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A Review on Solar Secondary Concentrator

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Abstract

Concentrating solar power (CSP) is a solar thermal technology that generates electricity from thermal energy through the sun.The electricitycan be generated with four different types of CSP technologies that include Parabolic Dish (PD) systems. In order to make this technology more practical, the efficiency of the solar technology should be improved.Solar concentration is one of the main aspects that can affect the system'sefficiency. This paper reviewed solar secondary concentrators and discussed their designs and performance. Besides, their strengths and weaknesses were compared. Generally, thesecondary concentrators couldincrease the solar concentration of the solar technologyup to 93 percent.

Keywords*: renewable energy, parabolic dish, solar concentration, secondary concentrator*

1. Introduction

PD system is one of CSP technologies which is used to convert solar energy to electrical energy [1]-[4]. In CSP systems, the concentration of sunlight is the key point and required as the input because thermodynamic cycle or stirling engine is used. Through over concentration and small thermal losses, the high temperatures can be efficiently achieved. The ability to track the daily sunlight is typically required for the concentrator either using focusing optics, non-imaging optics or combination of both principles [5].

Dual axis parabolic tracking research has been done with high accuracy used for High Concentrator Photovoltaic (HCPV) application [6]. PD aluminium Concentrator with 3.7 meters diameter is designed for the PD 1kW system based on Malaysian environment [7]. Therefore, many types of concentrators have been used previously [8]. Each design of concentrator has its own benefit and weakness [9] but there are still many improvements need to be done especially on the designs [10]. In order to gain higher concentration and system efficiency, secondary/two-stage concentrator has been introduced and developed into Photovoltaic (PV) systems and CSP systems [11]. This technology offers more open-ended structure for the systems, for example, upward-facing receiver [12] or appropriate heat storage design [13]. Besides, it provides higher concentration ratios [14]-[16] and effective power distribution [12]. The aim of this paper was to review secondary concentrators based on solar concentration and their other characteristics such as advantages, disadvantages, and performance.

2. Secondary Concentrators

2.1. Overview on Different Design

Many developments on various designs of secondary concentrators have been made. This section presents different designs of secondary concentrator.

2.1.1. Hyperbolic Mirror

Figure 2(a) shows the schematic diagrams of the two stage concentrator with hyperbolic mirror as secondary concentrator. The rays from sunlight transmit through the paraboloidal

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mirror along the Z-direction.The rays are concentrated through the primary paraboloidal mirror and reflected twice by the secondary hyperbolic mirror to concentrate behind the primary concentrator whichis at point F_2 as shown in Figure 2(b) [17]-[19]. The hyperbolic mirror should be made from glass with 0.95 reflectivity.

