Renewable and Sustainable Energy Reviews 15 (2011) 2588–2606

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Concentrated solar energy applications using Fresnel lenses: A review

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ARTICLE INFO

Article history:
Received 11 May 2010
Accepted 16 July 2010

Keywords:
Fresnel lens
Solar concentrator
Imaging
Non-imaging

ABSTRACT

Solar energy concentration technology using Fresnel lens is an effective way to make full use of sunlight. This paper makes a review about the recent development of the concentrated solar energy applications using Fresnel lenses. The ongoing research and development involves imaging systems and non-imaging systems. Compared with imaging systems, non-imaging systems have the merits of larger accept angles, higher concentration ratios with less volume and shorter focal length, higher optical efficiency, etc. Concentrated photovoltaics is a major application and the highest solar-to-electric conversion efficiency based on imaging Fresnel lens and non-imaging Fresnel lens are reported as over 30% and $31.5 \pm 1.7\%$, respectively. Moreover, both kinds of systems are widely used in other fields such as hydrogen generation, photo-bio reactors as well as photochemical reactions, surface modification of metallic materials, solar lighting and solar-pumped laser. During the recent two decades, such applications have been built and tested successfully to validate the practicality of Fresnel lens solar concentration systems. Although the present application scale is small, the ongoing research and development works suggest that Fresnel lens solar concentrators, especially non-imaging Fresnel lenses, will bring a breakthrough of commercial solar energy concentration application technology in the near future. Finally, the advantages and disadvantages of two systems are also summarized.

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doi:10.1016/j.rser.2011.03.031

1. Introduction

Energy is important for the existence and development of humankind and is a key issue in international politics, the economy, military preparedness, and diplomacy [1]. To reduce the impact of conventional energy sources on the environment, much attention should be paid to the development of new energy and renewable energy resources. Solar energy, which is environment friendly, is renewable and can serve as a sustainable energy source. Hence, it will certainly become an important part of the future energy structure with the increasingly drying up of the terrestrial fossil fuel. However, the lower energy density and seasonal doing with geographical dependence are the major challenges in identifying suitable applications using solar energy as the heat source. Consequently, exploring high efficiency solar energy concentration technology is necessary and realistic.

In the field of concentrated solar energy applications, Fresnel lenses recently have been one of the best choices because of the advantages such as small volume, light-weight, mass production with low cost as well as effectively increase the energy density. The early Fresnel lenses made of glass were used soon after their practical discovery by Augustin Jean Fresnel [2] in 1822 as collimators in lighthouse. Glass is an attractive option when lenses are to be used at high temperatures or when they are used for glazing. However, polymethylmethacrylate (PMMA) which is a light-weight, clear, and stable polymer with optical characteristics nearly same as that of glass, serves as a suitable material for the manufacturing of Fresnel lenses. Modern plastics, new molding techniques, and computer-controlled diamond turning machines have improved the quality of Fresnel lenses and have opened new horizons for the design of Fresnel lenses for solar energy concentration applications [2]. Fresnel lenses can be pressure-molded, injection-molded, cut, or extruded from a variety of plastics and the production costs for large outputs are considerably low.

The first attempts to use Fresnel lenses for collection of solar energy occurred at the time when suitable plastics such as polymethylmethacrylate (PMMA) became available in the 1950s. PMMA is resistant to sunlight, remains thermally stable up to at least 80 °C, its special transmissivity matches the solar spectrum, and its index of refraction is 1.49, which is very close to that of glass [2]. Consequently, most Fresnel lens designers of concentrated solar energy applications choose PMMA for their lenses because of its high optical quality combined with less costly manufacturing technologies.

In this paper a summarization of concentrated solar energy applications using Fresnel lenses systems is presented. These systems provide flexible options for numerous implementations such as solar power generation [4–6,17–35,43–47,69–84], hydrogen generation [39], photo-bio reactors as well as photochemical reactions [40,41], surface modification of metallic materials [48–50], solar lighting [51,52] and solar-pumped laser [53–55]. Most of the research and development works for concentrated solar energy applications using Fresnel lenses have been focusing on: (1) imaging Fresnel lens systems; (2) non-imaging Fresnel lens systems. Earlier works and new development of both systems are reviewed in detail. The prospect of concentrated solar energy applications using Fresnel lenses is also analyzed.

2. Concentrated solar energy systems using Fresnel lenses

Fresnel lenses are used as solar concentrators since they offer high optical efficiency along with minimal weight and low cost [78]. Though Fresnel lens concentrators have been used in solar energy concentration systems since 1960s, due to the above said potential development of Fresnel lenses in commercial solar energy concentration is still ongoing. However, major studies conducted on concentrated solar energy applications using Fresnel lenses for various purposes can be grouped under two main fields: imaging Fresnel lens systems and non-imaging systems. An overview of these studies is given under classified fields as below.

2.1. Imaging systems

A Fresnel lens is nothing but essentially a chain of prisms. Each prism represents the slope of the lens surface, but without the material of the full body of the conventional singlet. Fig. 1 shows the differences between a conventional lens and a Fresnel lens. Initially, most Fresnel lenses selected for solar energy application had not been originally designed for the collection of solar rays which were imaging devices. The imaging Fresnel lens refracts light from an object and forms an image in the focal plane which is impacted by aberrations because of the inaccurate manufacturing of the prism tips and grooves. Applications such as monocrystalline photovoltaic generation of electricity are often equipped with imaging Fresnel lenses and accurate tracking has to be employed to keep the focus of the lens in place on the receiver/absorber.

Fig. 2 illustrates the main technique used in the development of imaging Fresnel lens solar concentration systems. As seen, after the invention of Fresnel lens made of glass on lighthouse, imaging Fresnel lens began to be widely used in the field of solar concentration such as imaging solar concentrator, concentrated photovoltaic, solar thermal utilization and power generation, solar lighting, solar-pumped laser, and so on. In this section, an overview of technique development and representative applications are provided.

2.1.1. Fabrication of imaging Fresnel lens solar concentrators

In 1951, Miller et al. [3] made the world's first plastic material Fresnel lenses with high precision and excellent surface quality. The prismatic elements were very fine and were not visible to the average unaided eye and a high degree of correction for spherical aberration had been achieved by molding with the help of high precision molds. It was shown that these lenses had many applications as light collecting elements where weight and space were limited such as large condensers, large field lenses in finders, camera viewing screens, and translucent screens for projection which were considered as the early imaging systems. Boettner et al. [4] described the design and construction of Fresnel-type optics particularly suitable for use with area-type photoelectric receivers which was a point-focus system. Szulmayer [5,6] and Nelson et al. [7] both presented and investigated a solar concentrator based on linear Fresnel lens, which could reach temperatures between 60 and 143 °C for water heating, steam production, desiccants (silica gel) regeneration, as well as thermoelectric power generation [5]. The daily collection efficiencies were typically 50% at concentration ratios of near 5. Rice [8] also proposed a solar concentrator with linear Fresnel lens which has series of elongated, generally rectilinear, side-by-side, parallel solar ray focusing surfaces.

Besides, Hastings et al. [9] studied line-focusing acrylic Fresnel lenses which were durable and adaptable to mass production techniques with application potential in the 200–370 °C range analytically and experimentally. Franc et al. [10] presented optical properties of flat linear Fresnel lenses manufactured from glass and discussed the behavior of Fresnel lenses for use in buildings in perpendicular and inclined beams of rays. Tver'yanovich [11] analyzed the possible configurations of the working profile and their correlation with the lens production technology and indicated that the fundamental analytical dependency for the optical calculation of Fresnel lens profiles with plane working faces and a plane carrying layer. However, Appeldorn [12] considered more factors such as wind loads, gravity and other environmental factors causing sig-

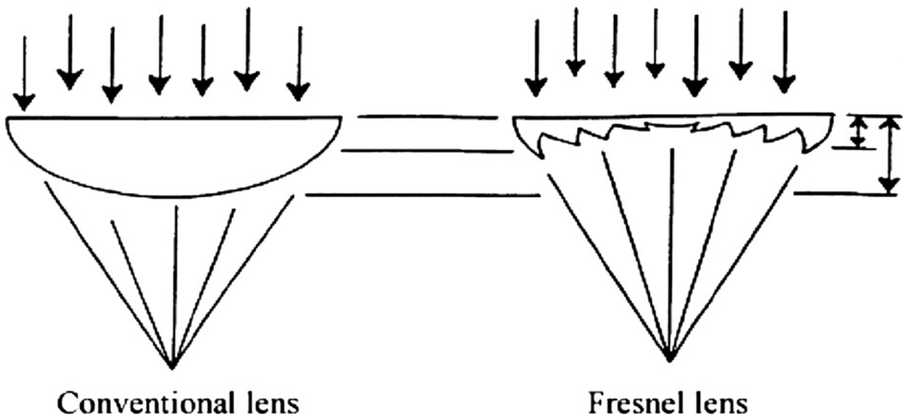

Fig. 1. Conventional lens and Fresnel lens [48].

nificant deterioration in the efficiency of the system and proposed a solar energy concentrator including a thin flexible Fresnel lens for focusing incident solar radiation not normal to the lens onto a target area by refraction. Krasina et al. [13] carried out the study on the optimum solar energy Fresnel lenses to identify the optimum design parameters to improve the efficiency of the whole system. It was desirable to decrease the lens's focal distance in order to improve the module's compactness, and reduce materials consumption and weight. Nevertheless, it was limited by a number of factors influencing the value of the lens's local efficiencies and, consequently, the overall integral efficiency.

Meanwhile, early two-stage imaging Fresnel lens solar concentration system has also been proposed. Collares-Pereira et al. [14] emphasized that the lens–mirror combinations were useful whenever concentration rather than image formation was important, especially in radiation detectors and solar energy collectors.

Other method of imaging Fresnel lens production is to design aspheric Fresnel lenses on a spherical surface [15], which is based on calculating solutions to Snell's law along the lens surface. These lenses are intended for the wavelength range of 8–12 μm. However, the method can be easily applied to lenses designed for other wavelengths and the procedure used to manufacture the lenses was to construct a diamond-turned master surface, followed by injection molding with high-density polyethylene.

