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Simulate a 'Sun' for Solar Research: A Literature Review of Solar Simulator Technology

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Abstract

The solar simulator is the key facility for indoor research of solar PV cells, solar heat collectors, space craft and CSP systems. This paper classifies the four types of solar simulators based on their characteristics and their design objects: space solar simulator, standard PV cell testing solar simulator, collector testing solar simulator and high-flux solar simulator. The review of solar simulator developments is mainly based on the developments of light sources and optical concentrators. The light source is the most important component for a solar simulator design; carbon arc lamp, metal halide arc lamp, quartz tungsten halogen lamp, xenon arc lamp, mercury xenon lamp, argon arc lamp and light-emitting diode lamp (LED) are used to be chosen as the light sources to meet the various requirements for the design objects. The optical concentrator is another key component; ellipsoidal reflector, compound parabolic concentrator (CPC), light cone, hyperboloid concentrator, parabolic dish concentrator and Fresnel lens are also reviewed in this paper. Finally, the near future developments of these four type solar simulators are discussed based on the requirements of research and the available technology of light sources and optical concentrators.

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Keywords

Solar simulator; Light source; Concentrator; Spectral composition

Nomenclature

AM	air mass
ASTM	American Society for Testing and Materials
CPC	compound parabolic concentrator
CPV	concentrated photovoltaic
CSI	compact source iodide
CSP	concentrated solar power
DLR	Deutsches Zentrum für Luft- und Raumfahrt
ESA	European Space Agency
HFSS	high flux solar simulator
LED	light-emitting diode lamp
LSS	large space simulator
NASA	National Aeronautics and Space Administration
PSS	pulsed solar simulator
PTC	parabolic trough collector

1. Introduction

The solar simulator is a device whose light source can offer similar intensity and spectral composition to the nature sunlight. It is widely used as a controllable indoor test facility offering laboratory conditions for solar cells, sun screens, plastics, and other materials and devices which are sensitive to sun light. A solar simulator usually consists of three major components: (1) light source(s) and associated power supply; (2) any optics and filters used to modify the output beam to meet the requirements; (3) necessary controls to operate the simulator [1]. Xenon lamps or other artificial light sources are usually chosen as the light source of a standard solar simulator. However, there are differences between artificial light source(s) and nature sun light, both in intensity and spectral composition, which only with the help of optics and filters can be modified to meet the nature sun light. Furthermore, as the outdoor condition is time dependent, it is necessary to define a standard test condition for the solar simulator. To rise a set of standard test conditions for the terrestrial application PV cell, two workshops, sponsored by ERDA and NASA, took place in 1975 and 1977, and a final report of standard terrestrial photovoltaic measurement procedures, including detailed descriptions of standard solar simulators, was published after the second workshop[2][3]. In this report, 1000W/m^2 were chosen as the standard intensity while air mass AM1.5 was chosen as the spectral composition, and both are still used in ASTM standards for commercial solar simulators [4]. The AM1.5 spectral composition is shown in fig 1. Moreover, 1000W/m^2 is usually chosen as a unit of solar irradiance ‘sun’ ($1\text{ sun}=1000\text{ W/m}^2$) which is widely used in concentrated solar system research.

Since the research of CSP, CPV and solar thermochemical reactions became hot at the end of 1990s, more research is focused on the high-flux concentrating type simulator, which can simulate the directional, spatial, and spectral distributions of a real CSP system, such as parabolic trough, dish, tower system and solar furnace [5]. Also, compared to the extremely expensive outdoor testing facility (like the solar furnace), it is relatively inexpensive. Several CSP research institutes have already constructed high-flux solar simulator with different power and flux level, and more institutes have their own high-flux solar simulator plan. Different to commercial standard non-concentrating solar simulators, which just offer a standard nature sun light conditions, high-flux solar simulators are designed to simulate the concentrated beam characteristic of a CSP system. In such a design, peak-flux, flux distribution shape and other CSP related parameters are considered as important as spectral composition.

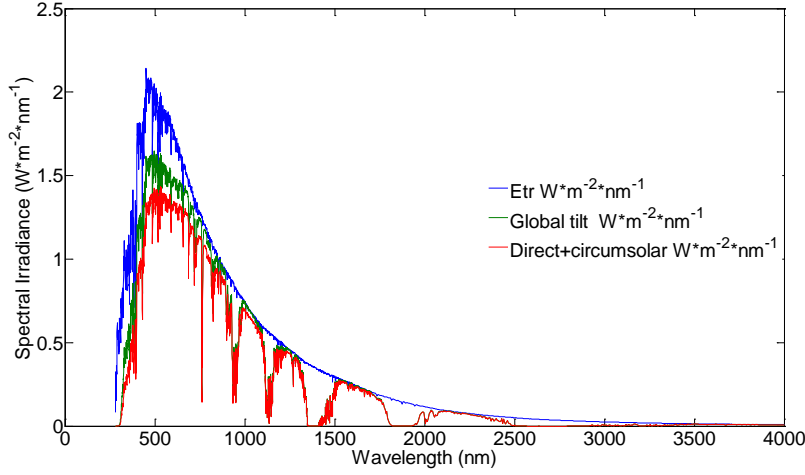


Fig. 1 ASTM G173-03 Reference Spectra

In this paper, solar simulators are classified by their applications: space solar simulator, standard simulator for PV cell testing, large scale solar simulator for solar collector testing, and high-flux solar simulator for CSP and CPV research. More information about high-flux solar simulators is available in section 2.4.

The main components, light source and concentrator, are also reviewed in this paper. Short-arc or long-arc xenon lamps are the most widely used light source, while metal halide arc lamps, carbon arc lamps and quartz tungsten halogen lamps are also chosen as the light source in some kinds of simulator designs. Recently, more research was done using LED as a light source due to its advantages when compared to traditional light sources, lower cost, more compact, less power consumption and so on [6].

The concentrator is one of the key components, particularly to a high-flux solar simulator. Since the first solar simulator design in the 1960s, various concentrators were used in different solar simulator designs, such as Fresnel lenses, ellipsoidal concentrators, parabolic dishes, CPCs and optical cones. More and more concentrator types will be introduced in solar simulator design to meet the increasing requirements of concentrated solar system research. More details about light source and concentrator are described in section 3.

2. Classification

2.1. Space solar simulator

Indoor solar simulator research started at the beginning of the 1960s with a serial of research programs sponsored by National Aeronautics and Space Administration (NASA) and were aimed at developing a ground-test facility which can simulate the space environment for earth satellite and other spacecraft testing. This was named space environment test chamber [16][8]. In this chamber, a solar simulator was used to simulate the space solar radiation. After a serial of tests and comparisons, a mercury xenon lamp was chosen as the light source. In the

following 3 years, a number of large thermal vacuum chambers with solar simulators had been constructed to simulate orbital altitudes for complete spacecraft testing by both the US government and private industry [9]-[11]. One of these simulators is shown in fig. 2. A mercury xenon lamp or carbon arc lamp is chosen as the light source in these simulators, and the intensities of these solar simulator systems are located between 1.4 kW/m^2 and 1.5 kW/m^2 due to their space applications. In order to meet the increasing test requirements of space technology, a 25ft (7.6m) diameter space simulation chamber with 5ft (1.52m) diameter solar simulator had been constructed in Jet Propulsion Laboratory NASA by extending the existing structure of 3m diameter simulator design[11]-[17]. After the 25ft space simulator's modification for the environment simulation of Venus and Mercury, the solar simulator diameter was extended to 4.72m, it became one of the largest solar simulator all over the world [15]-[18]. In 1984, European Space Agency (ESA) started a project aimed to develop a large space simulator (LSS) to meet the European space plan, and it finally became operational in 1986. Its solar simulator's optical design is similar to the JPL's, and the diameter reaches 6m, larger than JPL's 25-ft space simulator's [19]. Later, Russia, Japan and South Korea developed and constructed their own large scale space simulators [20][21][22]. The largest space simulator in the world is the Space Power Facility (SPF), which has a 400kW solar simulator [23]. With the help of these solar simulators, a large number of fundamental research and testing work related to the great space projects has been performed in the past 40 years[24]-[34].