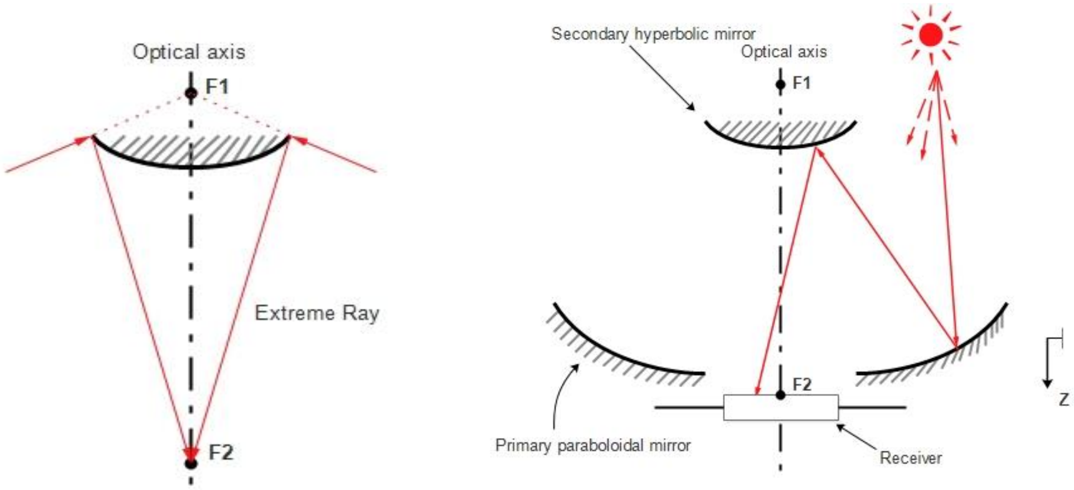


Figure 2. Geometric diagram of (a) two stage concentrator with hyperbolic mirror, (b) the hyperbolicsection

Based on the simulation, the average heat flux distribution on the receiver is near 1880 suns and about 77.5% optical efficiency of the system, indicating good performance for this design [18].

2.1.2. Elliptic mirror

Fundamentally, an elliptic mirror consists of two focal points F_1 and F_2, Figure 3 shows an elliptic mirror with two vertex Ve_1 and $Ve_2$and centre point of $C(h,k)$.Typically, two-stage concentrators with elliptic mirror as the secondary concentrators are designed using a Gregorian antenna model in which the primary concentrator is parabolic mirror. Gregorian model is like antenna reflector [20] and concave reflectors [21]. The incident rays from the primary reflector are reflected then reflected back by the secondary into the receiver at pointF_2.

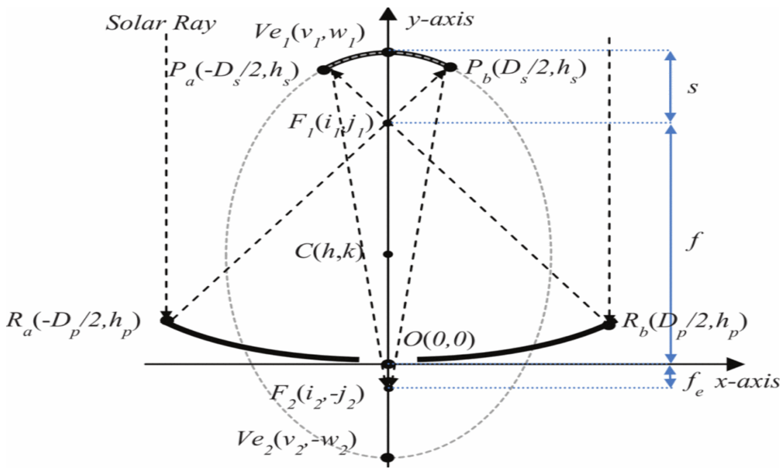
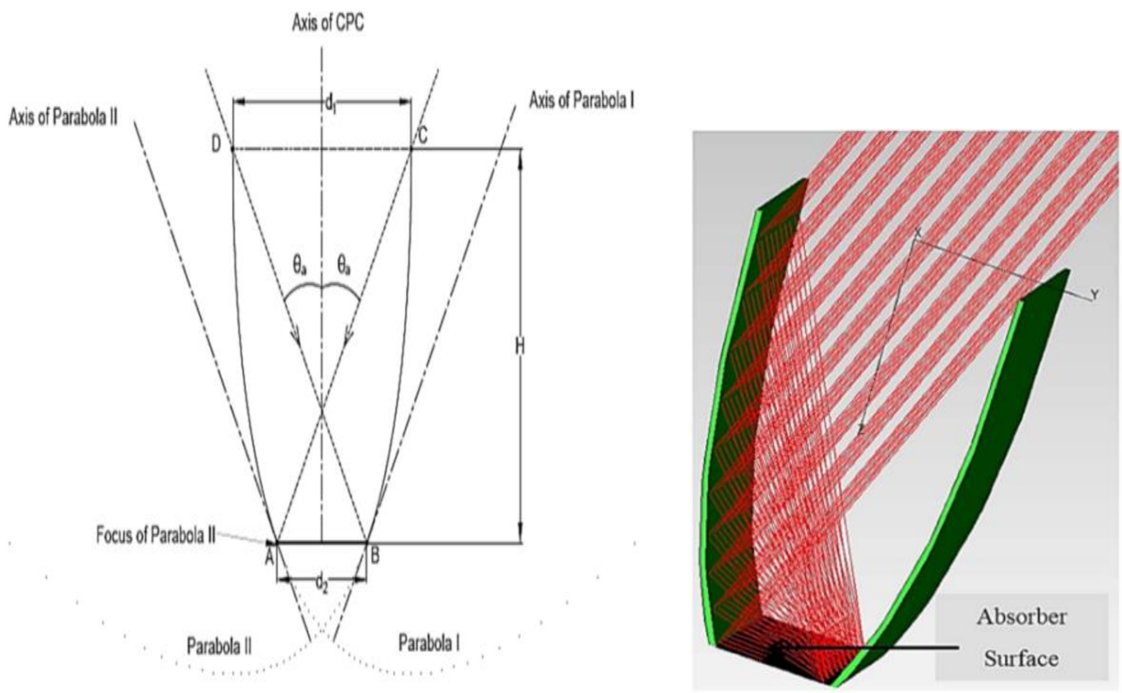


