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Optical Analysis of Paraboloidal Concentrated Solar Flux Receiver System

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ABSTRACT

This paper presents theoptical performance analysis of solar flux concentrator. The incident flux distribution on the surface of solar concentrator was computed, and then the concentration ratio in the focal plane wasanalyzed for the ideal and practical design scenarios. In the ideal design scenario where the receiver dish was a perfect reflector, that is, the dish was perfectly smooth, and all of the incoming rays are focused on a single point on the collector. In practical design scenario, the reflector surface is not perfectly smooth and the factors of ray absorption and limb darkeningwere taken into account. Radiation performance of paraboloidal solar concentrator was studied using ray tracing method coupled with optical properties. The results of the analysis showed that surfaceslope error predicated on the factors of surface roughness, ray absorption and solar limb darkening affects performance by broadening the flux distribution and reducing the peak value of the flux distribution to maintain energybalance.

Keyword: optical analysis, solar flux, absorption, ray tracing

I. INTRODUCTION

Very recently, solar flux concentrating system which is the technology that focuses solar energy at a single point has been trending due to its increasing compactness and efficiency. Solar concentrator technology is a promisingrenewable energy solution for many applications such aselectrical power generation, solardesalination, solar cooling, hot water supply, etc. (Fernández-García, 2010; Krüger et al, 2008). Common solar concentrator technologies are mainly of two types. These include: the line focus technology such as the Parabolic Trough Collectors (PTC) and the Linear Fresnel Collectors (LFC) and the pointfocus technology such as the parabolic dish and central receiver tower (Günther et al, 2011; Xie et al, 2011; Coelho et al, 2014).

Solar focusing receiver systems employ different orientation of reflective mirrors or refractive lenses to focus solar radiation on a collector in order to produce useful energy such as heat, electricity or fuels (Lovegrove and Stein, 2012). Parabolic dish systems exploit the geometric properties of a parabola, but as a three-dimensional paraboloid. The reflected beam radiation is concentrated to a point focus receiver and heat up the system to an operating temperature greater than 1,000ºC. Dish systems offer the highest potential solar conversion efficiency ofall the solar concentrator technologies, because they always present their full aperture directly towards the sun and eliminate the cosine loss effect, suffered by other configurations.As shown in Figure 1.1, the concentrated radiation must be intercepted by a receiver whichconverts it to another form, typically thermal energy.

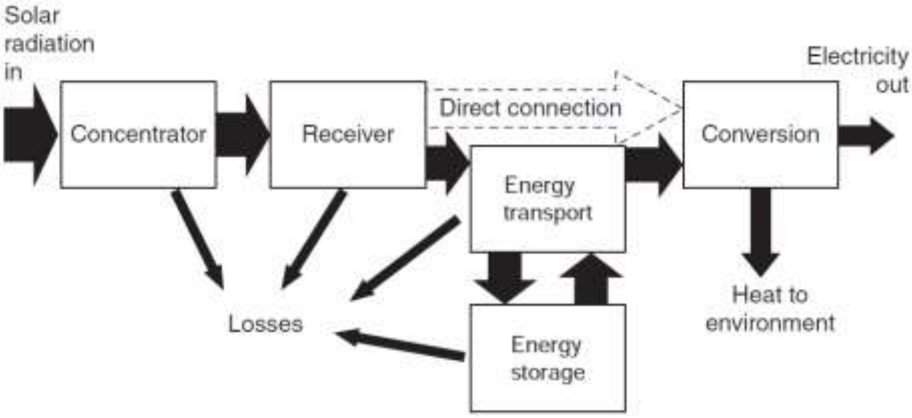

Figure 1.1: Components of a solar concentrator system(Lovegrove and Stein, 2012).

This paper is aimed at presenting theoptical analysis of solar flux concentrator. The incident solar flux distribution on the solar concentrator receiver surface was computed, and then the concentration ratio in the focal plane wasanalyzed for the ideal and practical scenarios. In the ideal design scenario, the receiver dish was assumed to be a perfect reflector, that is, the dish was perfectly smooth, and all of the incoming rays are focused on a single point on the collector. In practical design scenario, the reflector surface is assumed to have some degree of roughness and the factors of radiation absorption and limb darkening were taken into account.

II. LITERATURE REVIEW

In this section, the milestone developments in the making of solar energy concentrator in the past few years were reviewed covering technological advancement of solar concentrators and related performances. Additionally, typical applications of the small point-focusing concentrator in photovoltaic system, solar thermal system, solar chemical system, and day-lighting system were also reviewed.