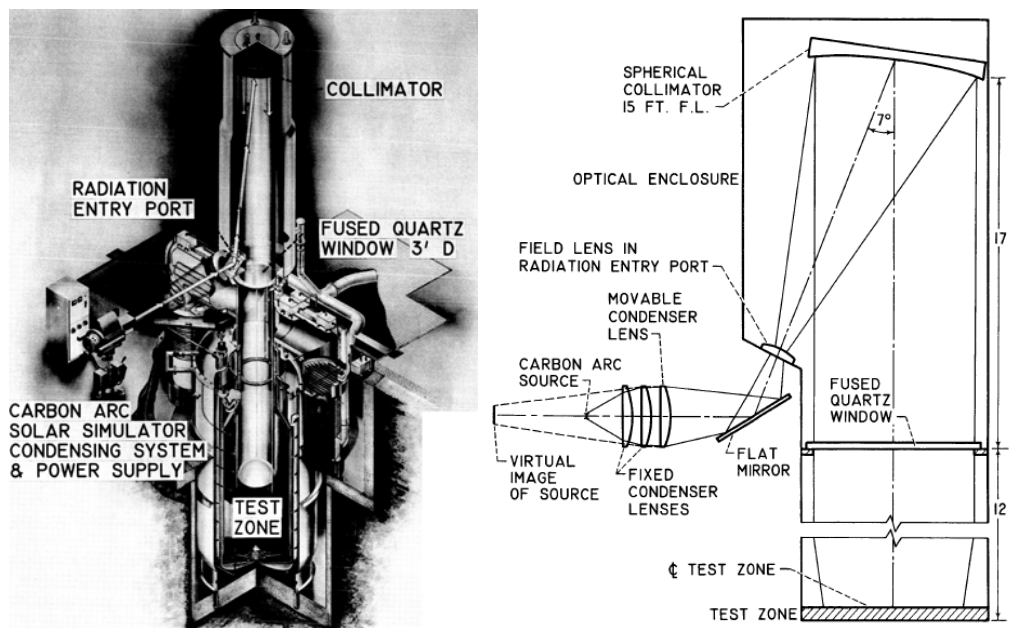


Fig. 2 Space environment simulator in Lewis Research Center NASA (left) and optical system of its solar simulator (right)

However, this doesn't mean that these large scale simulators can fit to all the requirements of space technology development, e.s., high flux level for testing Mercury spacecraft or other craft closer to the sun, solar dynamic space power system testing, high accuracy spectral distribution, and so on. Several solar simulators for special use have been developed [35][36], with the expanding of space research in the future, more and more small scale solar simulator for special use will appear.

2.2. *Standard solar simulator for terrestrial PV cell testing*

Early in the development of solar cell technology, the performance of PV cells was tested outdoor or indoor with artificial light sources which needed to be calibrated by standard PV cells or a pyrheliometer. PV cell arrays performances for space applications were tested by extremely expensive large scale space simulator chambers together with the spacecraft [29][32][34]. The solar simulator can offer a common basis for comparing solar cells and also provide data for the design of large arrays, which is important for solar PV cell development. So an industry need for testing solar cells and other devices in well-controlled simulated conditions was recognized.

However, the artificial light sources used for testing were pointed out inadequate for testing solar cells for space applications and therefore several combination and modified light sources had been investigated to get a closer spectral distribution to the sun radiation in the space AM0 [37][38]. The solar simulator designed by Hoffman Electronics Corp, which is shown in fig 3, used a combination of xenon arc lamp and tungsten bulb as the light source, so did the simulator developed by Optical Coating Laboratory. Spectrolab Corp is another pioneer in standard solar simulator design and manufacture, which use the modified light sources method by optical filters since 1962 [38]. The optical design schematic of the Spectrolab X25 solar simulator is shown in fig 4. The inert gases can also be used to modify the light sources [40].

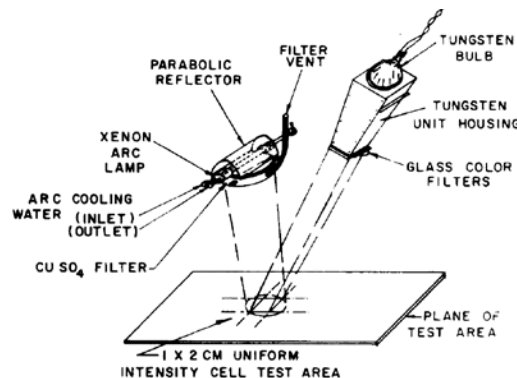


Fig. 3 Schematic diagram of Hoffman solar simulator [37]

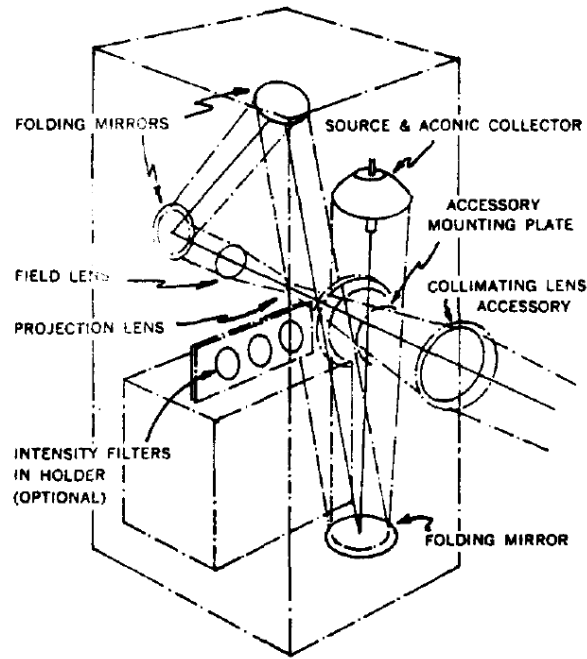


Fig. 4 Schematic diagram of spectrolab X25 solar simulator [40]

In the beginning of the 1970s, due to the developing of photovoltaic industry, setting a standard measuring method (including solar simulator) was becoming urgent. The significance of the standard method can be list as follows: (1) to determine the performance of a series of samples from a single source; (2) to compare samples of different designs from various processes or manufacturers; (3) to study changes in device performance as a function of time; (4) to provide systems design data to engineers and marketing experts [41]. For this reason, the first solar cell testing procedure standard was set in 1975 [2], which was updated in 1977[3]. In 1978, the standards-writing activities have been initiated with the objective to arrive at standard methods for measuring the electrical performance of photovoltaic devices in the Subcommittee on Photovoltaic Electric Power Systems of ASTM Committee E-44 [41]. One year later, the document of the Commission of the European Communities describing standardized methods of performance measurements, have also been consulted [42]. After a long period studying and consulting [43]-[45], a serial of revised ASTM standards were finally available in 1985[46]. The solar simulator is considered as the key facility of the photovoltaic measurement system in research or industry, its accuracy would significantly influence the measurement error [43][44]. The illuminated current versus voltage (I-V) characteristics of the PV cell is sensitive to the spectrum, intensity and temperature [47]. So looking for new light sources and developing higher accurate optical system based on the standards became the most urgent work, the closer to the standard solar irradiance, the better.