Figure 3. Geometric diagram of two stage concentrator with Elliptic mirror [22]

Previously, thetwo stage concentrator designed with 300 cm and 80.53 cm for primary and elliptic mirror as secondary concentrator using 92% material reflectivity for aluminium reflector [7] absorbed by 9 cm receiver could have the geometric concentration ratio and optical efficiency about 594.65 and 84.27% respectively [22]. Elliptic shaped secondary offers higher concentration ratio than hyperbolic shaped [23].

2.1.3. Compound Parabolic Concentrator (CPC)

The earliest type of the compound parabolic concentrator (CPC) that can be static or with a multiple rotation was invented in 1947 by Winston [24] which is shown in Figure 4(a). Basically, the CPC design is shown in Figure 4(b). CPC consists of two different parabolic profiles which are AD and BC with foci at the end points of the exit aperture (AB). The axes of the parabolas AD and BC form by the tangential lines with respect to BC and AD at the end points of exit aperture B and A. The incident rays enter the exit aperture, consequently the rays totally internally reflected from the parabolic profile and then they hit the exit aperture (receiver surface) as shown in Figure 4(b). The design of CPC should also consider the shape of the receiver which is either square or rectangle.



(a) (b)

Figure 4. (a) A compound parabolic concentrator (b) Raytracing simulation of the working principle of CPC [25]

CPC as a secondary concentrator has been generally utilized in various applications for example, solar concentrator for both PV and CSP [26]-[28]. CPC is used as a secondary concentrator which is in a central receiver system as shown in Figure 5 which uses the hyperboloid mirror as a primary concentrator and the CPC as a secondary concentrator. The incident rays from the heliostat are reflected by the reflector directly to the center point and the CPC place before the receiver in order to improve and boost the original concentration level [29].

The advantages of using this type of secondary concentrator isthat CPC offers a larger acceptance angle [24], [27], [30], promising various application and enhance the system and optical efficiency [29], [30]. Besides, the challenge are it affect circum solar radiation collection, it need better tracking system and expensive.