2.1.2. Concentrated photovoltaic applications

As plastic Fresnel lens is light-weight and capable of elevating the density of solar energy, it was soon used for concentrated photovoltaic power generation. Oshida [16] investigated the photovoltaic applications with Fresnel lenses based on spectral distribution considerations. Harmon [17] presented experimental and analytical methods to determine the efficiency and intensity variations of a circular Fresnel lens as a solar concentrator. The experimental part was done using a photovoltaic scan technique and a simulation was constructed to model the behaviour of the lens. It was found that the lens was an inefficient concentrator with losses that begin at 20% and rose to about 80% as the focal distance decreased. However, the lens was adequate for low concentration purposes with photovoltaic systems. Donovan et al. [18] designed a photovoltaic concentrator array, based on the use of an acrylic Fresnel lens to concentrate sunlight on high intensity solar cells and optimized to obtain economical photovoltaic power generation. It was considered that the major design aspects for optimization were the concentration ratio, size and shape of the Fresnel lens,

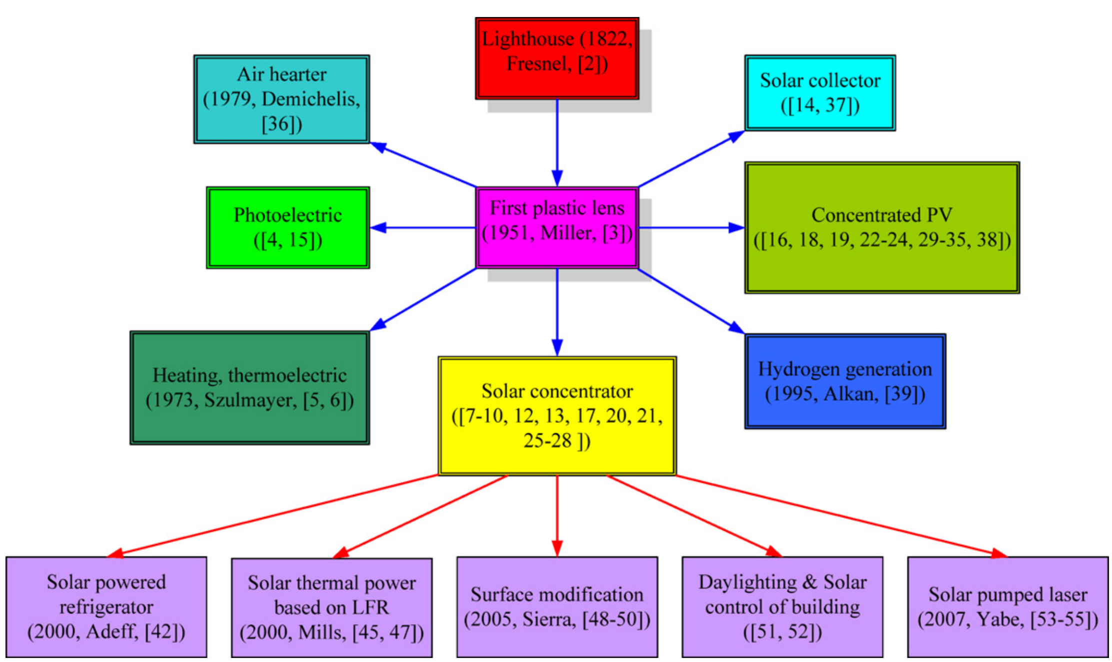

Fig. 2. Flow chart of technique development of imaging Fresnel lens solar concentration systems.

array size and shape, structure minimization, tracking and control as well as the practical aspects of operation and maintenance. It was found that several prototype photovoltaic concentrator modules exceeded 9.0% efficiency requirement established for this program. Besides, James et al. [19] discussed that the economic viability of concentrator photovoltaic systems which depended on maintaining high cell conversion efficiency, a high optics transmission (or reflection) efficiency, and a low structure cost per unit area. It was shown, both theoretically and experimentally, the conversion efficiency of concentrator solar cells was reduced by illuminating the cells with a non-uniform flux density and the structure cost was reduced by increasing the allowable tracking error. Thus flux density uniformity, optical transmission, allowable tracking error, cost per unit area and lifetime are some of the important criteria for Fresnel lens photovoltaic concentrating optics.

Nevertheless, a curved prismatic Fresnel-type lens primarily used for concentrating sunlight in a solar collector, proposed by O'Neil [20], was probably the best-known commercially introduced concentrator technology for photovoltaics. The lens comprised a substantially smooth, convex outer surface and a plurality of prisms arranged side-by-side along a curve on the inner surface to direct incoming light to a common area. Later, he proposed a refractive optical concentrator for focusing solar energy on to small focal spots, which is a linear Fresnel lens optically cross-coupled with simple cylindrical lenses namely "bi-focused solar energy concentrator". It was used and the study had shown that the bi-focused radiant energy was effectively concentrated upon a series of photovoltaic cells to obtain direct electrical power [21].

During 1980s, several concentrated photovoltaic products came out. Accordingly, new research was focused on tracking system, cooling techniques for solar cell, high concentration system and other shapes of imaging Fresnel lens. Nakata et al. [22] described a 300 W polar axis tracking concentrator with 36 circular Fresnel lenses (40 cm × 40 cm) and cells which were designed to obtain the uniform light distribution. It was shown that the optical efficiency of the lens is 83% and the output power was about 50% higher than that of the commercial lens. The output power from a typical concentrator cell was 9.13 W with 12.0% cell efficiency under 4.7 W/cm^2 sunlight at 38 °C and the output power from five concentrator units was 253.7 W with 10.2% total cell efficiency. Shepard et al. [23] presented a passively cooled point-focus photovoltaic concentrator module for use in remote, stand-alone, or intermediate load center applications. Moffat et al. [24] designed a high concentration photovoltaic module that uses a domed, point-focus Fresnel lens and described the design optimization process, and results from lens and receiver tests. Optical design, analysis, and testing of both secondary optical units and domed Fresnel lenses made a significant contribution to the project.

The concentrated flux distribution is a key problem, since photovoltaic cells require homogeneous flux and direct radiation for optimum performance. Mijatovic et al. [25] considered a cylindrical system Fresnel lens-absorber with uniform concentration and normal incoming rays to the absorber and obtained the unique solution to the problem by approximating the sun as a point source. Jebens et al. [26] proposed a specially designed Fresnel lens and a solar cell located on the axis of the lens at its focal plane. The lens is designed so that its central facets project the light from the sun toward the outer periphery of the cell. Likewise, the facets progressively toward the periphery of the lens project light progressively toward the center of the cell to obtain a uniform distribution of light on the cell. Finally, the adjacent groups of facets of the lens project the light alternately in front and beyond the cell to maintain a constant light intensity for a certain depth of focus of the lens.

In addition to the above work, Akhmedov et al. [27] developed a method for calculating geometrical parameters of solar energy concentrators in the form of round Fresnel lenses with flat band. It was found that the use of round Fresnel lenses in systems, requiring uniform flux distribution, was reasonable only at concentrations higher than 3000 and at lower concentrations the share of effective flow incident on a receiver was small which did not exceed 10%. Soluyanov et al. [28] presented a calculation method to obtain density distribution of solar radiation concentrated by a Fresnel lens taking into account of the main design factors such as real lens errors, orientation in accuracy of the lens optical axis to the Sun, longitudinal and lateral defocusing.

Fig. 3. Multiple point-focus Fresnel lenses, mounted in gimbals, with closed-loop tracking about both axes [33].

Since 1990s, concentrated photovoltaic systems based on imaging Fresnel lenses became more and more mature. The research and development works were directed to many fields such as bifocal Fresnel lens test for multijunction solar cells [29], space concentrator photovoltaic modules [30,31], field test of concentrator photovoltaic system [32], and so on. In addition, the demonstration concentrated photovoltaic systems based on imaging Fresnel lenses had been built and tested in several countries.

Whitfield et al. [33] compared some 90 possible small PV concentrator designs that might be suitable for use at remote sites including point-focus Fresnel lenses with two-axis tracking and linear Fresnel lens with solid CPC secondaries and two-axis tracking. Fig. 3 shows a two-axis tracked, point-focus system using flat acrylic Fresnel lenses. The advantages of this design include: maximum beam insolation collection due to two-axis tracking, potential for simple mass-produced optics and the use of the housing as heat sink. However, the system has a main disadvantage of increasing high cost because of the need for two-axis tracking. Flat Fresnel lenses are less efficient than domed ones at *f*-numbers below about 1.1, because the reflection losses at the second surface were high due to the large angle of incidence. It was found that linear Fresnel lens with solid CPC secondaries had the advantage of being simple and totally enclosed although it was more costly.

As curved prismatic Fresnel-type lens could further increase the system efficiency by higher concentration [20,21], O'Neill [34] proposed a novel, high-efficiency, extremely light-weight, robust stretched Fresnel lens solar concentrator for space power applications which consisted of a flexible Fresnel lens attached to end supports. These supports helped the lens to maintain its proper position and shape while the system was set on orbit in space. This new concentrator approach provided significant advantages over the prior space photovoltaic concentrator arrays. The photovoltaic concentrator arrays using the new stretched lens were much

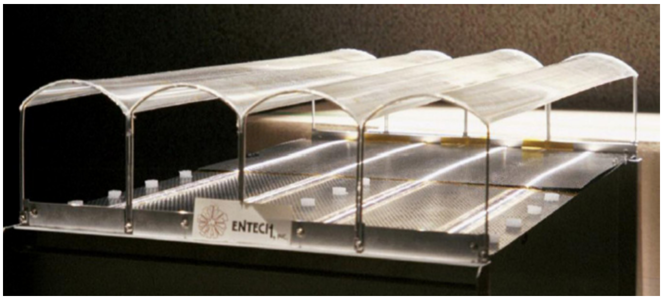

Fig. 4. Stretched Lens Array (SLA) with Four Lenses and Receivers [35].

lighter and more economical. Also, they were easier to be stowed into a compact volume for launch, and easier to deploy on orbit than prior space concentrator arrays. In addition, the new stretched lens would eliminate the need for a fragile glass superstrate to support the lens, substantially improving robustness of the lens. In 2003, O'Neill et al. [35] tested the Stretched Lens Array (SLA) which was measured at over 27% net solar-to-electric conversion efficiency for space sunlight, and over 30% net solar-to-electric conversion efficiency for terrestrial sunlight. More importantly, the SLA provided over 180 W/kg specific power at a greatly reduced cost compared to conventional planar photovoltaic arrays in space and the cost savings were mainly due to the use of 85% less expensive solar cell material per unit of power produced [35]. Fig. 4 illustrates the basic concept of the Stretched Lens Array (SLA) in an early functional prototype.

2.1.3. Solar thermal utilization and power generation

Major investigations to this field consists of six aspects, namely, Fresnel solar collectors including air heater [36–38], convex glass Fresnel lenses for hydrogen generation [39], photo-bio reactors and photochemical reactions [40,41], solar powered refrigerator [42], Linear Fresnel Reflector (LFR) technology [43–47], and metal surface modification [48–50]. The last three aspects have been demonstrated successfully.