A second focus of standard PV solar simulator design was to lower the average power and the temperature fluctuation caused by prolonged exposure to the light [49][50], which can be achieved with the help of the so called pulsed solar simulator. The research work of multi-sources simulator, which aimed to develop more accurate spectrum output, still continued [51][52]. With the quick developing of Light-Emitting Diode (LED) technology at the end of 1990s, simulators have shifted toward this new light source for its significant advantages: low-cost, compact, long operating life and high energy efficiency [53]. Light intensity insufficiency used to be the main problem of the fully LED solar simulator designs [53]-[56], a typical design is shown in fig. 5, but it seems that this problem has already been solved by recent advances in high power LED technology [57]. In 2012, researchers from the University of Illinois at Urbana-Champaign (UIUC) presented their fully LED solar simulator design, which covers the AM1.5G solar spectrum and achieves Class C uniformity over an area of 100mm×50mm [58]. Due to the LED's unique advantages and its fast development, LED solar simulators will attract more attention and become the next generation of standard solar simulators.

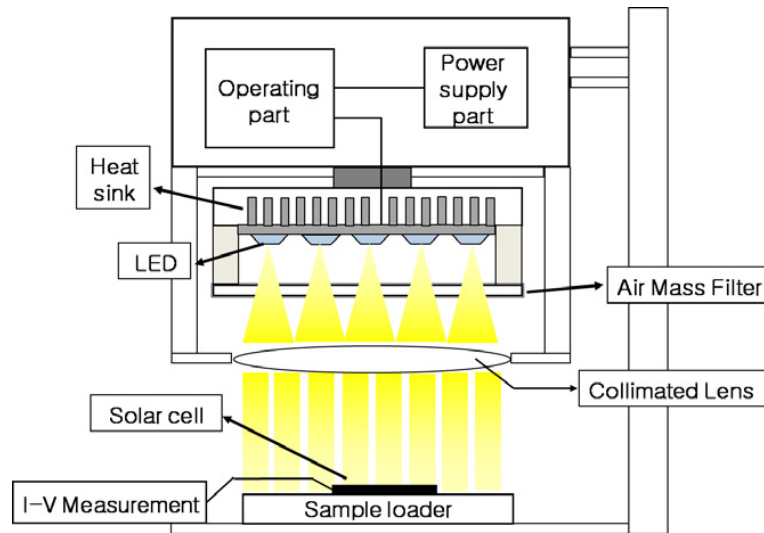


Fig. 5 Schematic of a typical LED solar simulator [56]

2.3. *Large scale solar simulator for solar collector testing*

The simplest and cheapest way of solar collector testing is outdoor testing during the noon of a clearly sunny day, however, it is very time consuming and weather depending. In the 1970s, the focus was directed towards the research of flat-plate solar collectors. For the fast development of new and efficient solar collectors [59][60], it was necessary to develop a facility which can offer standard conditions with high accuracy and short time consumption for solar collector testing. Hence, a solar simulator was designed as key facility for indoor

testing of the flat-plate solar collectors [60][62]. After a series of testing and modification, the results showed that the solar simulator testing results were in good agreement with outdoor testing for the same collector [63]-[69]. It was proven as a successful solar simulator design for solar collector testing. In the following 10 years, several simulators with similar design objects and structures were developed by solar energy research institutes in USA, Australia, Japan, UK, France, Denmark, Sweden, Switzerland, Canada, Germany and India [70]-[74]. Even today, the simulators in accredited SRCC test labs also use this structure [75].

Due to its application area, this type of solar simulator is not like the standard solar simulator for PV cell testing with high requirements on spectral composition, but high power output and large testing area. Hence, cheap tungsten halogen lamps were chosen as the main light sources in the early period, even in some recent simulator designs, to control the cost[76][79]. However, Compact Source Iodide (CSI) lamps [76][76]and Metal halide lamps [80]- [83] were used instead of tungsten halogen lamps to get closer spectral composition in most recent simulator designs.



Fig. 6 Solar simulator for solar heat collector testing (Fraunhofer ISE)[75]

2.4. High-flux solar simulator (HFSS) for CSP and CPV research

The High-flux solar simulator is a kind of solar simulator, which can offer not only spectrum similar artificial solar irradiation, but also approximate high light fluxes to a real concentrated

solar system with the help of optical concentrators. It was first designed for the study of chemical reactions under high temperature and flux in the Lawrence Berkeley Laboratory [83]. With the help of an ellipsoidal concentrator, it delivered 3 kW on a 7×7 cm target, and the peak flux reached 16 MW/m². Another solar simulator for thermochemical research was designed and established in ETH-Zurich in 2001[84]. Based on a 200 kW DC high-pressure argon arc lamp light source and 2D Ellipsoidal concentrator, this simulator is able to deliver at its focal plane up to 75 kW of continuous radiative power at a peak flux of 4.25 MW/m². One 2D-CPC concentrator is applied as a secondary concentrator to obtain higher and more uniform light flux for circular testing application, and various mean power fluxes can be obtained with changing the circular target's diameter, which is shown in fig 7.

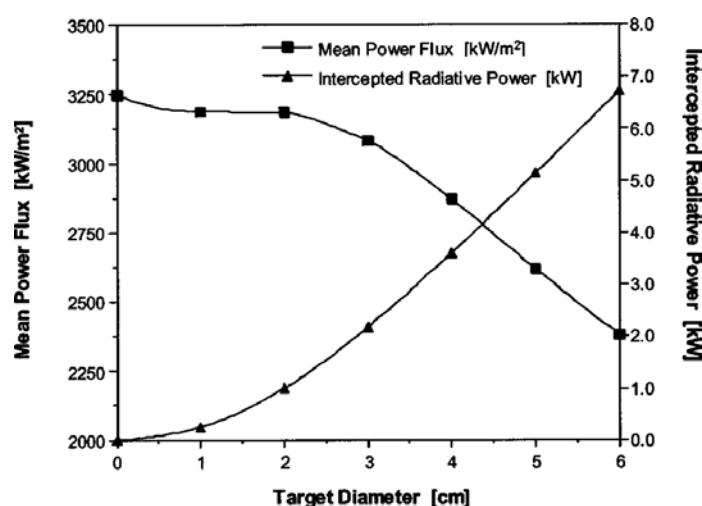


Fig. 7 Radiative power and mean power flux intercepted by circular target as a function of its diameter, for an arc electrical current of 500A (ETH 75 kW HFSS) [84]