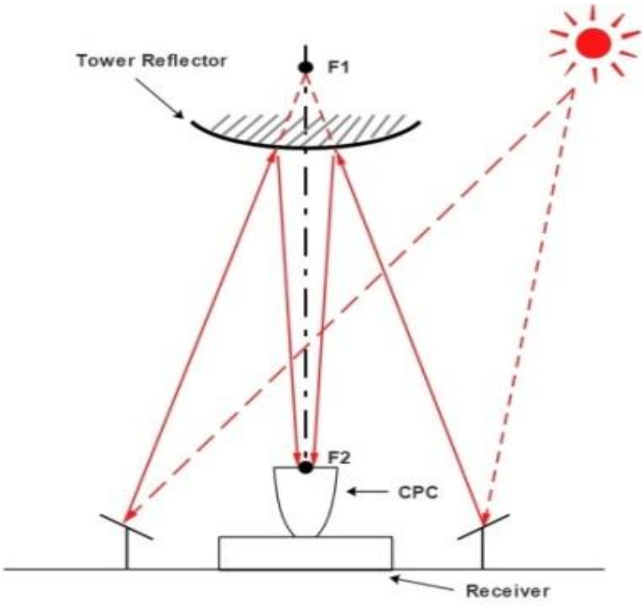


Figure 5. Geometry of tower reflector

2.1.4. Dielectric Totally Internally Reflecting Concentrator (DTIRC)

In 1987, Ning et al [31] introduced DTIRC concept. This type of concentrator has theability to reach concentration close to the thermodynamically allowed limits. Basically, DTIRC consist of three components: (1) a curved front surface, (2) a totally internally reflecting side profile and (3) an exit aperture as shown in Figure 6. The incident rays pass through the curved front surface and, refracted, and then consequently the rays totally internally reflected from side profile to hits the exit aperture.DTIRC can be produced using two design methods; maximum concentration method and phase conserving method.

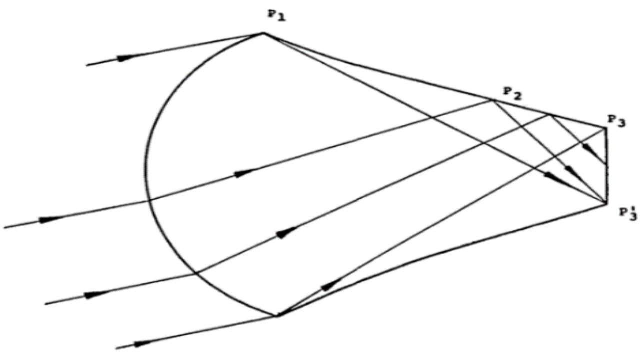


Figure 6. Side view for basic design of a DTIRC [31]

DTIRC as a secondary concentrator has been widely used in various applications such as the pumping of power laser systems [32], concentrated photovoltaic (CPV) [14], and solar thermal application in space [33], [34]. Recently, Cruz-Silva et al. [16] reformulate the Ning's formulation of DTIRC [31] to obtain an analytical framework for feasible designs which are easily implemented for computer numerical control (CNC) manufacturing and presented solar flux distribution in Linear Fresnel reflector (LFR) and parabolic through collector (PTC) using DTRIC as secondary concentrator.

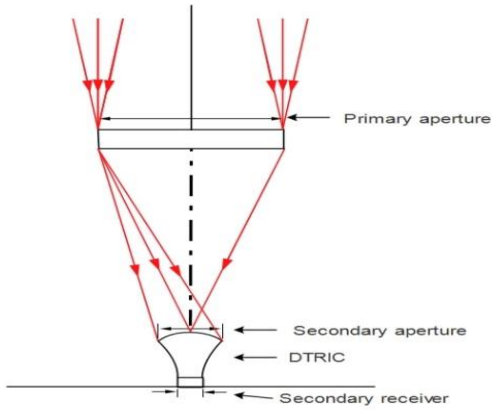


Figure 7. Two-stage concentrator, Fresnel lens as primary and DTIRC as secondary

A two stage concentrator with DTIRC as secondary concentrator design is illustrated in Figure 7. The ratio of the primary aperture area to the secondary exit area is the geometric concentration ratio. Four parameters need to be completely determined for the secondary concentrator which are the refractive index of dielectric material and the diameter of exit aperture that are often given, the curvature of the curve front angle and the acceptance angle need to be determined. In order to gather all the rays, the acceptance angle must be matched with the rim angle of the primary concentrator [14] and the DTIRC should be placed in the focal line of the primary [16]. The benefit of DTIRC is it provides higher geometrical concentration gain, higher efficiency, flux tailoring and smaller size [9] and the drawback is the DTIRC cannot efficiently transfer all the solar energy that it collects into a lower media [33].