As seen in Fig. 5, a thermoacoustically driven thermoacoustic refrigerator (TADTAR) powered by solar thermal energy was demonstrated. Adeff et al. built and tested the system successfully. A 0.457 m diameter Fresnel lens focused sunlight onto the hot end of a 0.0254 m diameter reticulated vitreous carbon prime mover stack, heating it to 475 °C, thereby eliminating the need for the most troublesome component in a heat driven prime mover, the hot heat exchanger. The high intensity sound waves produced by the prime mover could drive the refrigerator to produce 2.5 W of cooling power at a cold temperature of 5 °C and a temperature span of 18 °C [42].

Linear Fresnel Reflector (LFR) technology relies on an array of linear mirror strips which concentrates light on a fixed receiver mounted on a linear tower. The LFR field can be imagined as a broken-up parabolic trough reflector, but unlike parabolic troughs, it does not have to be of parabolic shape, large absorbers can be constructed and the absorber does not have to move. So Fresnel reflectors are considered as the representative imaging devices [2]. A representation of an element of an LFR collector field is shown in Fig. 6. The greatest advantage of this type of system is that it uses flat or elastically curved reflectors which are cheaper compared to parabolic glass reflectors. Additionally, these are mounted close to the ground, thus minimizing structural requirements [43]. The great solar pioneer Giorgio Francia [44] was the first to use this principle to develop both linear and two-axis tracking Fresnel reflector systems at Genoa, Italy in 1960s. These systems showed that elevated temperatures could be reached using such systems but had to be transferred on to two-axis tracking, possibly because advanced selective coatings and secondary optics were not available then [45]. The Israeli Paz Company in the early 1990s also used an efficient secondary CPC-like optics and an evacuated tube absorber [46].

However, one difficulty with the LFR technology is that avoidance of shading and blocking between adjacent reflectors leads to increased spacing between reflectors. Blocking can be reduced by increasing the height of the absorber towers, but this increases cost. To address this issue to certain degree, Compact Linear Fresnel Reflector (CLFR) technology has been recently developed at Sydney University in Australia. Mills et al. [47] evaluated Com-

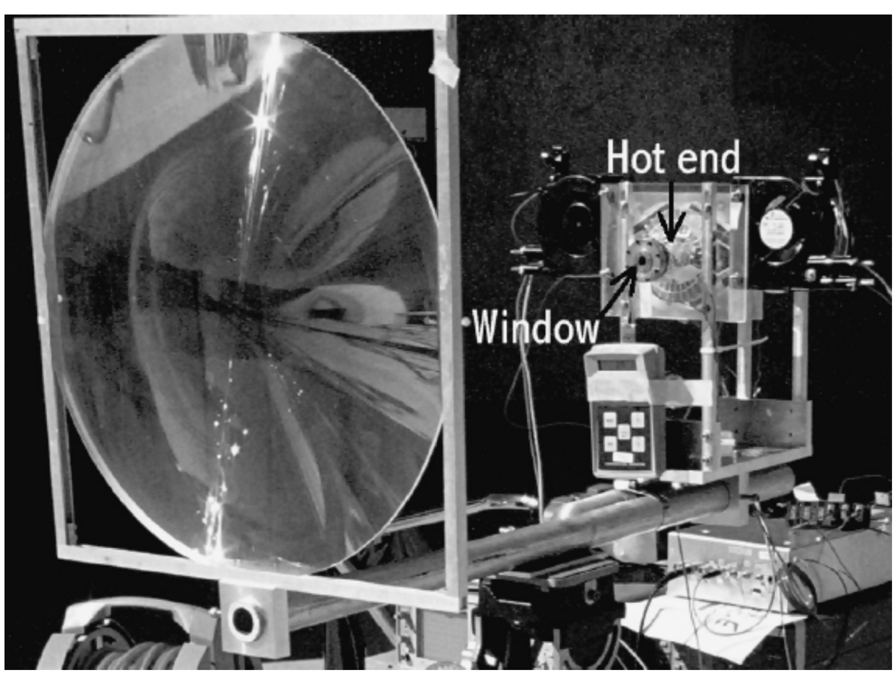

Fig. 5. The solar powered TADTAR including a point-focus Fresnel lens [42].

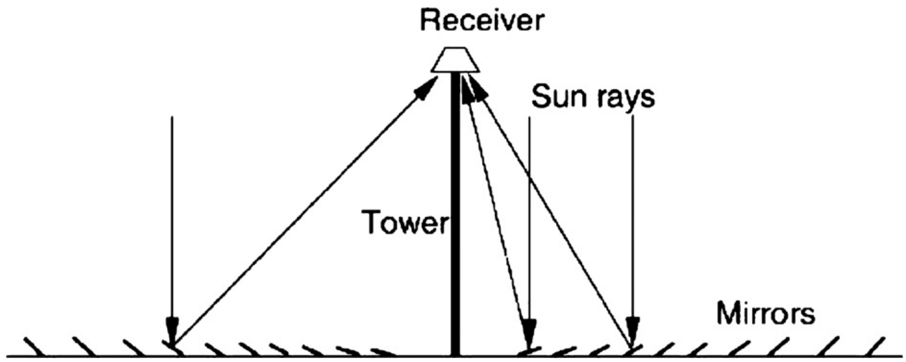

Fig. 6. Schematic diagram of a downward facing receiver illuminated from an LFR field [43].

pact Linear Fresnel Reflector (CLFR) concepts suitable for large scale solar thermal electricity generation plants. In the CLFR, it was assumed that there would be many parallel linear receivers elevated ontower structures that were close enough for individual mirror rows to have the option of directing reflected solar radiation to two alternative linear receivers onseparate towers (Fig. 7). Alternative versions of the basic CLFR concept that were evaluated include absorber orientation, absorber structure, the use of secondary reflectors adjacent to the absorbers, reflector field configurations, mirror packing densities, and receiver heights.

High concentrated solar energy with high temperature serves as a suitable energy source for superficial modification of metallic materials. Sierra et al. [48–50] built an equipment (Fig. 8) in Department of Corrosion and Protection, National Center for Metallurgical Research (CENIM-CSIC) to apply concentrated solar energy in the field of high and very high temperatures by using simple and cheap Fresnel installation to achieve high solar energy density for surface modifications of metallic materials. It was found that high temperatures (1500–2000 K) were achieved in a few seconds and usually the materials treatments were completed in minutes. Hence, Fresnel lens installations could serve as an alternative to the conventional equipment for material treatment and even applicable to the large solar installations. For example, solar energy concentrated by a Fresnel lens could ignite a self-propagating high-temperature synthesis in a powder mixture of nickel aluminum, for producing NiAl coatings on a carbon steel substrate successfully [48–50].

2.1.4. Solar lighting

Solar lighting is a new field of imaging Fresnel lens utilization which drew a little attention. Tsangrassoulis et al. [51] presented the development of a method to control the light output from a prototype hybrid lighting system which transported daylight from a heliostat with a concentrating Fresnel lens to a luminaire in a windowless room, via a large core liquid fiber optic. The main artificial lighting system was located outside of the building without the possibility for dimming due to the chosen lamp type.

Furthermore, Tripanagnostopoulos et al. [52] emphasized that Fresnel lenses were suitable optical devices for solar radiation concentration and were of lower volume and weight, smaller focal length and lower cost, compared to the thick ordinary lenses. The advantage to separate the direct from the diffuse solar radiation made Fresnel lenses suitable for illumination control of building interior space, providing light of suitable intensity level and without sharp contrasts. They suggested the Fresnel lens concept for solar control of the buildings to keep the illumination and the interior temperature at the comfort level. Laboratory scale experimental results were presented, giving an idea about the application of this new optical system. It was found that the collection of 60-80% of the transmitted solar radiation through the Fresnel lenses on linear absorbers leaves the rest amount to be distributed in the interior space for the illumination and thermal building needs. In low intensity solar radiation, the absorber could be out of focus, leaving all light to come in the interior space and to keep the illumination at an acceptable level (Fig. 9). The Fresnel lenses could be combined with thermal, photovoltaic, or hybrid-type photovoltaic/thermal absorbers to collect and extract the concentrated solar radiation in the form of heat, electricity or both. By using thermal absorbers and for low operating temperature, efficiency of about 50% could be achieved, and considering photovoltaics, satisfactory electrical output could be obtained. Regarding the effect of the suggested system to building space cooling, the results showed a satisfactory

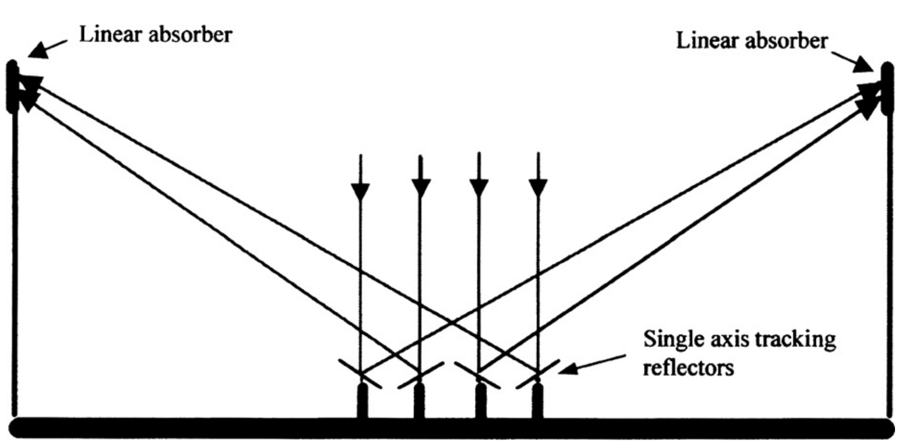

Fig. 7. Schematic diagram showing interleaving of mirrors in a CLFR without shading [47].

Fig. 8. Fresnel lens installation at CENIM [48–50].

temperature reduction, exceeding 10 °C for cold water circulation through the absorber.