With the speed up research of Concentrated Solar Power (CSP) and Concentrated Photovoltaic (CPV) during the 2000s, HFSSs are not designed just for solar thermochemical research. A 50 kW 11,000 suns (1sun=1kW/m²) was developed in the Paul Scherrer Institute (PSI) mainly for the research of highly concentrating solar systems and thermochemical processing of solar fuels [85]. In this simulator design, a xenon arc lamp and an ellipsoidal concentrator are integrated as one unit, 10 of these units array are assembled as the light source, the principle optical design is shown in fig 8. It is easy for scaling to various power capacities for solar simulator design and maintenance. Hence the same designs are successfully used in latter DLR [86] and University of Minnesota [87] HFSS designs. However, the price of a xenon arc lamp is quite expensive and there is no need to have this extreme high flux simulator for low concentration ratio CSP system research, such as

parabolic trough collector system (PTC) and CPC system. To solve the cost problem, a low cost solar simulator was fabricated in MIT [88], which use seven 1.5 kW metal halide lamps as the light source, as shown in fig 9. It can offer approximately 60 kW/m² peak and 45 kW/m² average flux level but the total cost is controlled within \$10,000. Concentrating Photovoltaics (CPV) is a system that uses an optical system which concentrates solar radiation onto a photovoltaic receiver with a smaller area, due to its high efficiency and low system cost per watt electricity output, it is considered to be widely used in the future. To meet the increasing requirements of CPV research, solar simulators for CPV were developed [90]. The PV cells used in CPV systems are multijunction (MJ) cells, which are a series-connected stack of two or more sub-cells, each one generating current in response to the light of different spectral bands. This makes system performance quite sensitive to spectrum, which cause the spectral composition of the CVP type solar simulator much higher compared to the CSP type HFSS [89]. Furthermore, the flux level of the CPV type solar simulator designs are closer to the CSP type HFSS, with the increasing concentration ratio of the CPV systems [91]. One commercial CPV type solar simulator is shown in fig 10.

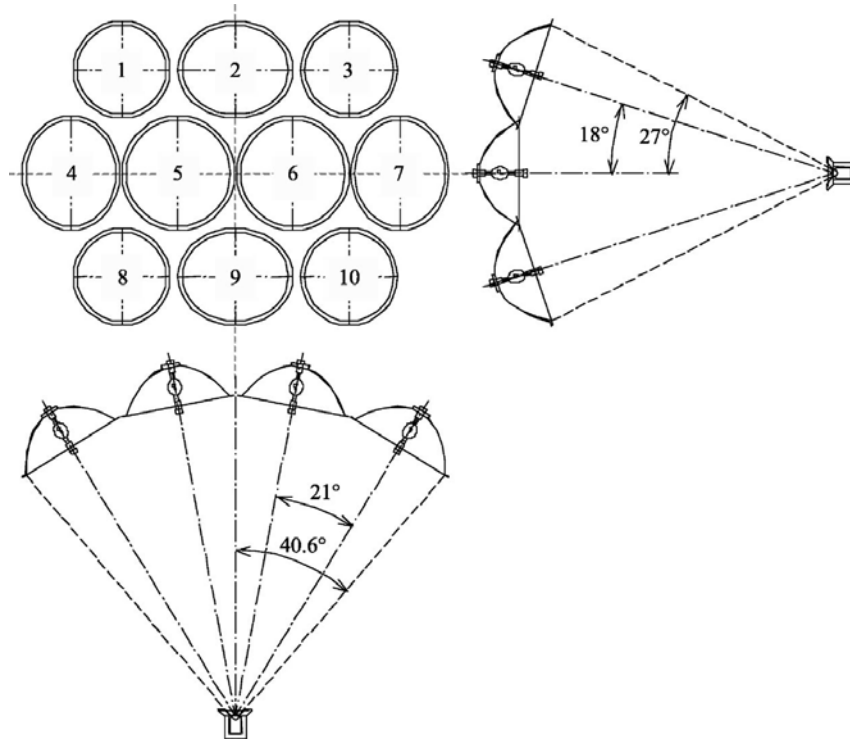


Fig. 8 Optical layout of an array of ten Xe-arc lamps HFSS at PSI [85].

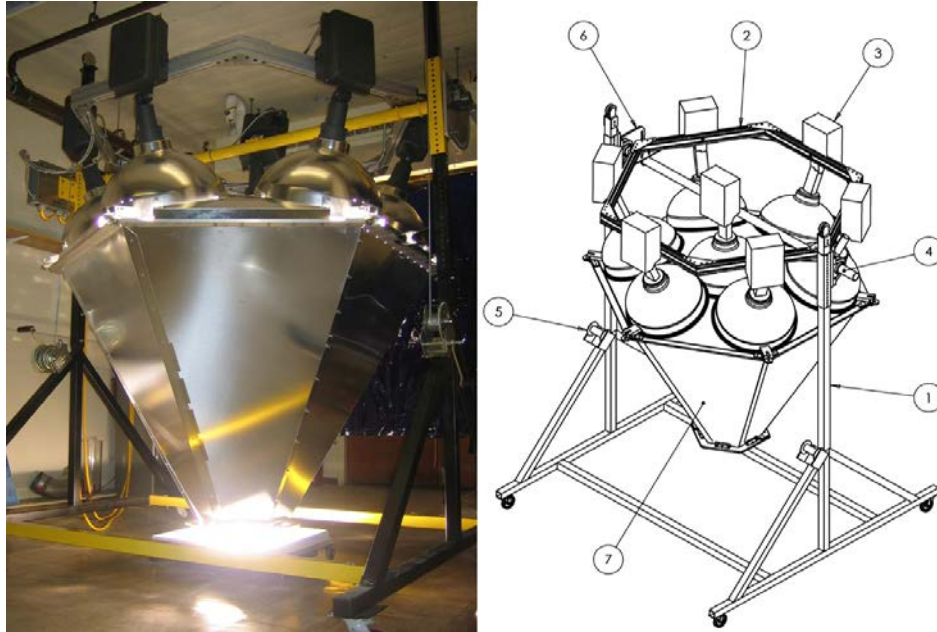


Fig. 9 MIT metal-halide CSP solar simulator Subassemblies: (1) frame; (2) light mounting frame; (3) MH light; (4) pivot tube; (5) lifting winch; (6) tilt adjustment plate; (7) secondary concentrator [88].

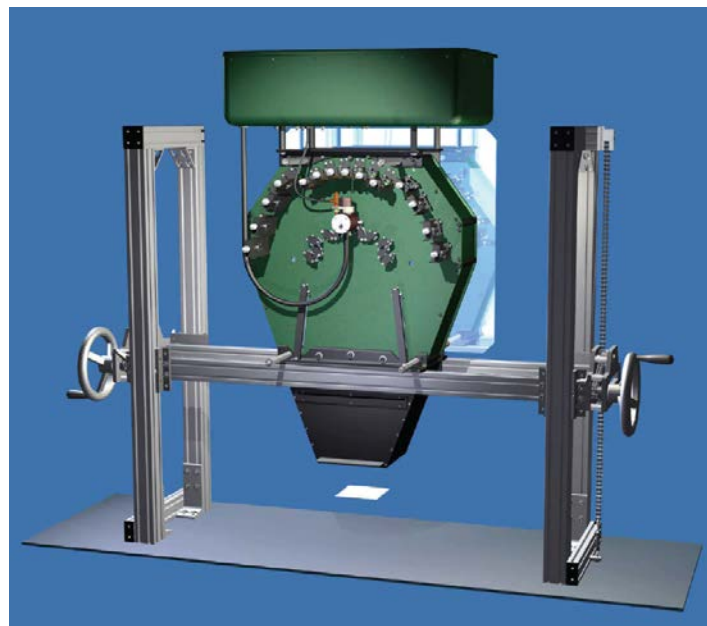


Fig. 10 Commercial Terrestrial-High Intensity Pulsed Solar Simulator (T-HIPSS) [92]

3. Main components

3.1. *Light source*

The selection of a suitable light source to simulate sunlight and its intensity is the foremost work for a solar simulator design. Normally, a light source for solar radiation simulation should be examined under the aspects of: 1) spectral qualities; 2) uniformity of illumination; 3)

collimation; 4) stability of flux; and 5) range of flux obtainable [93]. In the history of solar simulation, various lamps have been proposed, which can be listed as follows: carbon arc lamp, metal halide arc lamp, quartz tungsten halogen lamp, xenon arc lamp, mercury xenon lamp, argon arc lamp and light-emitting diode lamp (LED). And the light sources information of published solar simulators is shown in table 1.