2.1.5. Compound Parabolic Reflective Secondary Concentrator

Fraunhofer Institute for Solar Energy Systems (ISE) has investigated the refractive of secondary concentrator for concentrator modules. Basically the module, FLATCON® module with 48 solar cell assemblies (SCA) [8] consist of a Fresnel-lens as a primary concentrator and the reflective secondary concentrator install exactly on the solar cells. Fundamentally, the reflective secondaries are designed in a conical shape with20° to 24° angle and between up to 6 mmheight as shown in Figure 8 which is verified to be a good performance, taking into accountease of manufacturing using commercially available metallic mirror sheets.

After implementing the conical reflective secondary concentrator, the module presents an increment on acceptance angle about 0.7° whereas, 0.4° without secondary concentrator. The first bigger module with aperture area of 768 cm^2 was constructed with a reflective secondary concentrator which had shown very encouraging results where system efficiency of 28.5% could be reached under outdoor conditions in Freiburg, Germany [35]. The manufacturing process for this type concentrator is suitable for mass production but amajorres traint in designing the optical of the secondary concentrator is the efficiency of solar cells declinewith the growing radiation of the incidence angles.

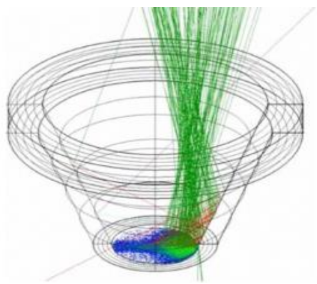
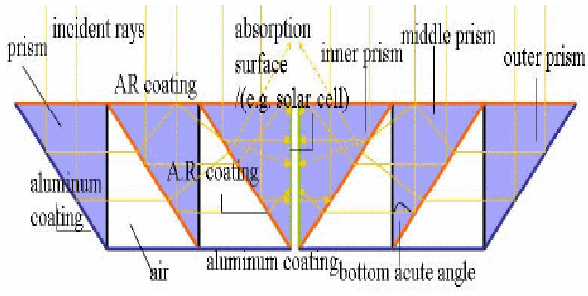


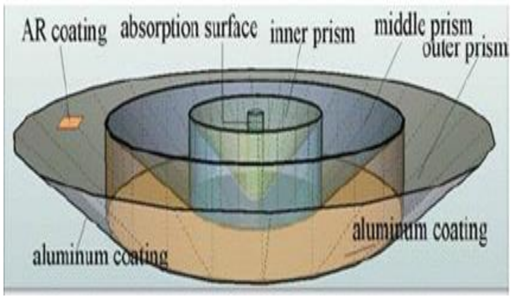
Figure 8. A raytracing simulation showing rays are partially reflected in the secondary optic [35]

2.1.6. Secondary Concentrator with Circular Micro Prism Array

Fundamentally, the structure of this type of concentratoras presented in Figure 9(b) is a circular micro prism array that gives direction to the incident ray through its centreby total internal reflection. This concentrator can be made from glass material. The incident ray will often pass through the outer prism then experience total internal reflection on the inclined surface of the prism that makes the rays change its direction and propagates horizontally as shown in Figure 9(a).The rays then experience refraction and deflect slightly upward in the second prism. Then, the rays reach the top of the surface and undergoes the second total internal reflection. Later, it reaches at the inner surface of inner prism. At this surface, the solar cells intended to be in place and the rays will be absorbed to convert into electrical energy [36].



(a)



(b)

Figure 9. The secondary solar concentrator: (a) 2-D cross-sectional view and (b) 3-D view [36]

The construction of the two stage concentrators is shown in Figure 10 which is the Fresnel lens concentrator as the primary concentrator and the secondary concentrator is placed at the focal plane of the primary concentrator.