2.1.5. Solar-pumped laser

Solar-pumped laser by high concentration Fresnel lens is another investigation direction which is very popular in Japan. Yabe et al. [53] achieved 11%–14% slope efficiency of solar-pumped laser by Cr-codoped Nd: yttrium aluminum garnet ceramic and Fresnel lens focusing from natural sunlight. The laser output of 24.4 W was achieved with 1.3 m^2 Fresnel lens. The maximum output for unit area of sunlight was 18.7 W/m^2, which is 2.8 times larger than mirror collector. The fluorescence yield at 1064 nm for various pumping wavelengths was measured both for Crcodoped and non-doped laser media, and 1.8 times enhancement of laser output from sunlight was predicted. Fig. 10 illustrates the solar-energy-pumped laser with Fresnel lenses system. In 2008, they had developed a solar-pumped laser system with 7%–9% slope efficiencies. A Fresnel lens (2 m × 2 m, f = 2000 mm) was mounted on a two-axis sun tracker platform and focuses solar radiation toward laser cavity (Fig. 11), which embraced Cr: Nd: YAG (yttrium aluminum garnet) ceramic rod. It was shown that the maximum emitted laser power was 80 W corresponding to maximum total area performance of 20 W/m^2 for the Fresnel lens area and 4.3% net conversion efficiency has been achieved by using direct solar radiation into laser. It was indicated that this solar laser system would be used as a section of power plant in a magnesium energy cycle as a cost-efficient solar energy converter [54,55].

From the above research, it is obvious that solar power generation is the main aim of imaging Fresnel lens solar concentration systems because Fresnel lens offer more flexibility in optical design, thus allowing for uniform flux on the absorber, which is one of the conditions for efficiency in photovoltaic cells.

2.2. Non-imaging systems

Non-imaging concentrators have been more widely used in solar energy collection systems since its discovery in 1965. Because the concentration of solar energy does not demand imaging qualities, but instead requires flexible designs of highly uniform flux concentrators coping with solar disk size, solar spectrum, and tracking errors. Therefore, Fresnel lenses of non-imaging design are usually of convex shape in order to get high concentration ratio and flux distribution with short focal length. The main characteristic of the non-imaging systems is their concentration ratios (i.e. the geometric concentration ratio C) which are commonly classified as being low for C≤10, or medium for 10<C≤100, or high for C>100 [2].

Fig. 12 depicts the main technique development of non-imaging Fresnel lens solar concentration systems. As seen, after the inven-

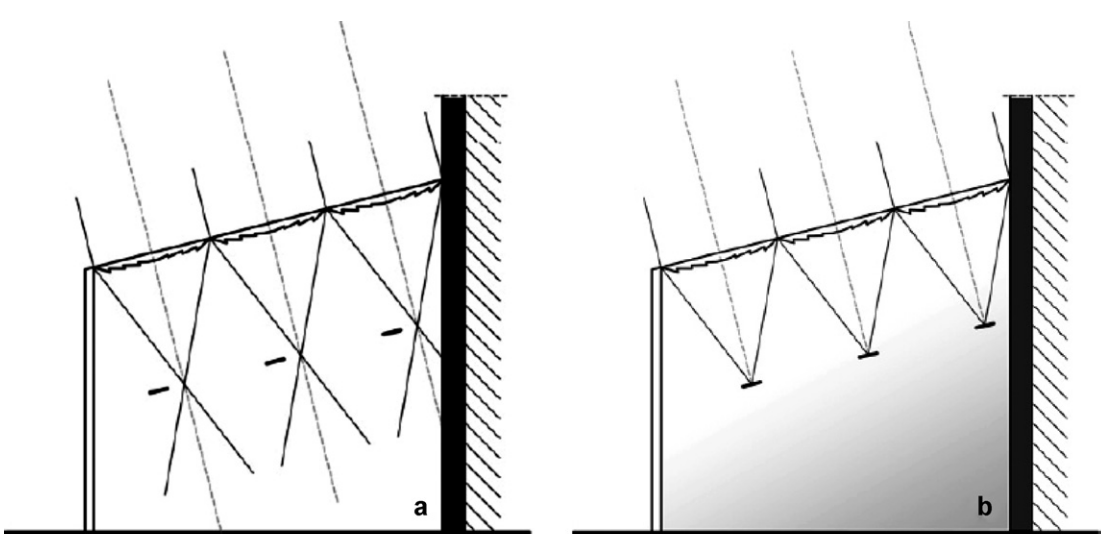

Fig. 9. Lighting effect of the Fresnel lens system to a building sunspace, with (a) the absorbers out of focus and no shading effect and (b) on focus with shading effect [52].

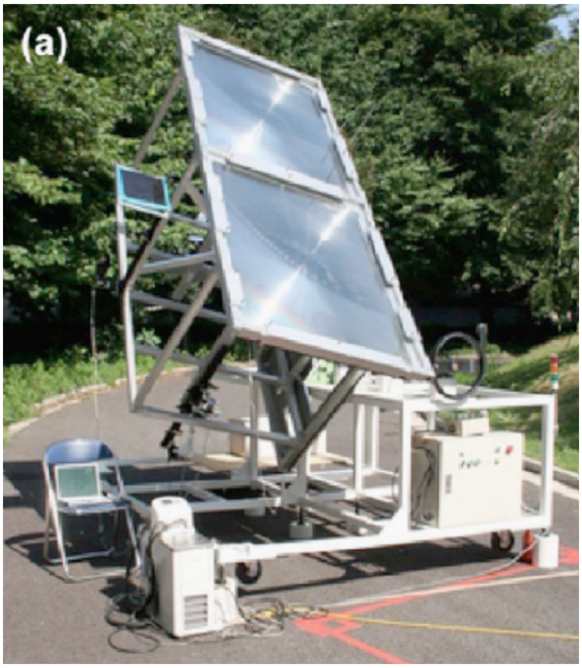

Fig. 10. Test system for laser from natural sunlight. Two pieces of Fresnel lens are used. All the system was in one unit and moves together. Once alignments of the laser cavity were fixed, realignment would not be necessary even if all the system moved following the sun [53].

Fig. 11. Solar-pumped laser setup using Fresnel lenses [54].

tion and application of the earliest non-imaging concentrator compound parabolic concentrator (CPC), non-imaging optics was applied to Fresnel lenses and began to be widely used in the field of solar concentration such as non-imaging solar concentrator, concentrated photovoltaic applications, solar thermophotovoltaic system, and so on. In this section, an overview of technological development and representative applications are presented in the following sections.

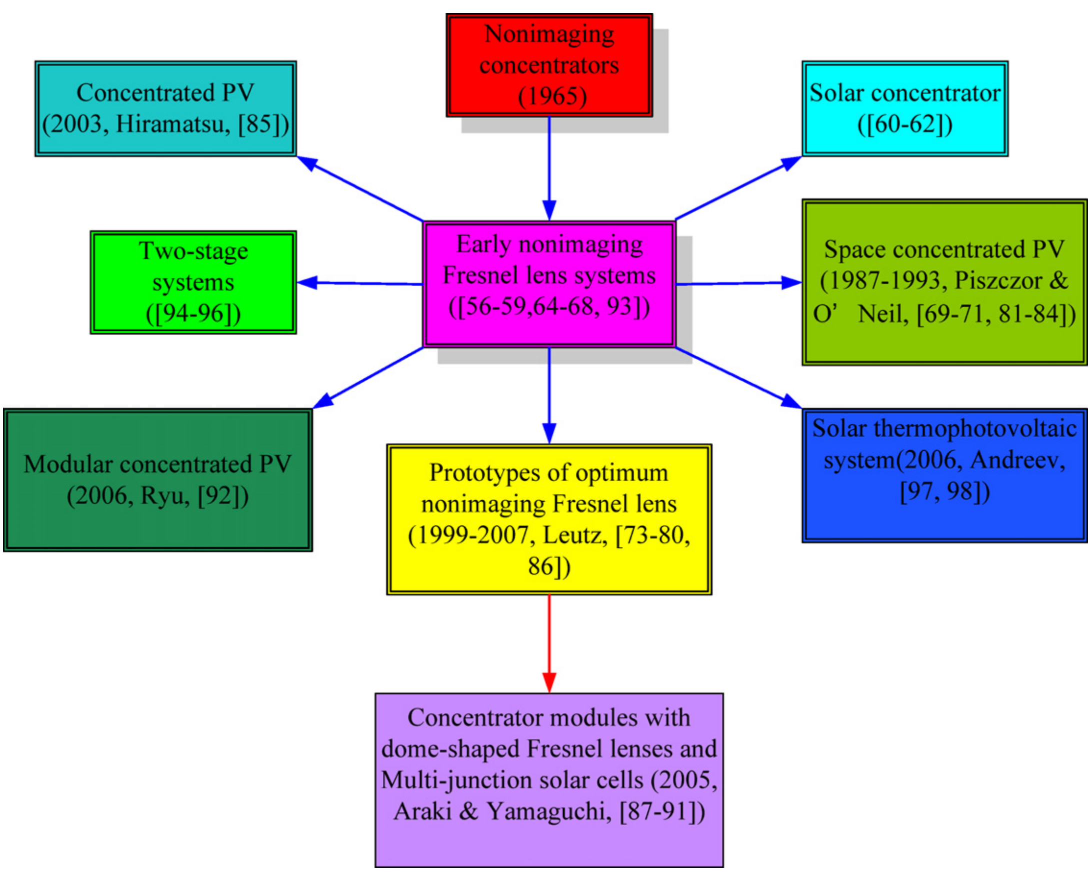

Fig. 12. Flow chart of technique development of non-imaging Fresnel lens solar concentration systems.

Fig. 13. ENTECH's fourth-generation concentrator module [63].

2.2.1. Characterization of non-imaging solar concentration systems

Concentration systems when using Fresnel lenses the effect of the chromatic aberration can become important. In order to take this effect into account, Lorenzo [56] defined a parameter that allows one to estimate the degradation of the thermodynamic quality of the concentrator due to this effect. Moreover, Lorenzo et al. [57] analyzed an arbitrarily shaped linear Fresnel lens acting either as sole concentration stage or as the first stage of a two-stage concentration system in which the second stage considers the first as a Lambertian optical source. Yet in another study [58], the gain that could be achieved with a one or two-stage concentrator was compared, wherein the first stage using a Fresnel lens or a parabolic mirror, as a function of the luminosity of the concentrator. It was shown that the achievable gain using a parabolic mirror was greater than that obtained using a flat or roof lens but was lower than that obtained using a curved lens. They were also concerned with symmetrical bidimensional concentrators and proved that for a given source's angular extension a curve exists that divided the plane into two regions. No ideal concentrator could be found with its edges on the outer region and no Lambertian concentrator could be found with its edges on the inner region. It was concluded that a concentrator was forced to cast some of the incident energy outside the collector in order to obtain the maximum power [59].

Apart from the above studies, the design and fabricating procedure for medium and high concentration non-imaging Fresnel lens was also well investigated by many researchers [60–62]. Lin et al. [63] used optical software TracePro to simulate the non-imaging Fresnel lens each pitch size of which was 0.3 mm and 200 mm focus distant. The losses of non-imaging Fresnel lens was also discussed and found out the relation of efficiency and F-Number. For the said system, the optical concentration ratio could reach 15× (2-D) and 230× (3-D).