3.1.1. Carbon arc lamp

The carbon arc lamp used to be the first option light source for space solar simulator design, due to its closely approximate spectral composition to the sun [7]. However, its drawbacks limited its further application: 1) its short operation time; 2) its instability during its operation; 3) carbon arc emitting too much blue radiation [37]. It is reported that with a 12 inch standard negative electrode can only offer two hours continuous operation, and as the junction of the electrodes enters the arc gap there is a 15 second period of arc instability usually accompanied by a 7 percent decrease in radiance [10].

3.1.2. Quartz tungsten halogen lamp

The color temperature is the temperature of an ideal black body radiator with the peak irradiance at the same wavelength as the test source. Quartz tungsten halogen lamps as well as other filament lamps, can only work under maximum color temperature of 3500 K, however, the color temperature of the AM 0 Sun is approximately 5900 K [45]. Quartz tungsten halogen lamps have a color temperature of less than 3400 K, and as a result, they radiate weaker in the shorter wavelengths (blue and UV portion) but stronger in the infrared portion [37]. However, its inexpensive and excellent light output, maintenance and improved consistency [100] make it widely used as the infrared light source in multi-source solar simulators and the solar simulators with less spectrum requirements, such as the solar simulator for collector testing, shown in table 1.

3.1.3. Mercury xenon lamp

Mercury xenon lamps used to be another kind widely used light source in the early space solar simulators. However, mercury arc lamps have narrow bands of energy emission, and with more than 300 atmospheres operating pressure, which is not available the spectral distribution begins to approach the standard sun's spectral distribution [8][37]. Furthermore, after a period of using mercury xenon lamp based solar simulator in the JPL 25-ft space simulator, a series of security problems was experienced: 1) Ozone creation; 2) lamp explosion and 3) mercury

vapor from the lamp [25]. In latter solar simulator designs, mercury xenon lamps were replaced by xenon arc lamp as the first light source option, which can be seen in table 1.

3.1.4. Xenon arc lamp

The xenon arc lamp is the most widely used light source for almost all kinds of solar simulators, especially favored by commercial standard solar simulator manufacturers. Principally because of its stable spectral qualities in providing an excellent continuum in the ultra-violet and through the visible band. But it has strong emission lines in the infrared between 800-1000 nm, which can be filtered by filter glasses [37]. Another advantage of the xenon lamp is that variation in power does not cause any appreciable shift in its spectral balance. This reduces the requirement of voltage supply stability [37]. Furthermore, high pressure short arc xenon lamps can provide a brighter point source than other light sources, which is required to produce a collimated high intensity light beam [45]. However, xenon lamps have its inherent drawbacks which limit its application in all kinds solar simulator: 1) xenon lamp require more complex and expensive power supply which makes it nearly the most expensive commercial light source; 2) similar to mercury xenon lamp, the xenon gas pressure in the xenon lamp is approximate 10 bars and can reach 40 bar during its operation, which causes a high security risk; 3) irradiance peaks shift slightly away from the UV to the IR as the lamp ages; 4) amplitude instabilities in the lamp output caused by the power supply instabilities [37][45][88]. Due to these advantages and drawbacks, in the design of modern solar simulators which has low spectrum and intensity requirements, Quartz tungsten halogen lamp and metal halide arc lamp are superior than xenon lamp. Otherwise, the xenon lamp will be the first choice.

3.1.5. Metal halide arc lamp

The metal halide arc lamp was introduced as the light source option of solar simulators when the compact source iodide (CSI) was developed. It is advantageous because of its high light efficacy of over 90 lm/W, good balance in spectral qualities, closely matching of sun light as well as long life time (>1000 hours) and relative inexpensive cost [100]. Furthermore, the sealed beam version of CSI can provide high intensity irradiation of a directional nature without any additional optical equipment. However, comparing the spectral distribution with other light sources and two different air masses, CSI lamps emit too much IR energy while insufficient in the UV portion, which is shown in table 2. Another main drawback of the CSI lamp is its low collimation quality, which limits its application in high collimation

requirement area, such like high concentrating solar simulators and standard solar simulator for PV testing [45][93]. Therefore, the CSI lamps are mainly used in the solar simulation application allows non-collimated light, such as collector testing solar simulators and some PV testing solar simulators which only need constant large-area illumination and less exact spectral characteristics [45]. Due to the low cost and high spectral distribution quality of modern metal halide lamps, it is still widely used all over the world, even in low concentrating ratio solar simulation [80][81][82][88]. One metal halide lamp's spectral distribution is shown in fig 11, which is used as the light source of a DIN CERTCO-accredited solar collector testing simulator [80].

3.1.6. Light-emitting diode lamp (LED)

An LED is a semiconductor light source based on the electroluminescence phenomenon, which emits a narrow-spectrum light when electrically biased in the forward direction of the p-n junction. The LEDs emitting mechanism is neither similar to a filament lamp nor an arc lamp. In the early period, LEDs were only used as indicators and signs for their low light intensity. In the beginning of 2000s, with the development of high power LED technology, LEDs were introduced as a new light source option for solar simulator design [54]. Due to their unique characteristics, LEDs have many advantages compared to the conventional light sources used in solar simulators: 1) LEDs can be controlled very fast within microseconds or operated stable at one light output intensity continuously for long time; 2) LEDs have a relatively narrow monochromatic output spectrum (except white LEDs) and are available in a wide variety of colors and wavelengths, which means combining a number of required colors LEDs can obtain a close-matched AM0, AM1.5, AM2 or other special application spectrum; 3) with the develop of high power LEDs, 1000W/m² level light intensity LEDs are available, higher intensity LEDs are expected in the future. 4) LEDs have very long lifetime up to 50,000 to 100,000 hours in general, which means that they not only compensates higher cost per light intensity but also reduce the maintenance cost to a minimum; 5) more compact and energy saving. In contrast to xenon lamp type solar simulators with large size, LED solar simulator can be designed very compact due to the higher efficiency light source, less electronic devices and without large size concentrator [53][55][58]. However, LEDs also have their inherent drawbacks. One is that LEDs' light output energy, efficiency and lifetime drops sensitively with the operation temperature rising of the junction. So a good cooling system is essential, but this reduces the output efficiency as well. Furthermore, LEDs also have some dependence of the output spectrum to the light output (drive current). Another unavoidable

disadvantage is the degradation of the LEDs throughout their lifetime [53]. Last but not least, the light intensity of LEDs is still too low for concentrating solar simulator design. In summary, the advantages of LEDs are shown to outweigh their drawbacks and make them as a perfect candidate light source for future advanced solar simulator design, at least for non-concentrating type solar simulator.

