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Light source selection for a solar simulator for thermal applications: A review

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ABSTRACT

Solar simulators are used to test components and systems under controlled and repeatable conditions, often in locations with unsuitable insolation for outdoor testing. The growth in renewable energy generation has led to an increased need to develop, manufacture and test components and subsystems for solar thermal, photovoltaic (PV), and concentrating optics for both thermal and electrical solar applications. At the heart of any solar simulator is the light source itself. This paper reviews the light sources available for both low and high-flux solar simulators used for thermal applications. Criteria considered include a comparison of the lamp wavelength spectrum with the solar spectrum, lamp intensity, cost, stability, durability, and any hazards associated with use. Four main lamp types are discussed in detail, namely argon arc, the metal halide, tungsten halogen lamp, and xenon arc lamps. In addition to describing the characteristics of each lamp type, the popularity of usage of each type over time is also indicated. This is followed by guidelines for selecting a suitable lamp, depending on the requirements of the user and the criteria applied for selection. The appropriate international standards are also addressed and discussed. The review shows that metal halide and xenon arc lamps predominate, since both provide a good spectral match to the solar output. The xenon lamp provides a more intense and stable output, but has the disadvantages of being a high-pressure component, requiring infrared filtering, and the need of a more complex and expensive power supply. As a result, many new solar simulators prefer metal halide lamps.

1. Introduction

The growing demand for energy, combined with issues of environmental pollution, climate change, and the rapid depletion of fossil fuels, have encouraged the research and development of cost effective renewable alternatives [1–3]. Solar electrical and thermal energy research groups have focused on developing novel technologies and on improving existing renewable solutions. In 2014, the global combined installed capacity of solar hot water and concentrating solar power (CSP) was 410.4 GW, representing 8% of the world's renewable energy sources [4].

The transient nature of solar energy represents a critical challenge for technologies testing. Outdoor experiments are carried out in real but uncontrollable environments. For example, incident solar energy levels are highly dependent on atmospheric conditions and sky clarity over time [5]. Therefore, achieving the rapid and low-cost development of solar thermal and PV systems requires a controlled environment with key parameters that can be adjusted and monitored. Consequently, a range of solar simulators have been designed and used since the 1960's.

A solar simulator is a device with a light source which offers both an intensity level and a spectral composition close to that of natural sunlight [6]. It is used to simulate either extra-terrestrial or terrestrial radiation [7]. Early solar simulators were designed and built in the 1960's to be used in space applications research projects sponsored by the National Aeronautics and Space Administration (NASA) for spacecraft ground-testing by simulating environments at orbital altitudes [8–10]. More recently, research work has focused on terrestrial radiation simulators. These devices are used for a wide range of applications including testing, calibrating and characterising photovoltaic (PV) cells [11–14] and for the clinical testing of sunscreens [15–17]. The list of applications extends to the automotive industry for testing dashboards, steering wheels and air bags [18–20]; PV materials ageing tests [21–24]; studying the effects of light on the growth of plants and algae [25–27] and testing of thermal/thermo-chemical devices for use in the chemical reforming and production of chemical elements [28–30]. This paper deals with solar simulators built for thermal applications, although they are also relevant to PV and concentrating PV (CPV) testing [31–35]. More applications are covered in section 3. Such simulators

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have output fluxes ranging from a few suns (1 sun = 1 kW/m^2 [36–38]), to more than 30 suns, which are classified as low and high-flux solar simulators, respectively [39]. Those simulators consist of three main parts: a light source, a power supply and an optical component. Each part is selected to obtain a controlled output conforming to specific requirements. The current work focuses on the selection of a suitable light source, which is critical to ensure simulated solar radiation quality and reliability [40].