2.2.2. Line-focus systems

Comparing actual linear solar concentration systems based on Fresnel lenses: imaging systems had optical concentration ratios of less than 5, while non-imaging systems yield optical concentration ratios greater than 10 [2]. Therefore, Kritchman proposed a new type of convex Fresnel lens which was capable of concentrating solar radiation very close to the ultimate concentration limit [64]. He also considered the transmission elements, particularly a new design for an efficient linear Fresnel lens capable of high concentration for a given acceptance angle and predicted that the performance of the lens was comparable to that of the "ideal" reflector, while providing greater reliability at a lower cost [65]. In 1980, Kritchman tested a new linear convex Fresnel lens with its groove side down. The design philosophy was similar to that of the highly concentrating two-focal Fresnel lens but includes a correction for chromatic aberration. It was found that a solar concentration ratio as high as 80 was achieved. For wide-acceptance angles, the concentration neared the theoretical maximum [66]. Moreover, the performance of coma and color corrected linear Fresnel lenses were tested in polar tracking applications in 1981 [67]. In 1984, yet another new design of a second stage reflective element was presented, which was closely related to the earlier trumpet configuration. The implementation for linear Fresnel lenses was derived, leading to a high solar concentration with both convex and flat lenses [68].

Meanwhile, O'Neil et al. [69] documented the current status of a space concentrator array which used refractive optics, gallium arsenide cells, and prismatic cell covers to achieve excellent performance at a very low array mass. The prismatically covered cells had established records for space cell performance (24.2% efficient at 100 AM0 suns and 25 °C) and terrestrial single-junction cell performance (29.3% efficient at 200 AM1.5 suns and 25 °C). In 1991, they presented the most important of developments related to a linear Fresnel lens photovoltaic concentrator technology. The measured performance parameters for both of these systems (the 300 kW system and an improved 20 kW PVUSA "Emerging Technology" system deployed in March 1991) are presented and discussed [70]. In 1993, significant improvements in manufacturing technology for the fourth-generation concentrator modules were clearly listed and discussed [71]. Fig. 13 shows the fourth-generation concentrator module.

Besides, Piszczor et al. [72] proposed a refractive linear photovoltaic concentrator array for use in space which was a high-efficiency optical device and was easily manufacturable using a low-cost, roll-to-roll fabrication process. This concentrator lens design was being combined with a novel line-focus GaAs/GaSb tandem cell receiver which used an optical secondary to direct light away from the cell interconnects as well as provided increased sunlight concentration and radiation protection to the cell. The linear Fresnel lens concentrator had the advantages of high array efficiency and an inherently radiation-hard array design while requiring precise tracking only within a single axis.

Since the late 1990s, the prototypes of non-imaging Fresnel lens used for solar concentration application had been manufactured which accelerated the improvement of non-imaging system. Leutz R et al. [73,74] designed an optimum convex shaped non-imaging Fresnel lens following the edge ray principle. The lens was evaluated by tracing rays and calculating a projective optical

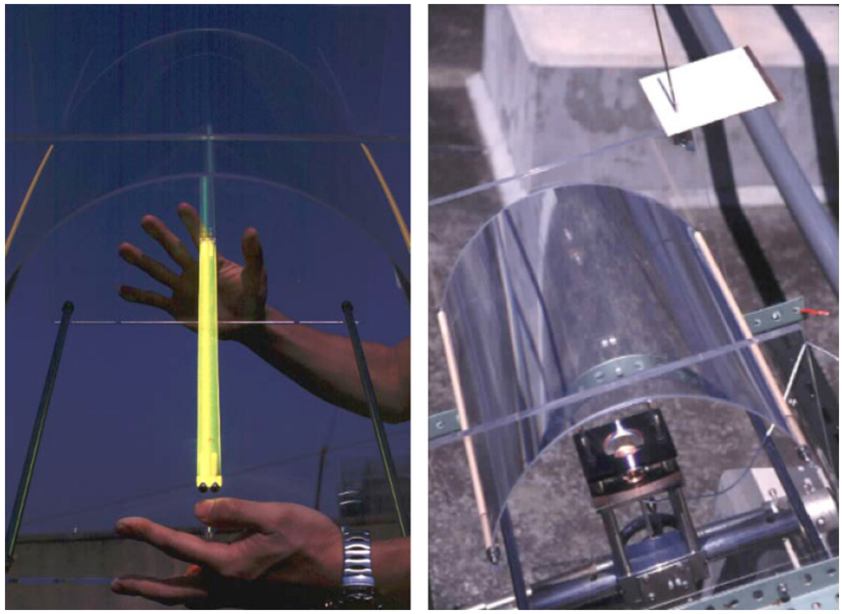

Fig. 14. Experimental setup to measure the radiation flux distribution of a linear non-imaging Fresnel lens in Tokyo, Japan [74,76].

concentration ratio and was intended for use in evacuated tube-type solar concentrators, generating mid-temperature heat to drive sorption cycles, or provide industrial process heat. It could also be used along with a secondary concentrator in photovoltaic applications. It was concluded that if the outer surface of the lens must be smooth, the lens shape would be convex. A linear lens prototype intended to concentrate solar energy had been designed, manufactured and tested (Fig. 14). The flux distribution and the optical concentration ratio were presented, and it was found that shaped non-imaging Fresnel lenses were suited for application as solar concentrators, or as collimators, or in lighting applications, where they could fulfill all of the technological requirements as well as being adaptable to the necessities of fashionable design [75,76]. In 2000, they investigated the flux densities of the novel non-imaging Fresnel lens which were described as dependent on optical concentration ratio of the lens, solar disk size and related brightness distribution, and spectral dispersion of incident sunlight. It was concluded that the optimum linear non-imaging Fresnel lens concentrator was proposed in terms of concentration ratio, i.e. acceptance half angle pairs to using in space photovoltaics [77].

The suitability of Fresnel lenses of imaging and non-imaging designs for solar energy concentration applications were discussed and presented as well [78]. It was emphasized that non-imaging optics were presented as offering the possibilities needed for a breakthrough of Fresnel lenses in commercial solar energy concentration, both in photovoltaic and thermal power conversion. In 2001, they studied geometrical and optical concentration ratios of the optimum non-imaging arched linear Fresnel lens. Theoretical results were compared with tests of the existing prototypes of the non-imaging lens, used for the concentration of solar radiation and the novel non-imaging lens was put into the context of historic research, and was made comparable to other non-imaging concentrators, notably the Compound Parabolic Concentrator. Finally they proposed the use of a linear kaleidoskope-based secondary concentrator to achieve a uniform flux distribution and the reproduction of the spectrum of the incoming light [79]. The design quality of the optical elements in a solar photovoltaic concentrator was the key element to enable the exploitation of the efficiency of multijunction devices. The cells as such require homogeneous flux over the cell area to obtain higher efficiencies, and the potential impact of inhomogeneous flux on the cell efficiencies have been investigated [80].

2.2.3. Point-focus systems

The non-imaging Fresnel lens has distinct superiorly compared to the imaging Fresnel lens, such as shorter focal length, larger accept angle, smaller volume and higher concentration. Hence, much attention has been paid to advanced non-imaging solar concentration systems research and development. Piszczor et al. [81] reported an advanced photovoltaic concentrator system for space applications using a domed Fresnel lens concentrator and a prismatic cell cover, to eliminate metalization losses, dramatic reductions in the required area. Fig. 15 shows the advanced concentrator concept in the future space station. The advanced concentrator concept also had significant advantages when compared to solar dynamic Organic Rankine Cycle power systems in Low Earth Orbit applications where energy storage was required. In 1990, they pointed out that the three critical elements of the array concept

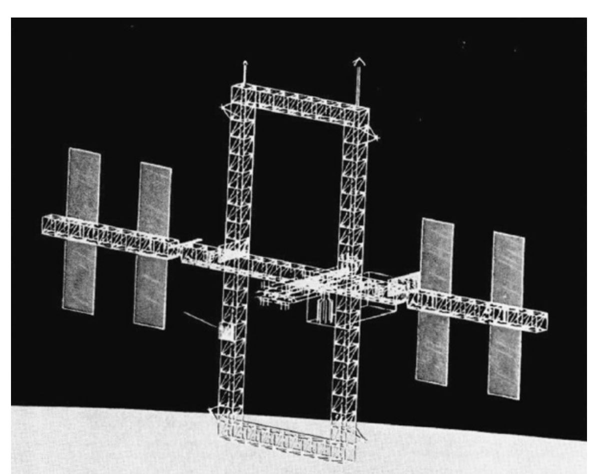

Fig. 15. Space station with a 300 kW power system using advanced PV concentrator [81].

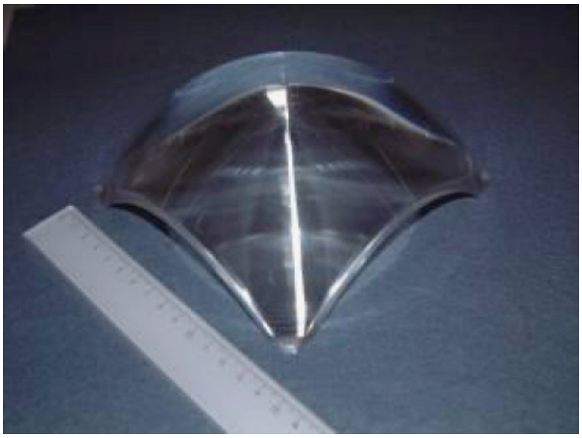

Fig. 16. Dome-shaped 500× Fresnel lens produced by Daito Metal Co [86].

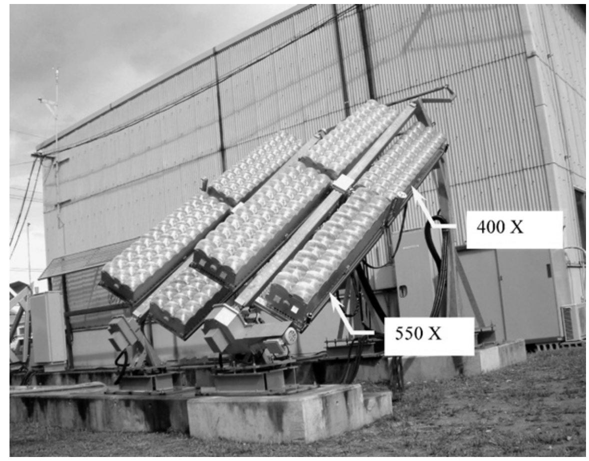

Fig. 17. 550× and 400× modules on two-axis trackers using open-loop control. The bottom right module with two lines of dome-shaped Fresnel lenses was a 550 × 150 W module. The remainder were 400 × 200 W modules. The overall system rating was 1550 W [87].

were the Fresnel lens concentrator, the prismatic cell cover and the photovoltaic cell. The prototype concentrator lenses had been fabricated and tested, with optical efficiencies reaching 90% [82]. They also emphasized that the recent advances in 30% efficient stacked cell technology would have a significant effect on the array performance. It was concluded that near-term array performance goals of 300 W/m^2 and 100 W/kg were feasible [83,84].