Table.1. Main information of published solar simulators

Simulator Type	Light Source	Power Discription	Organization / Country	Time
Space solar simulator	Carbon Arc Lamp	26 1/2 in diameter & 28 kW	Lewis Research Center / USA	1960 [10]
	Xenon Arc Lamp	10 ft diameter & 250 w/ft ²	Republic Aviation Corporation / USA	1961 [9]
	Mercury Xenon Lamp	6 ft diameter & 130w/ft ²	Chance Vought Corporation / USA	1961 [9]
	Mercury Xenon Lamp	4 ft diameter & 190 w/ft ²	Jet Propulsion Laboratory (25ft) / USA	1962 [9]
	Xenon Arc Lamp	20ft diameter& 140 w/ft ²	General Electronic Company / USA	1962 [9]
	Mercury Xenon Lamp	20 ft diameter & 275 w/ft ²	Goddard Space Flight Center / USA	1963 [9]
	Carbon Arc Lamp	11×11 ft & 260 W/ft ²	Space Technology Laboratories, Inc / USA	1963 [9]
	Carbon Arc Lamp	5 ft×32 ft & 130 W/ft ²	Arnold Engineering Development Station / USA	1963 [9]
	Mercury Xenon Lamp & Xenon Arc Lamp	6 ft diameter & 130w/ft ²	Jet Propulsion Laboratory (10 ft) / USA	1965 [14]
	Xenon Arc Lamp	15 ft diameter & 130 w/ft ²	Jet Propulsion Laboratory (25 ft modified) / USA	1967 [15]
	Xenon Arc Lamp	3.6m diameter & 173 kW	IBAG / Germany	1983 [94]
	Carbon Arc Lamp	24 kW	Wright Patterson Air Force Base / USA	1991 [93]
	Xenon Arc Lamp	30 kW	Lewis Research Center / USA	1994 [35]
	Xenon Arc Lamp	55 kW	NIICHIMMASH / Russia	1997 [20]
	Xenon Arc Lamp	10 kW	University of Bern / Switzerland	2011 [36]
Standard solar simulator for PV	Xenon Arc Lamp & Quartz Tungsten	1×2cm	Hoffman Electronics / USA	1962 [37]

cell testing	Halogen lamp			
	Xenon Arc Lamp	AM0 & 2.5 kW	Spectrolab (X-25) / USA	1967 [39]
	Quartz Tungsten Halogen	AM 2 & 650 W	Argonne National Laboratory / USA	1979 [96]
	Xenon Arc Lamp & Quartz Tungsten Halogen lamp	4 inch diameter & 1650 W	Solarec Corporation / USA	1990 [99]
	Xenon Arc Lamp	4kW	JMI Institute / Japan	1993 [97]
	LED	205×205 mm	Tokyo University of Agriculture and Technology / Japan	2003 [54]
	LED	220×550 mm & 144 W	Myong Ji University / Republic Korea	2010 [56]
	LED		Aescufot GmbH / Germany	2011 [57]
	LED	150×150mm & 17 W	University of Illinois at Urbanna-Champaign / USA	2012 [58]
Solar simulator for collector testing	Quartz Tungsten Halogen	1.2×1.2 m & 42.9 kW	Lewis Research Center / USA	1974 [61]
	Quartz Tungsten Halogen	2×3 m & 121.5 kW	The Marshall Space Flight Center / USA	1978 [98]
	Quartz Tungsten Halogen	1.2×1.8m & 56.1 kW	Government Industrial Research Institute Nayoya/Japan	1979*[70]
	Quartz Tungsten Halogen	1.6m2 & 60 kW	National Bureau of Standards & Honeywell / USA	1979*[70]
	Xenon Arc Lamp	1.6m diameter & 65 kW	DFVLR / Germany	1979*[70]
	Xenon Arc Lamp	7m2 & 140 kW	National Bureau of Standards & Boeing Aerospace Co. / USA	1979*[70]
	Quartz Tungsten Halogen	1×1 m & 14 kW	Indian Institute of Technology / India	1985 [73]
	Metal Halide Arc Lamp	1.5*2.2m & 42 kW	Pontificia Universidade Catolica de minas Gerais / Brazil	2005 [80]
	Metal Halide Arc Lamp	3.88*4.5m & 75.2 kW	Xi'an Jiaotong University / China	2011 [82]
High-flux solar simulator (HFSS)	Xenon Arc Lamp	16 MW/m2 & 20 kW	Lawrence Berkeley Labortory & Paul Scherrer Institute (PSI) / USA & Switzerland	1991 [83]
	Argon Arc lamp	75 kW & 200 kWe	ETH-Zurich / Switzerland	2003 [84]

3.2. Concentrator

Due to the fact that the light sources used in solar simulators are approximate point sources or line sources, optical systems are usually applied for the purpose of obtaining required flux distribution on the testing area. The optical concentrator is the key optical component for every solar simulator system, especially for a high-flux solar simulators. Its main functions are: 1) working as a collector to collect various direction light radiation emitted by light source and project to the required direction; 2) increasing the power density of light flux to meet the requirement. As shown schematically in figure 12, the input and output surfaces can face in any direction, and it is assumed that the aperture 'A' is just large enough to permit all rays passed by the internal optics that have entered within the specified collecting angle to emerge. In the history of solar simulator design, the ellipsoidal reflector, compound parabolic concentrator (CPC), light cone, hyperboloid concentrator, parabolic dish concentrator and Fresnel lens were chosen in various solar simulator designs.

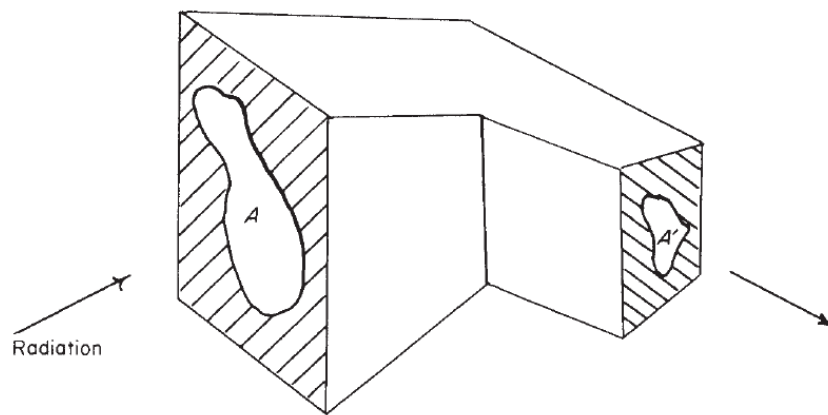


Fig. 12 Schematic diagram of a concentrator.[101]

3.2.1. Ellipsoidal concentrator

An ellipsoidal concentrator is defined that all rays originating at one of its foci must pass through the other after a single specular reflection [85], as shown in fig 13. Ellipsoidal concentrators are widely used in the systems which require not only collecting emitting light but also increasing light intensity, because they can achieve both these two requirements without any additional optical components. This can make the optical systems more compact and efficient. In the HFSS design, this characteristic becomes even more important. In a HFSS for solar point focus system simulation (solar dish or solar power tower system), which usually operate with very high light flux, more additional optical components mean higher

security risk and more cost on the cooling equipment for the optical components. Furthermore, more installing errors will be introduced to the optical system, which will influence the total power delivered on the target and the flux distribution. Until now, most of the HFSSs are designed based on the ellipsoidal concentrators [83]-[87].