Madala and Boehm (2017) observed that the parabolic troughaccounts for a vastmajority of the concentrating solar power (CSP) global installations due to its cost advantage. It does not matter which type of CSP technology was implemented, a common goal is the real-time tracking of theSun in order to achieve meaningful concentration. The concentration of solar radiation is typically achieved byusing an active solar tracking mechanism coupled with a point- or linefocusimaging concentration system. Perhaps more importantly, the concentration ofsolar energy does not demand imaging qualities, but instead requiresflexible concentrator designs coping with solar disk size, solar spectrum,and tracking errors while delivering a highly uniform flux (Pitz-Paal,2014; Jones andBouamane, 2012).

Wang et al (2019)reviewed the design process, characteristics and applications of solar energy concentrator. Three mirror fabrication techniques for dish concentrator were presented, namely, highly polished metal, silver-glass mirror and vacuum-membrane. Application areas of the system reported based on the working characteristics include, photovoltaic system, solar thermal system, solar chemical system etc. Noting the advantage of fixed focus of the solar collectors, it was noted that they are suitable for use in power generation, cooking, water desalination, thermochemical reaction, and the biomass pyrolysis.

Shuai et al (2008)conducted a performance analysis ofsolar concentrator-receiver system using Monte-Carlomethod. The study showed that variation in circumsolar values have reduced effect on concentrationratio of the system. Five cavity receiver geometries were evaluated keeping the wall radiation flux constant. The results obtained indicated that cavitygeometry has a significant effect on overall flux distribution.

Anne-Laure et al (2014) investigated the Luminescent Solar Concentrators (LSC) with and without Photonic Band Stop (PBS). The LSC served as waveguide to concentrate light towards the photovoltaic (PV) cells. Simulations for different LSC with and without PBS were realized to study the effect of photonic components on the systems. The results revealed that the combination of PBS with LSC allows for the enhancement of conversion efficiency.

Gil (2018) presented solar energy application possibilities in cork harvesting and processing. It was noted that cork-based products havedifferent operational steps in which electricity, heat and thermal fluids derived from solar technologies can be used. Perhaps more significantly, it was reported that the cork sector is a viable application area where solar energy may be used in various ways and cork material could be a component in various solar energy systems.

Ydrissi et al(2019)evaluatedthe performance of solar Parabolic TroughConcentrator (PTC) in terms of their optical and thermal efficiencies. An experimental analysis of the geometrical and optical errors of the solar concentrator was performed. Additionally, the slope error,misalignment error, and receiver position related errors were also analyzed using the photogrammetrymeasurement technique. The results of analysis revealed the impact of optical efficiency on conversion to thermal energy and system performance.

Louis and Sanchez (2016) analyzed the performance of a low-cost solar concentrator using a spot-type Fresnel lens, and a solar absorbersized for moderate temperature range of between 80°C to 250°C. The thermodynamic properties of the system weredetermined from theoretical and experimental estimates of temperature and pressure. Efficiencies as high as 50%were estimated from irradiance and heat losses measurements. The proposed system was recommended for varied domestic applications such as boiling water, solar cooking etc.

Huang et al (2010) presented a novel solar concentrator with enhanced geometric concentration ratio. In the proposed system sun rays travel within the disk, saving the space that is reserved for ray propagationin other concentrators. Simulation analysis of the system for both singlewavelengthand broadband lightwas carried out and an overall system efficiency of92% was realized.

To overcome thelarge areas of solar collectors needed to efficiently produce thermal energy from the sun, Chemisana et al (2011) proposed an integrated solar concentrator system with temperature capabilitylevel of 150 ºC. The proposed system realized 87.5% reduction in size of area occupied by the solar collectors compared with standard solar thermal installation.

Pavlovic et al (2016) presented the study of opticaland thermal characteristics of a parabolic dish concentrator with aspiral coil receiver. The analysis results revealed that the optimal distance of 2.1m from the reflector to the absorber will maximize the optical efficiency. A thermal conversion efficiency of 65% was also realized from the presented system.

III. METHODOLOGY

The methodology for computing the concentration ratio in the focal plane for concentrated solar reflector using ray tracing was adopted in this work. In Figure 3.1, suppose, the differential area elements on thesurface of the concentrator at $r_c$and on the focal plane of the receiver at r, is shown.

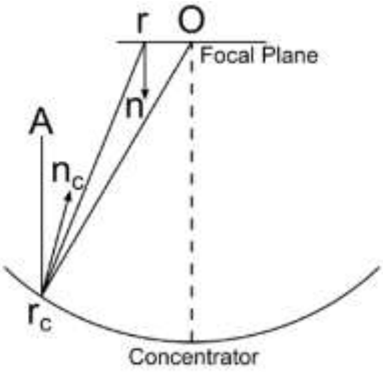

Figure 3.1: Paraboloidal solar reflector

Given that the surface normals at the concentrator and focal plane are $r_c n_c$and rn,respectively, and O is the focus. The following angles are defined:

$$\delta_1 = < 0r_c r \quad \theta_c = < rr_c n_c \qquad \theta = < r_c rn$$

The concentration ratio at r is given by

$$C(r) = \frac{1}{I_0} \int_\Omega \frac{f\cos(\theta)\cos(\theta)}{|r-r_c|^2} dA_c \qquad (3.1)$$

$$f(\delta) = \begin{cases} I_0/(\pi\sin(\psi_m)^2 & \delta \le \psi_m \\ 0 & \delta > \psi_m \end{cases} \qquad (3.2)$$

where:
f = the radiant intensity,
Ω = surface integration over the collector surface,
I_0= the incident solar flux,
ψ_m= the maximum solar disk angle, and
dA_c= differential area element on the surface of the collector.