Furthermore, Hiramatsu et al. [85] designed and built 300× condensed light, flat and half-dome non-imaging Fresnel lenses prototypes, and verified satisfactory performances with condensing efficiencies of 77.3% for the flat type and 81.5% for the half-dome type. In addition, further examination was made on lens material strength and weather resistance to verify that the present material meet the required performance. Meanwhile, a two-axis sun tracking apparatus was developed, and was put into operation and its excellent tracking ability was verified by yielding excellent results in all three tracking performance evaluations.

However, the demonstration of high concentration system applications with prototypes of non-imaging Fresnel lenses had been built and tested which would be widely used in the future commercial solar energy concentration with cost-effective products appearing. In 2007, Akisawa et al. investigated new design method for non-imaging Fresnel with flat upper surface (Fig. 16) so that the production could be easier. The design of prisms was formulated by means of non-linear optimization to have maximum acceptance half angle with edge-ray principle. It was shown that designing more than 500× Fresnel lens was possible [86].

Japanese researchers continued to study the non-imaging Fresnel lens by joining these dome-shaped prototypes together for high concentrated photovoltaics. Araki et al. [87–89] investigated concentrator modules with dome-shaped Fresnel lenses and triple-junction concentrator cells (Fig. 17). They had achieved a 26.6% peak uncorrected efficiency from a 7056 cm^2 400× module with 36 solar cells connected in series, measured in laboratory. The peak uncorrected efficiencies of the same type of the module with 6 solar cells connected in series and 1176 cm^2 area measured by Fraunhofer ISE and NREL were reported to be 27.4% and 24.8%, respectively. The peak uncorrected efficiency for a 550× and 5445 cm^2 module with 20 solar cells connected in series was 28.9% in laboratory. The temperature-corrected efficiency of the 550× module under optimal solar irradiation condition was 31.5 ± 1.7%. In terms of performance, the annual power generation was discussed based on a side-by-side evaluation against a 14% commercial multicrystalline silicon module.

Similar to the above study, Yamaguchi et al. [90,91] presented their research and development (R&D) activities on III–V compound multi-junction (MJ) solar cells and demonstrated high-efficiency and large-area (7000 m^2) Fresnel lens solar concentrator could improve the out door efficiency of InGaP/InGaAs/Ge 3-junction solar cell modules to about 27%. This was possible because of the combination of high-efficiency InGaP/InGaAs/Ge 3-junction cells along with low optical loss dome-shaped Fresnel lens and homogenizers. Fig. 18 shows the 400× and 7000 cm^2 concentrator module fabricated with the newly developed dome-shape Fresnel lenses and 36 pieces of randomly selected solar cells connected in series.

Several researchers have further tried to develop new non-imaging systems in order to obtain high solar concentration. In this direction, Ryu et al. [92] proposed a new configuration of solar concentration optics utilizing modularly faceted Fresnel lenses (Fig. 19) to achieve a uniform intensity on the absorber plane with a moderate concentration ratio. The uniform illumination was achieved by the superposition of flux distributions resulting from modularly faceted Fresnel lenses. Based on the concept of modularly faceted Fresnel lenses, the cost effective 3-D concentration solar PV system was designed for future applications and mathematical modeling for deriving the flux distribution and the concentration efficiency at the absorber plane were developed. As an example, the distribution of the solar flux, at the cell position, was simulated using ray-trace technique for 9, 25, 49, 81, and 121 suns concentration systems. It was found that the irradiance distributions at the cell plane were estimated to be uniform within ∼20%, with a transmis-

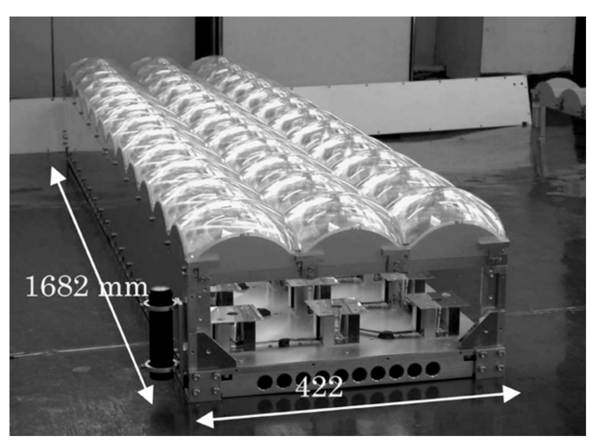

Fig. 18. 7000 cm^2 and 400× concentrator module with 36 receivers connected in series and dome-shaped Fresnel lens made by injection mold [90,91].

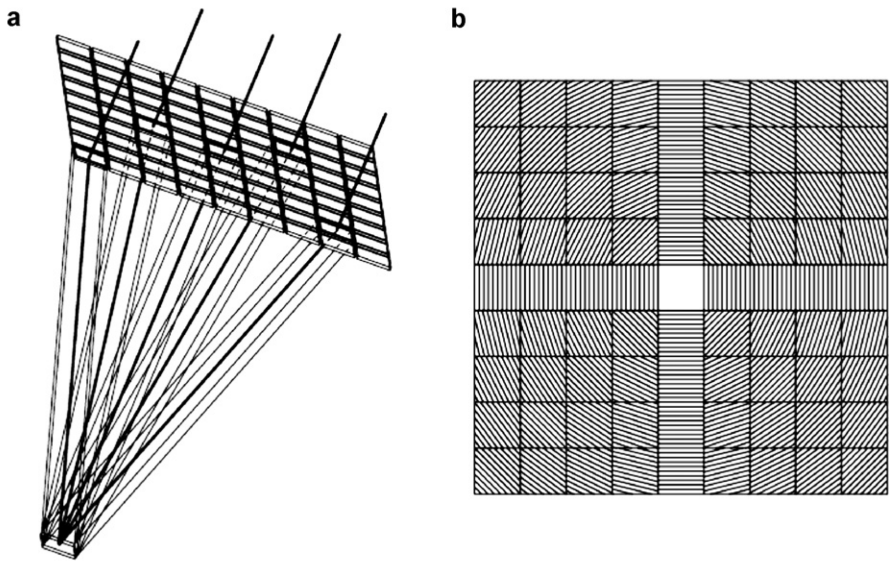

Fig. 19. Concept of modular Fresnel lenses for solar flux concentration. (a) Three-dimensional view of the concentration optics, (b) facet directions of the modularly faceted Fresnel lenses [92].

sion efficiency larger than 70% for low and medium concentration ratios (less than 50 suns).

2.2.4. Two-stage systems

The first two-stage non-imaging Fresnel lens solar concentration system was brought forward by Collares-Pereira [93] in 1979, who investigated a non-evacuated collector consisting of a linear Fresnel lens and a second stage concentrator of the CPC type. It was shown that the use of a Fresnel lens accomplished two different objectives simultaneously: (i) it allowed for the design of a nearly ideal light collector (of the CPC type) of high concentration and height-to-aperture ratio close to 1, (ii) it plays the role of a cover, making the collector less sensitive to the environment than one with exposed reflector surface.

Besides, two-stage concept is also used in concentrated photovoltaic systems. Ning et al. [94] investigated the two-stage photovoltaic concentrators with Fresnel lenses as primaries and dielectric internally reflecting non-imaging concentrators as secondaries, which presented the general design principles of such two-stage systems. Their optical properties were studied and analyzed in detail using computer ray-trace procedures. It was found that the two-stage concentrator offered not only a higher concentration or increased acceptance angle but also a more uniform flux distribution on the photovoltaic cell than the point focusing Fresnel lens alone. Terao et al. [95] presented a novel non-imaging optics design for a flat-plate concentrator PV power system which consisted of a conventional primary/secondary lens combination, but used aspheric and TIR (total internal reflection) lens components in the primary to reduce the focal length and, hence, the thickness of the whole module. Ray tracing simulations indicated that an acceptance angle in excess of $\pm 2.6^\circ$ could be achieved, which made this design suitable for light-weight, low-cost tracking systems.

Furthermore, Han et al. [96] pointed out that the optical efficiency of transmitted solar radiation was improved compared to thick ordinary lenses and the solar tracking accuracy required by a Fresnel lens group was lower than for other reflection schemes. They investigated a modular device composed of a two-stage Fresnel lens. Based on the analysis of rays passing through the wedge structure of the lens, the incident angle was kept within 1° such that the focal point would not move out of the receiver domain with the dimensions of 10 mm × 10 mm. Optical efficiency measurements had been carried out on a practical Fresnel lens group which included another Fresnel lens group under a condition of over 1000 suns, and the deviation range of the focal spot fundamentally agreed well with the simulation results.

Two-stage solar thermophotovoltaic (STPV) system for power generation had also been developed. Andreev et al. [97,98] carried out theoretical modeling for system design parameters (emitter aperture absorptance, emitter efficiency, PV cell band gap etc.) to identify optimum values of each input parameter as well as to predict of the system overall efficiency. The calculations were mainly oriented to ensure all the parts of the system matched each other, such as the choice of tungsten emitter dimensions, PV cell material etc. It was shown that 20% STPV module efficiency was realizable for GaSb based receiver with a possible increase to 29% for a tandem PV cell and advanced technology of STPV module. A cost-effective two-stage concentrator module based on a primary Fresnel lens and secondary quartz concave-convex lens had been fabricated (Fig. 20) and concentration ratio of ~4000×, was necessary to obtain high efficiency of the concentrator emitter system. Two types of TPV receivers were tested under outdoor conditions (850 W/m^2 average direct sun intensity) and with the solar simulator setup. Emitter temperatures in the range of 1400–2000 K were registered and GaSb PV cell short circuit current density up to 5 A/cm^2 was observed. Finally, BeO ceramics was used for mounting

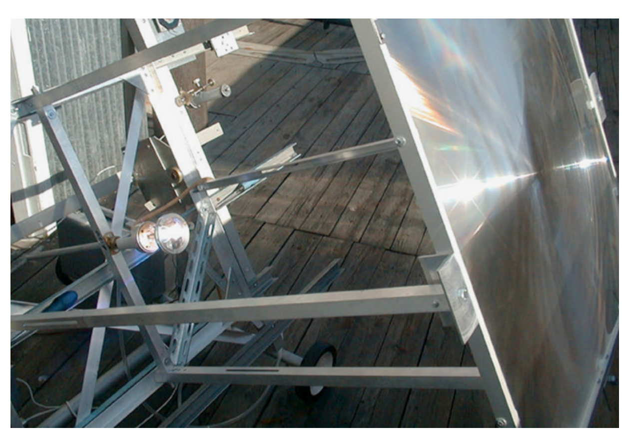

Fig. 20. Two-stage concentrator based on a Fresnel lens and a quartz meniscus lens [97].