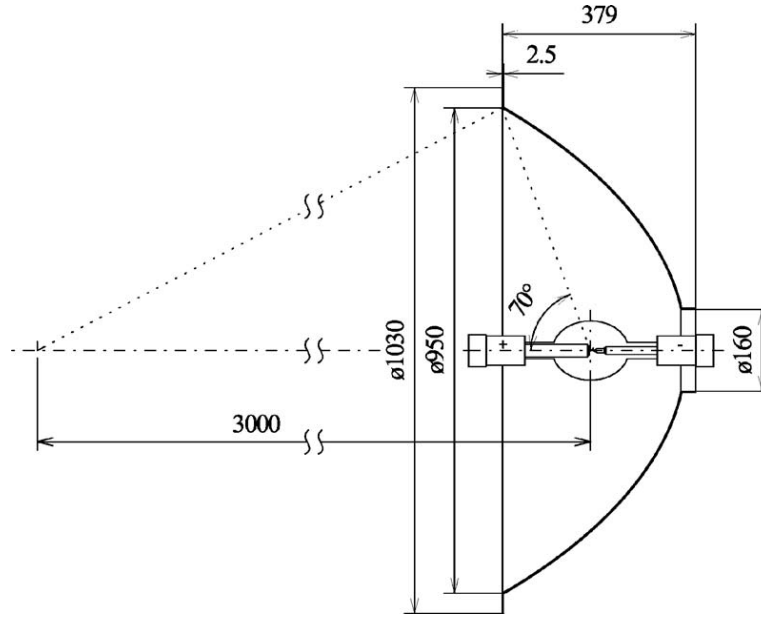


Fig. 13 Schematic of an ellipsoidal concentrator which used in the 50kW 11,000 suns solar simulator in ETH-Zurich

3.2.2. Parabolic dish concentrator

A parabolic dish concentrator can be defined based on the geometry characteristic of a parabola curve such that all rays originating at its focal point must become parallel to its axis after a single specular reflection, or rays parallel to its axis must pass through its focal point after a single specular reflection, which is shown in fig 14. Parabolic dish concentrators are widely used in CSP system due to their characteristic which can concentrate parallel light on its focal spot. In the solar simulator design, its characteristic also makes it perfect for the collectors of the light source without any concentrating requirement. Furthermore, if the light is already collimated, a parabolic dish can also be used as the concentrator of a HFSS [89][90].

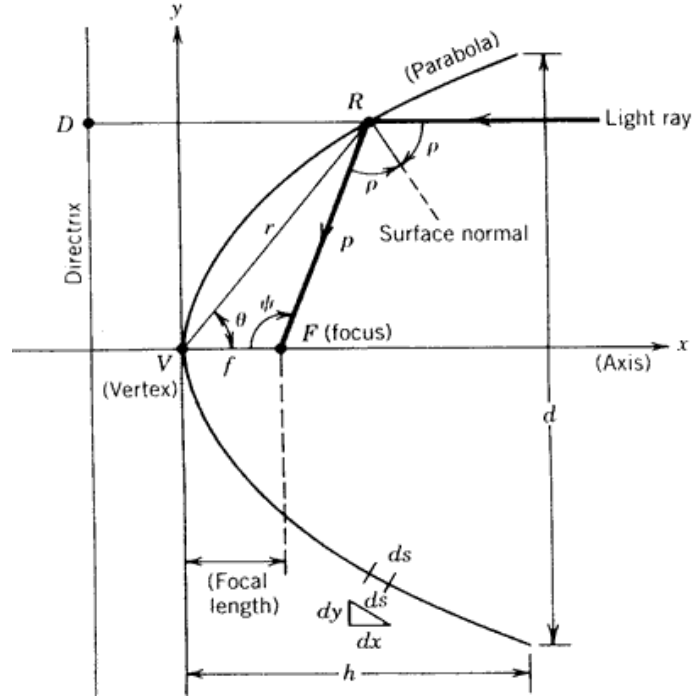


Fig. 14 Schematic of a parabolic dish concentrator [102]

3.2.3. Compound parabolic concentrator (CPC)

A basic shape of the compound parabolic concentrator (CPC) is shown in fig 15. Its 2D curve is comprised of two parabolic mirror segments with different focal points. The focal point for parabola A (F_A) lies on parabola B whereas the focal point of parabola B (F_B) lies on parabola A. 2D CPC is extruded based on the curve along the axis perpendicular to the curve while 3D CPC is rotated around its symmetry axis. All entering rays within the acceptance angle θ_{accept} will be perfectly concentrated at the exit aperture $F_A F_B$. The concentration ratio together with the geometry parameters are explained by Winston in [101], take a 3D CPC system for example, which can be list as follows:

$$f = \frac{a'}{1 + \sin \theta_i} \quad (1)$$

$$a = \frac{a'}{\sin \theta_i} \quad (2)$$

$$L = \frac{a'(1 + \sin \theta_i) \cos \theta_i}{\sin^2 \theta_i} = (a + a') \cot \theta_i \quad (3)$$

$$C = \frac{a}{a'} = \frac{1}{\sin \theta_i} \quad (4)$$

Where: f is the focal length, a is the radius of the enter aperture, a' is the radius of the exit aperture, θ_i is the maximum input angle (half acceptance angle θ_{accept}), L is the total length of the CPC, C is the concentration ratio. The CPC concentrator has been proved as a perfect concentrator in the low concentration ratio CSP system and CPV system. Furthermore, it will be a good concentrator option for a solar simulator based on commercial approximate parallel light sources. Unfortunately, seldom application research has been published in solar simulator design.

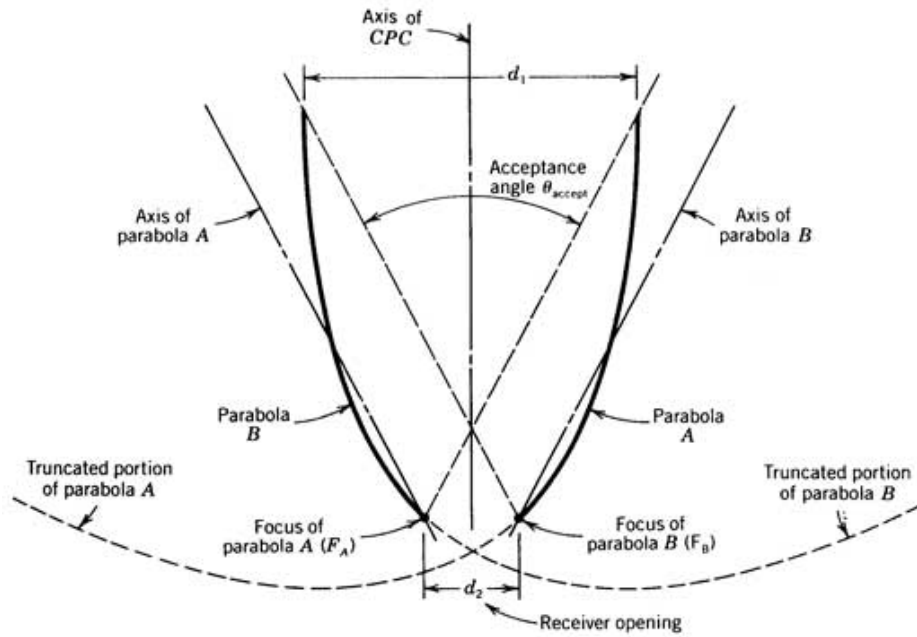


Fig. 15 Compound parabolic concentrator (CPC) [102]

3.2.4. Hyperboloid concentrator

A truncated hyperboloid concentrator is a kind of a concentrator which uses the geometry characteristic of a hyperboloid to concentrate the rays on its exit aperture area, and its structure is shown in fig 16. All rays entering the aperture and pointing somewhere inside the disk area with a diameter of $2C$ between two focal points (F-F) [101]. However, this kind of concentrator does not show more merits compared to the CPC concentrator, so it is not so widely used in neither concentrated solar system nor solar simulator design. The low cost solar simulator design which has been developed by MIT [88] is one of its applications, where a flow-line concentrator constructed by a truncated hyperboloid and light cone is chosen as the main optical system.