It is assumed that the incident solar flux does not vary as a function ofposition on the solar dish which means no solar limb darkening is account for in Equation 3.1. This equation can be extended to take into cognizance solar limb darkening by the inclusion of the term dependent on the angle δ.

The paraboloidal concentrated solar receiver dish was modeled in COMSOL Multiphysics with a focal length of 3m. The geometry also includes a small cylinder, one surface of which lies in the focal plane. The incident flux distribution on this surface was computed, and then the concentration ratio in the focal plane is analyzed for two design scenarios, namely the ideal and the real case scenarios. In the ideal design scenario where the receiver dish was a perfect reflector, that is, the dish was perfectly smooth, all of the incoming rays would be focused on a single point on the collector, at the focus of the paraboloid concentrator. In real design scenario, the reflector surface is not perfectly smooth and factor of limb darkening is considered. The phenomenon of solar limb darkening describes decrease in solar intensity from the greatest center point towards the peripheral side. Solar intensity profile is known as sunshape.

Dedicated boundary condition was used to release rays directly from the surface of the dish. The direction at which the rays are released from the surface of the dish depends on the incoming ray direction vector **n**i and the outward surface normal **n**s, with following relation:

$$n_r = n_i - 2(n_i . n_s) n_s \qquad (3.3)$$

The intensity of each individual ray was computed along its trajectory. The evolution ofray intensity depends heavily on the curvature of the dish. Each ray released is assigned a fixed power. When the rays reach the surface of the solar collector, they are stopped.The incident heat flux in the focal plane was therefore computed. By taking the ratio ofthe deposited flux to the incoming solar flux, the concentration ratio on the surface wascomputed. It is to be noted that some of the incoming radiation is absorbed by the dish itself.

In the real scenario model, the absorption coefficient is set to 0.1, meaning that 90% of the incoming radiation is reflected.An additional correction is included due to the finite size of the sun. Not all incident rays will be parallel; instead, the incident rays are sampled from a narrow cone with maximum angle, ψ_m, of 4.65 mrad. Since the surface of the dish is not perfectly smooth, the reflected rays are not all releasedat the exact direction given by Equation 3.3. Instead, the surface normal is perturbed by anadditional angle that is sampled from a Rayleigh distribution:

$$P(\emptyset) = \frac{\emptyset}{\sigma_\emptyset^2} \exp\left(-\frac{\emptyset^2}{2\sigma_\emptyset^2}\right) \qquad (3.4)$$

where $\sigma_\emptyset$= the surface slope error.

The model includes two study scenariosFor each study, rays are released from 100,000 distinct points.At each point, the incident ray direction is perturbed by a random angle; the probabilitydensity of these perturbations is uniform within a cone of angle ψ_s.For the first study, no limb darkening model is used and the surface is assumed to beperfectly smooth and reflective. For the second study, a limb darkening model is used to reduce the intensity of solarradiation emitted from the edge of the solar dish. The built-in limb darkening modelfollows an exponential fit, with wavelength-dependent exponents.For each study, the concentration ratio is computed on a small circular disc, centered atthe origin, which lies in the focal plane. To eliminate statistical noise, the average concentration ratio is taken over all azimuthal angles for each value of the radial coordinate in the focal plane based on equation 3.5:

$$C(\rho) = \frac{1}{2\pi} \int_0^{2\pi} C(\rho, \theta)\, d\theta \qquad (3.5)$$

IV. RESULTS AND DISCUSSION

Figure 4.1 depicts the solar flux distribution for an ideal solar concentrator. It shows the chart of the averaged concentration ratio against the radial plane from the center of the plane to the peripheral side. The result showed that solar flux was concentrated around the center of the focal plane and drops sharply to zero away from the center towards the peripheral side. This is the result of the ideal scenario with perfect reflectivity, surface smoothness and without the factor of solar limb darkening.