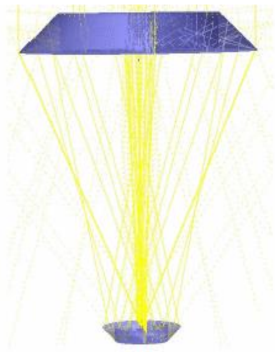


Figure 10. The construction of two stage concentrator [36]

Besides, the geometric concentration ratio of the secondary solar concentrator and the efficiency is 93 and 90%, respectively while the overall geometric concentration ratio is 810 with 92% efficiency. To brief the various designs of secondary concentrators, the comparison on the strength and weakness of each design shown in Table 1.

Table 1. Strength and Weakness of the Secondary Concentrator

Type of Secondary Concentrator	Strength	Weakness
Hyperbolic mirror	• Uniform distribution of heat fluxon the receiver.	• A few rays escaping out from focused point at the receiver.
Elliptic mirror	• Uniform distribution of heat fluxon the receiver.	• A few rays escaping out from focused point at the receiver.

Table 1. Strength and Weakness of the Secondary Concentrator

Type of Secondary Concentrator	Strength	Weakness
Compound Parabolic Concentrator	• Versatility. • High acceptance angle.	• Optical efficiency decreases as secondary.
Dielectric Totally Internally Reflecting Concentrator	• Versatility. • Uniform flux distribution. • Higher concentration at small acceptance angle.	• Height of device will be increased. • High temperature coating should apply to the crystal inlet surface.
Compound Parabolic Reflective Secondary Concentrator	• High acceptance angle. • Compromise between performance and ease manufacturing.	• High Radiation incidence angle causes efficiency of cells decrease.
Secondary Concentrator with Circular Micro Prism Array	• High concentration ratio • High efficiency	• Raysincompletelycollected.

2.2. Performance of Secondary Concentrator

At present, there are several projects that implement the secondary concentrators. In order to study the performance of the secondary concentrators, universities, research centres and companies various projects that implement the secondary concentrator have been done. Table 2 shows several projects that implement the secondary concentrators around the world, presenting the investigator's name, location, estimated output found and the efficiency of the system. Concentration ratio 'X' for the table represents 1X as equal to $1000 W/m^2$.

Based on the projects from the Table 2, the secondary concentrator focuses on the sun rays from primary concentrator to show its capability to increase the efficiency of the system. Therefore, one of the secondary concentrator types such as the DTIRC could be implemented to PD system under the Malaysian environment which could provide higher efficiency.

Table 2. Implementation of the secondary concentrators throughout the world

Name	Location	Type of secondary concentrator	Output (kW)	Concentr ation Ratio (X)	Tracking (yes/no)	Efficiency of the system	Ref
NASA Glenn Research Center (GRC)	Cleveland, Ohio, USA	DTIRC	20	n/a	no	93.0%	[33] [37]
Indian Institute of Technology Madras	Vallipuram, India	CPC	500	58	no	60.0%	[38]
University of Ulster	Northern Ireland, UK	CPC	n/a	n/a	no	7.8%	[28]
Solar-Hybrid power plants (REFOS)	Plataforma Solar de Almeria, Spain	CPC–like with Hexagonal entry and exit aperture	450	n/a	no	86.0%	[39]
Srinakarinwirot University	Nakhon Nayok, Thailand	Elliptic mirror	0.359	n/a	yes	26.3%	[40]
SolFocus	Ben Gurien University, Israel	Hyperbolic mirror	0.25	500	yes	81.0%	[41]
Fraunhofer-Institute for Solar Energy Systems	Freiburgh, Germany	CPC	n/a	214	yes	77.5%	[42]

3. Conclusion

This paper reviews the secondary concentrator based on solar concentration by discussing various designs of secondary concentrators, basic principles, strength and weakness and performance based on simulation. Besides, the performance of various projects that implement secondary concentrators have been reviewed. Generally, the secondary concentrators have been designed based on optical principles of the primary concentrator of the system. Hence, the efficiency of PD system could be optimized by implementing secondary concentrators. Therefore, research and innovative development of secondary concentrators should be conducted for PD system to promise that the PD system is feasible to develop under the Malaysian environment.

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