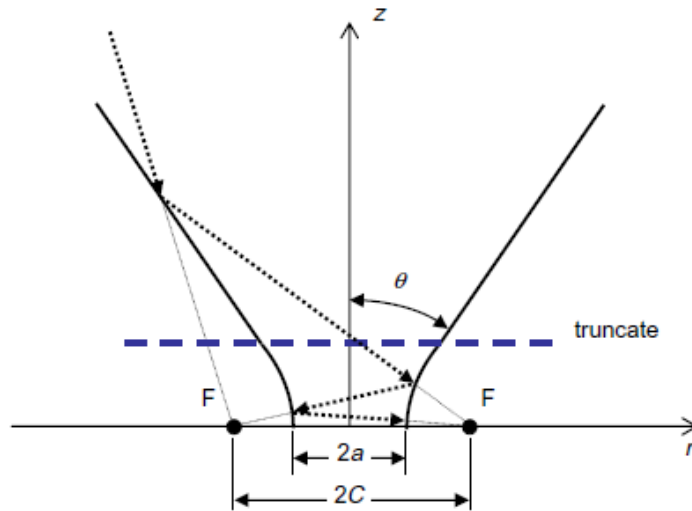


Fig. 16 Schematic of a flow-line concentrator which constructed by a truncated hyperboloid and light cone [88]

3.2.5. Light cone

Light cone, a primitive form of non-imaging concentrator, has been widely used for many years before the CPC concentrator. As shown in fig 17, if the cone has a semiangle γ and if θ_i is the extreme input angle, then the ray indicated will just pass after one reflection if $2\gamma = (\pi/2) - \theta_i$. It is easy to design and manufacture, so it is still used in some areas, such as for solar cookers and for solar simulators combined with other concentrators to reduce the cost [88].

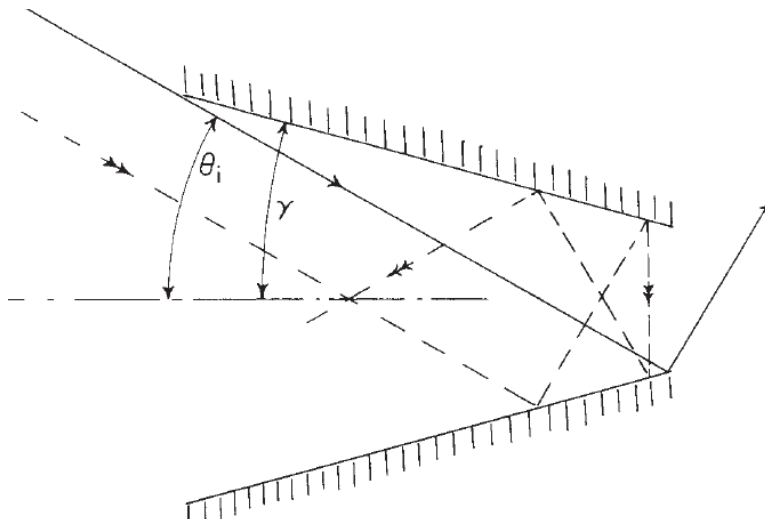


Fig. 17 Schematic of a light cone [101]

3.2.6. Fresnel lens

A Fresnel lens is a flat approximation of a curved lens, which can be used as a cost-effective lightweight alternative to a corresponding conventional curved lens [104], a typical Fresnel lens is shown in fig 18. Fresnel lenses can concentrate parallel entering rays to its focal point by refraction, and also make entering which origination at its focal point parallel. This characteristic makes Fresnel lens a perfect concentrator not only to concentrated solar systems, but also solar simulators, especially for the solar simulator with an approximate light source. The AM2 solar simulator developed by Lewis Research Center is one of the earliest solar simulators which used plastic Fresnel lenses as the main concentrators for the lamps [61]. Fresnel lenses were chosen as the concentrator in several following similar solar simulator designs [70][98].

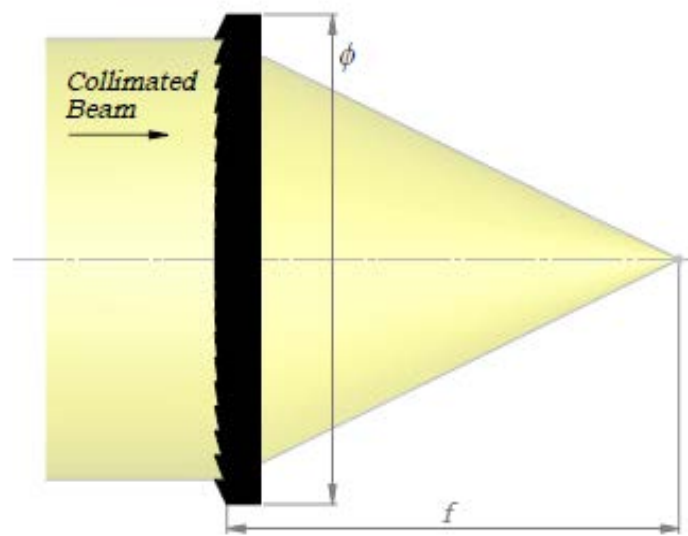


Fig. 18 Schematic of a Fresnel lens [104]

4. Conclusions and perspectives

The solar simulator is a device that can approximately simulate the sun irradiation. It was first designed for testing PV cells and space craft (include PV panel performance in space) in the 1960s. Latter, with the development of solar collectors, solar collector testing type solar simulators were developed together with the collector testing standards in 1970s. High-flux solar simulator's appearance was in the early 1990s, it is first design for solar thermochemical research but can also be used for the research of concentrated solar power (CSP) and concentrated photovoltaic (CPV) technologies.

This paper classifies the four types of solar simulators based on their characteristics and reviews their developments. For space solar simulators, mainly simulators were designed based on the earth orbital space environment. With the paces of human's space exploration, much more solar simulation research will be done to meet the requirements. For standard PV testing solar simulators, lots of research work has been done for improving the spectrum accuracy and reducing the cost, which will continue with the emergence of novel light sources and optical designs. Furthermore, portable, low power consumption and long life time are the other trends in the future simulator design. For the collector testing solar simulator, with the requirements of testing collectors with various selective absorption coatings, more tracking accuracy, more spectral distribution accuracy and flux distribution uniformity will become the design objectives of the future collector testing solar simulator. For high-flux solar simulator (HFSS) design, lots of researches on peak flux and flux distribution have been done since the 1990s. However, no simulator was designed compared to a real concentrated solar system. With the requirements of receiver testing, more accurate 3D flux distribution to a real CSP system or CPV system will become the main design object in the future HFSS design. More concentrators will be introduced to meet this design object.

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