design had the focus well outside the shielding of parabolic reflector thus exposing the absorber to cooling effect due to wind and draught. Further improvements may include a design that covers the aperture with transparent membrane to shield the absorber from heat loss by convection currents. These modifications would significantly improve performance and reliability of the solar energy concentrator.

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