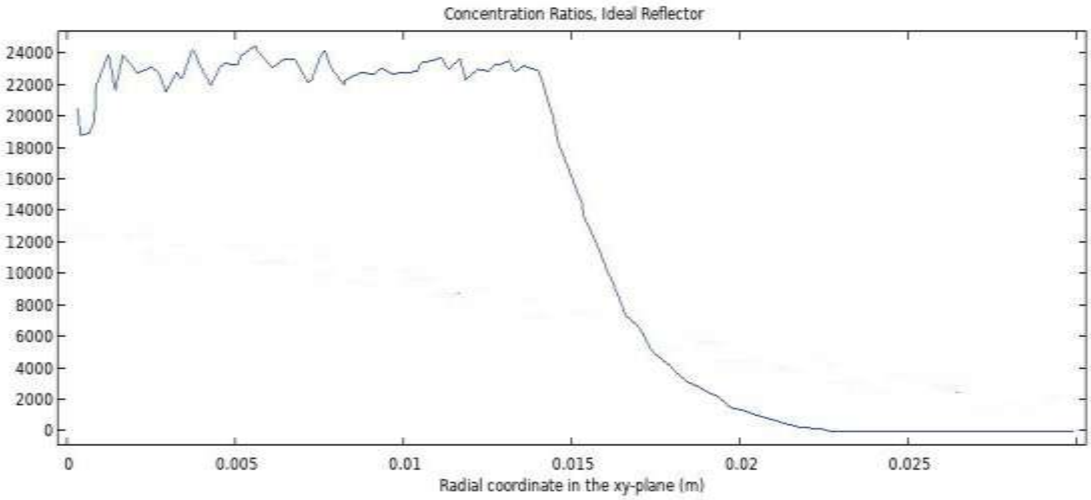

Figure 4.1: Computed azimuthally averaged concentration ratio in the focal plane of ideal paraboloidal solar reflector model

The solar flux distribution resulting from the second design study scenario with imperfect reflectivity which accounted for surface roughness, ray absorption and solar limb darkening is depicted in Figure 4.2. It reveals that a substantial number of rays now miss the receiver and continue to propagate,reducing the efficiency of the cavity receiver. The result showed that the flux distribution is much more widespread, lacking any well-defined plateau. The peakflux has also been considerably reduced. As can be observed in chart, the concentration ratio gradually deceases from the center towards the edge of the focal plane.

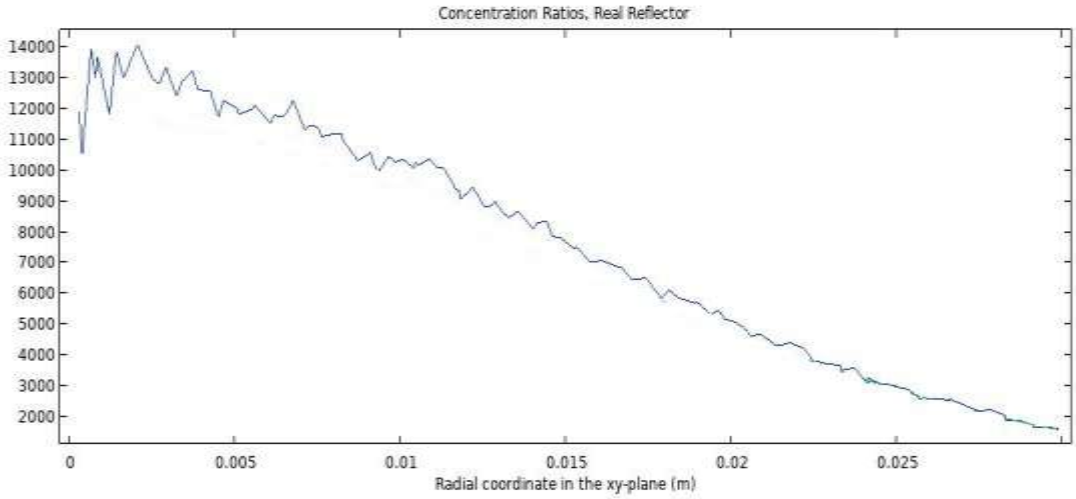

Figure 4.2: Computed azimuthally averaged concentration ratio in the focal plane of practical paraboloidal solar reflector model

The implication of these results is that surfaceslope error predicated on the factor of surface roughness, ray absorption and solar limb darkening affects performance by broadening the flux distribution and reducing the peak value of the flux distribution to maintain energybalance.

V. CONCLUSION

In conclusion, computational estimation of solar flux distribution on solar receiver surface is at the center of optical analysis of a solar concentrator. This analysis can be expanded to integrate the solar radiation and absorption of the concentratedflux wherein incident-angle dependent properties are taken into cognizance. Radiation performance of dish solar concentrator system is studied using ray tracing method coupled with optical properties. The results of the analysis showed that that surfaceslope error predicated on the factors of surface roughness, ray absorption and solar limb darkening affects performance of solar concentrator by broadening the flux distribution and reducing the peak value of the flux distribution to maintain energybalance.

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