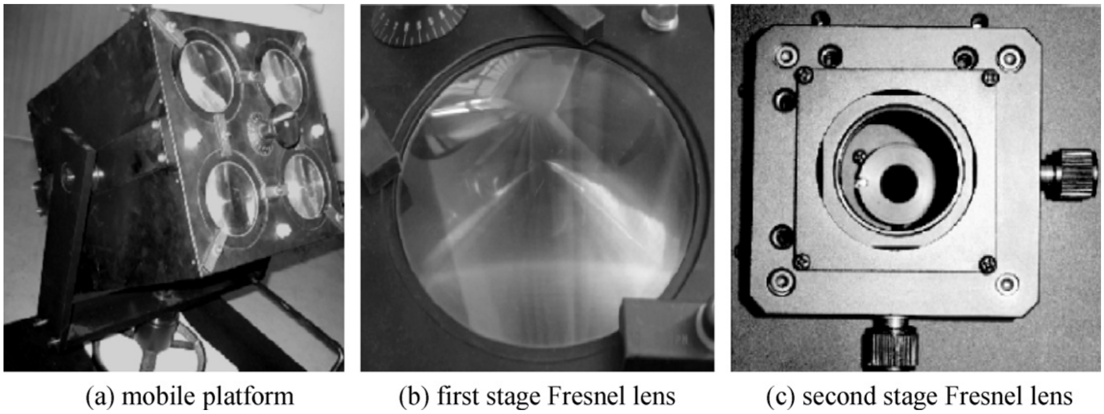

Fig. 21. Two-stage refraction system and components [101].

the PV cells allowing high thermal conductivity and series connection of the cells and high PV efficiency (19% under tungsten emitter irradiation) was obtained in GaSb TPV cells.

It is found that non-imaging Fresnel lens solar concentration system has been commonly used for photovoltaic which has the flexibility to be designed as single-stage or two-stage systems utilizing convex linear Fresnel lenses, dome-shaped Fresnel lenses or flat Fresnel lens with secondary. However, for medium or high flux applications, non-imaging Fresnel lens solar concentration system resulting errors due to installation, lower precision tracking comparing with imaging system, and the finite size of the sun. It should be noted that not the photographic imaging counts, but the homogeneous illumination of a receiver in order to obtain high efficiencies of the system. Consequently, non-imaging Fresnel lens solar concentration system will have a promising future in the field of solar power generation.

3. Recently developed applications

The demonstration of concentrated solar energy applications using Fresnel lens has been well-developed since the 1990s. However, it is still a long way to go for the commercial application of Fresnel lens solar concentration system. Recent research and development work has several new trends such as elliptical-based non-imaging Fresnel lens concentrator, two-stage non-imaging modularization high concentration system, imaging Fresnel lens (reflection or refraction) concentrator combined with different types of cavity receivers/absorbers. In this section, several representative applications will be briefly described to show an overview of the recent development.

3.1. New development of non-imaging systems

Though imaging Fresnel lenses can be used as solar lighting elements [51,52] in buildings, non-imaging Fresnel lens concentrators is another choice for building integrated photovoltaics. Chemisana et al. [99] proposed two optical devices which were based on stationary linear Fresnel lenses and secondary CPC to develop concentrating photovoltaic systems for building integration applications. It was found that the moving focal area was ten times smaller than the Fresnel lens aperture. The three-dimensional optical analysis of the non-imaging concentrating systems was presented and in terms of solar radiation, photovoltaic moving modules placed in the focal area of stationary concentrators were compared with simply fixed photovoltaic modules. It was indicated that in favorable weather locations, the beam radiation incident on the concentrating modules would be of a large percentage, more than 50%, of the global radiation received by the fixed photovoltaic devices.

Based on dome-shaped non-imaging Fresnel lens prototype produced by Akisawa et al. [86], Yeh [100] formulated an elliptical-based Fresnel lens concentrator system using optical geometry and ray tracing technique. He incorporated solar spectrum with the refractive indices of lens materials to form different color mixes on the target plane and the model illustrated the effect of solar spectrum distributions under the Fresnel lens. It could be used to investigate each spectral segment's distribution patterns which would help to match the concentration patterns of different wavelengths and be used for different solar energy applications. This concept design would be a new kind of non-imaging Fresnel lens compared to the conventional convex or dome-shaped ones.

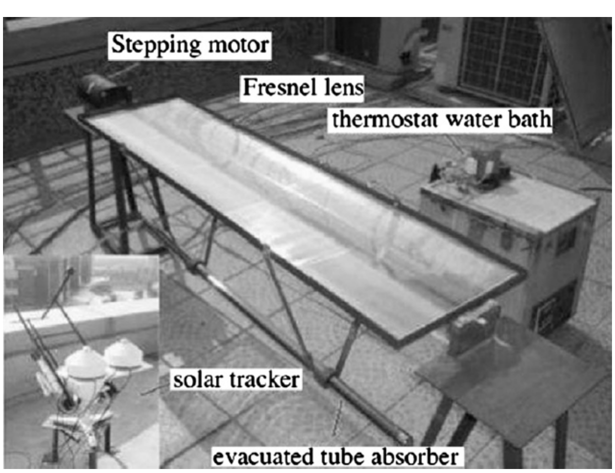

Fig. 22. The linear Fresnel lens solar collector and test system [105].

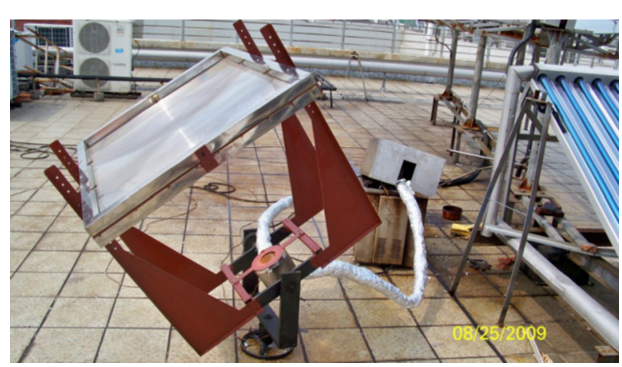

Fig. 23. The point-focus Fresnel lens solar collector and test system [106].

Table 1
Major improvements in concentrated solar energy applications using Fresnel lens.

Year	Authors	Location	Application	Type of Fresnel lens				Type of study	
				Imaging	Non-imaging	Line-focus	Point-focus	Theoretical	Experimental
1951	Miller et al. [3]	USA	Condensers	√	×	N/A	N/A	√	×
1951	Boettner et al. [4]	USA	Photoelectric	√	×	×	√	×	√
1961	Oshida [16]	N/A	Photovoltaic	√	×	N/A	N/A	√	×
1973	Szulmayer [5,6]	Australia	Heating, thermoelectric	√	×	√	×	√	×
1975	Nelson et al. [7]	USA	Solar concentrator	√	×	√	×	√	×
1977	Collares-Pereira et al. [14]	USA	Solar collector	√	×	√	×	√	×
1977	Rice [8]	USA	Solar concentrator	√	×	√	×	√	×
1977	Harmon S [17]	USA	Solar concentrator	√	×	×	√	√	×
1978	Donovan et al. [18]	USA	Concentrated PV	√	×	√	×	√	√
1978	James et al. [19]	USA	Concentrated PV	√	×	N/A	N/A	√	×
1978	O'Neil [20]	USA	Solar concentrator	√	×	√	×	√	×
1979	Demichelis [36]	Italy	Air heater	√	×	√	×	√	×
1979	Hastings LJ [9]	USA	Solar concentrator	√	×	√	×	×	√
1979	Collares-Pereira [93]	USA	Solar collector	×	√	√	×	√	√
1979	Kritchman et al. [64–68]	Israel	Solar concentrator	×	√	√	×	√	√
1980	Nakata et al. [22]	Japan	Concentrated PV	√	×	×	√	×	√
1981	Shepard et al. [23]	USA	Concentrated PV	√	×	×	√	√	√
1981	Lorenzo [56]	Spain	Solar concentrator	×	√	N/A	N/A	√	×
1981	Lorenzo et al. [57]	Spain	Solar concentrator	×	√	√	×	√	×
1982	Moffat et al. [24]	USA	Concentrated PV	√	×	×	√	√	×
1982	Lorenzo et al. [58]	Spain	Solar concentrator	×	√	N/A	N/A	√	×
1982	Luque et al. [59]	Spain	Solar concentrator	×	√	N/A	N/A	√	×
1983	Tver'yanovich [11]	Russia	N/A	√	×	N/A	N/A	√	×
1985	O'Neil [21]	USA	Solar concentrator	√	×	√	×	√	×
1986	Franc et al. [10]	Czechoslovakia	Solar concentrator	√	×	√	×	√	×
1987	Mijatovic et al. [25]	Yugoslavia	Solar concentrator	√	×	√	×	√	×
1987 –1993	Piszczor et al. [72,81–84]	USA	Space concentrated PV	×	√	√	√	√	√
1987	Ning et al. [94]	USA	Two-stage photovoltaic concentrator	×	√	√	×	√	×
1988 –1993	O'Neil [69–71]	USA	Space concentrated PV	×	√	√	×	×	√
1989	Jebens [26]	USA	Solar concentrator	√	×	×	√	√	×
1989	Appeldorn [12]	USA	Solar concentrator	√	×	√	×	√	×
1989	Krasina ta al. [13]	Russia	Solar concentrator	√	×	N/A	N/A	√	×
1990	Kaminar et al. [60]	USA	Solar concentrator	×	√	√	×	√	×
1992	Akhmedov et al. [27]	Russia	Solar concentrator	√	×	×	√	√	×
1993	Soluyanov et al. [28]	Russia	Solar concentrator	√	×	N/A	N/A	√	×

Table 1 (*Continued*)

Year	Authors	Location	Application	Type of Fresnel lens				Type of study	
				Imaging	Non-imaging	Line-focus	Point-focus	Theoretical	Experimental
1994	Kurtz et al. [29]	USA	Concentrated PV	√	×	√	×	√	×
1994	Yoshioka et al. [61]	Japan	Solar concentrator	×	√	N/A	N/A	√	√
1995	Alkan et al. [39]	Turkey	Hydrogen generation	√	×	×	√	×	√
1995	Miñano et al. [62]	Spain	Solar concentrator	×	√	N/A	N/A	√	×
1996	Grilikhes et al. [30]	Russia	Concentrated PV	√	×	×	√	×	√
1997	Erismann [15]	USA	Photoelectric	√	×	N/A	N/A	√	×
1998	Al-Jumaily et al. [37]	Iraq	Solar collector	√	×	√	×	×	√
1999	Whitfield et al. [33]	UK	Concentrated PV	√	×	√	√	√	√
1999	Leutz et al. [73–80,86]	Japan	Solar collector, Concentrated PV, Collimator, Thermal power conversion et al.	×	√	√	√	√	√
2000	O'Neil et al. [34,35]	USA	Concentrated PV	√	×	√	×	√	√
2000	Adeff et al. [42]	USA	Solar powered refrigerator	√	×	×	√	√	√
2000	Mills et al. [45,47]	Australia	Solar thermal power	√	×	√	×	√	√
2000	Terao et al. [95]	USA	Two-stage Concentrated PV	×	√	√	×	√	×
2002	Rumyantsev et al. [31]	Russia	Concentrated PV	√	×	√	×	√	√
2003	Kemmoku et al. [32]	Japan	Concentrated PV	√	×	×	√	×	√
2003	Hiramatsu et al. [85]	Japan	Concentrated PV	×	√	×	√	×	√
2005	Sierra et al. [48–50]	Spain	Surface modification	√	×	×	√	√	√
2005	Tsangrassoulis et al. [51]	Greece	Daylighting	√	×	×	√	√	√
2005	Lin et al. [63]	Taiwan	N/A	×	√	√	×	√	×
2005	Araki et al. [87–89]	Japan	Concentrated PV	×	√	×	√	√	√
2005	Yamaguchi et al. [90,91]	Japan	Concentrated PV	×	√	×	√	√	√
2006	Monteagudo et al. [40,41]	Spain	Solar photocatalytic degradation	√	×	×	√	√	√
2006	Ryu et al. [92]	Korea	Modular concentrated PV	×	√	×	√	√	×
2006	Andreev et al. [97,98]	Russia	Solar thermophoto-voltaic conventer	×	√	×	√	√	√
2007	Tripanagnostopoulos et al. [52]	Greece	Solar control of building	√	×	√	×	√	√
2007	Yabe et al. [53–55]	Japan	Solar-pumped laser	√	×	×	√	√	√
2007	Zhai et al. [38]	China	Concentrated Solar PV/T system	√	×	√	×	√	√
2007	Akisawa et al. [86]	Japan	Concentrated PV	×	√	×	√	√	×
2007	Han et al. [96]	China	N/A	×	√	×	√	√	√
2008	Zhang et al. [104]	China	Solar collector	√	×	√	×	√	√
2009	Chemisana et al. [99]	Spain	Concentrated PV	×	√	√	×	√	×

Table 1 (*Continued*)

Year	Authors	Location	Application	Type of Fresnel lens				Type of study	
				Imaging	Non-imaging	Line-focus	Point-focus	Theoretical	Experimental
2009	Yeh [100]	Taiwan	Solar concentrator	×	√	×	√	√	×
2009	Han et al. [101]	China	N/A	×	√	×	√	√	√
2009	González [102]	Spain	Concentrated PV	×	√	√	×	√	×
2010	Singh et al. [103]	India	Solar collector	√	×	√	×	√	√
2010	Zhai et al. [105]	China	Solar collector	√	×	√	×	√	√
2011	Xie et al. [106]	China	Solar collector	√	×	×	√	√	√

Unlike Chemisana's non-imaging systems, Han et al. [101] analyzed and compared different types of high concentration devices, such as Fresnel lens, convex lens or parabolic dish, to obtain the optimized design for collecting solar energy. Based on theoretical analysis, it was found that the efficiency of the optical system depends on the optical configuration and structure designed for optical components. It was concluded that concentrating system with two-stage reflection could have higher optical efficiency than that with two-stage refraction, but more accurate tracking was required to adapt the critical range limited by the same dimension detector, and improving tracking precision would increase the complication and the cost of collecting system. Based on this analysis, a set of highly concentrated solar energy system with two-stage refraction process, namely, two-stage Fresnel lens solar concentrator (Fig. 21) was built and initially tested for comparison.

In addition to the above mentioned study, González [102] presented a new type of convex Fresnel lens for linear photovoltaic concentration systems. The lens designed with this method could attain 100% of geometrical optical efficiency, and the ratio (Aperture area)/(Receptor area) was up to 75% of the theoretical limit. The main goal of the design was high uniformity of the radiation on the cell surface for each input angle inside the acceptance. It was shown that the ratio between the maximum and the minimum irradiance on points of the solar cell was less than 2. The lens had been designed with the simultaneous multiple surfaces (SMS) method of non-imaging optics, and ray tracing techniques had been used to characterize its performance for linear symmetry systems.

3.2. Imaging systems using cavity receivers

Solar collector or solar thermal conversion device consists of imaging Fresnel lens (reflection or refraction) and cavity receiver is becoming an investigation hot topic because of the characteristics of distributable, modularized, cost-effective and comparatively better thermal performance. Singh et al. [103] studied and compared thermal performance of the four identical trapezoidal cavity absorbers for linear Fresnel reflecting solar device. The absorbers were designed for operating in conjunction with a prototype Fresnel solar reflector having rectangular as well as round pipe sections. The absorber pipes were placed in a trapezoidal cavity coated with ordinary dull black board paint and black nickel selective surface. The bottom of the cavity was provided with plane glass to allow the solar radiation to be reflected from the Fresnel reflector and the other three sides of the cavity absorber were insulated to reduce heat loss. It was found that the thermal efficiency was influenced by the concentration ratio and selective surface coating on the absorber. In addition, the thermal efficiency decreased with the increase in the concentration ratio of the Fresnel reflecting collector and the selective surface coated absorber had a significant advantage in terms of superior thermal performance as compared to ordinary black painted absorber.

In Shanghai Jiao Tong University (SJTU), several researchers have paid much attention to this field. Zhang et al. [104] analyzed thermal characteristics of the solar collecting system both experimentally and theoretically based on Fresnel lens-Hemi-circle cavity receiver with three different glass covers, which were compared with no cover. The transient thermal efficiency test experiments for this system were carried out under similar weather conditions. It was seen that Hemi-Circle cover was the optimal one. Zhai et al. [105] investigated a concentrating solar collector based on linear Fresnel lens which was expected to acquire a higher thermal efficiency at a relatively high temperature level than the commonly used flat-plate or evacuated tube solar collectors. It was realized that the thermal efficiency could attain about 50% when the conversion temperature (water) was 90 °C. In addition, a mathematical model was developed to analyze the effect of the Fresnel lens concentration on an evacuated tube absorber and the validation showed that the model agrees well with the experimental data. It also indicated that Fresnel lens collector with evacuated tube absorber could attain good efficiency (50%) on a clear day even when the conversion temperature approached 200 °C. Fig. 22 illustrates the linear Fresnel lens solar collector and test system of the described study.

Besides, the authors [106] have designed a cost-effective solar collector based on point-focus rectangular Fresnel lens and several kings of cavity receivers (Fig. 23) to test the efficiency of solar thermal conversion at different temperature levels. It was found that the thermal efficiency was about 55% when the conversion temperature (synthetic heat transfer oil) was about 100 °C. Meanwhile, for higher conversion temperatures of about 150 °C, the thermal efficiency was further increased to about 45%. If the thermal insulation is good enough, it is expected that the thermal efficiency can still further be improved.

Table 1 gives an overview of most of the major improvements in concentrated solar energy applications using Fresnel lens toward solar concentration. Nearly 60 years have passed since the first plastic material Fresnel lenses were invented and most of the early research was done in the USA, but during the recent two decades researchers all over the world have paid much attention to the superiority of Fresnel lens in solar power generation. Non-imaging Fresnel lens, which was invented in 1979, does offer the possibilities for a great breakthrough of commercial solar energy concentration systems.

4. Conclusions and perspectives

With the improvements of lens material since the official invention of Fresnel lens in 1822, especially polymethylmetacrylate (PMMA) which has a good transmissivity and resistance for sunlight, interest in Fresnel lenses for concentrated solar energy applications rose in the latter half of the 20th century. This paper reviews the recent developments of concentrated solar energy applications using Fresnel lenses systems including imaging Fresnel lens solar concentration systems and non-imaging systems. Imaging Fresnel lens solar concentrators are designed as focusing devices and the research has focused on the improvement of evaluation technologies for them under solar radiation using ray tracing technology commonly. While non-imaging Fresnel lens solar concentrators are well suited for the collection of solar energy, because the goal is not the reproduction of an accurate image of the sun, but instead the collection of energy. Convex line-focus Fresnel lenses or dome-shaped Fresnel lenses of bifocal, or non-imaging type are more recently developed for collection of solar rays.

Most of the research and development works have been directed at imaging systems and non-imaging systems which represent the future trends of solar concentration applications.

For imaging Fresnel lens solar concentration systems which often use flat lenses focusing paraxial rays with concentration ratios ideally approaching infinity and accurate two-axis tracking system is needed. However, their suitability for most solar applications is questionable due to their sensitivity of tracking and the aberrations are impractically large, unless high precision tracking is to be employed. Additionally, imaging Fresnel lens systems create a more or less defined focal area, which leads to "hot spots" problem on oversized receivers. This problem is of concern not only for photovoltaic energy conversion but also for solar thermal applications. Thus, the only way to successfully utilize imaging systems is to employ accurate tracking which is a main part of the total cost of the whole solar concentration application systems blocking their commercialization.

For non-imaging Fresnel lens solar concentration systems which always adopt convex, dome-shaped or two-stage lenses to realize low, medium and high concentration. Non-imaging Fresnel lens concentrators are thought to be very competitive solar collectors because of their high optical efficiency, light-weight and cost effectiveness. If tracking requirements are kept to a minimum, savings in crystalline photovoltaic surface area due to concentration will off set the cost of the whole system. With the improvement of lowing manufacturing complexity, non-imaging Fresnel lens solar concentration systems are expected to extensive using in the field of commercial solar power generation.

Acknowledgement

This work was supported by National Natural Science Foundation Program under the contact No. 50876063 and the key scientific and technological project of Science and Technology Commission of Shanghai Municipality under the contact No. 10dz1203402.

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