2. Standard solar spectrum

2.1. Blackbody radiator spectrum

A blackbody is an idealised object which is a perfect radiation emitter and absorber [41]. A blackbody radiator has the maximum possible spectral radiance for a heated body at a particular specified temperature. Therefore, this temperature is usually used as a convenient baseline for comparison with real radiation sources [42]. The sun can be considered as a blackbody radiator at a temperature of 5777 K, which can be approximated to 5800 K [43–46]. Spectral radiance of a blackbody can be determined, in W.m^{-3}.sr^{-1}, by applying Planck's law [47]:

$$E_\lambda = (2hc^2/\lambda^5)(e^{hc/\lambda kT}-1)^{-1} \quad (1)$$

Where h is Planck's constant (6.6262 $\times 10^{-34}$ J.s), c is the velocity of light (2.9979 $\times 10^8$ m/s), λ is the wavelength (m), k is the Boltzmann's constant (1.3806 $\times 10^{-23}$ J/K), and T is absolute temperature (K).

2.2. Solar spectrum

The actual solar spectrum differs from a blackbody radiance at 5800 K because of absorption in the cool peripheral solar gas (Fraunhofer lines) [70,71]. While passing through the Earth's atmosphere, direct solar radiation is attenuated by scattering and absorption by gaseous molecules (i.e. nitrogen, oxygen, aerosols and water vapour) [48]. Therefore, an Air Mass (AM) coefficient has been defined to characterise the solar spectrum after the solar radiation has travelled through the atmosphere [49]. The AM coefficient is defined as the ratio of the solar radiation path length through the atmosphere (L), incident at a zenith angle (z), and the atmosphere thickness in the zenith direction (L_0) [50]:

$$AM = L/L_0 = 1/\cos z \quad (2)$$

Although this relation can be refined by modelling more accurate path thicknesses through the horizon [51–53], Eq. (2) remains commonly used to define standard conditions for solar applications. It is expressed using the syntax "AM" followed by its value [49]. The variation between different AM definitions (i.e. AM0, AM1.0 and AM1.5) is illustrated in Fig. 1.

The extra-terrestrial solar spectrum (AM0) is used to characterise PV

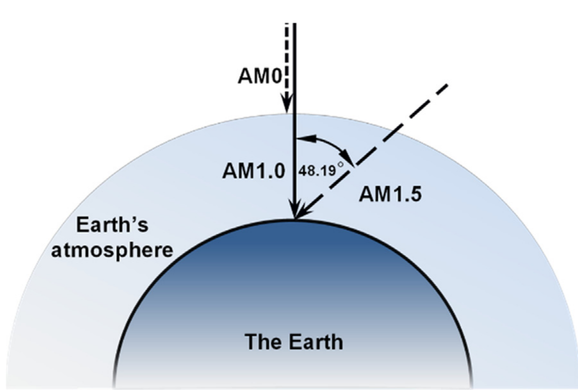

Fig. 1. Air Mass (AM) definition (adapted from [54]).

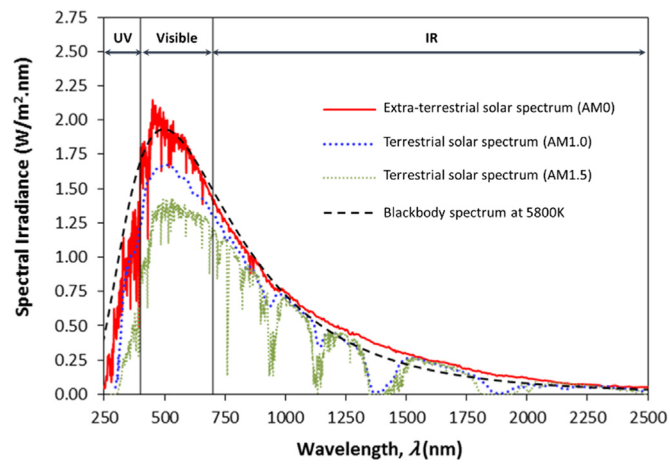

Fig. 2. Comparison between solar spectra (AM0 [58], AM1.0 [59], AM1.5 [64]) and black body radiator spectrum [69].

panels used for space applications [55]. There are various solar irradiance spectra constructed from single and/or multiple measurement sets or models [56,57]. However, for space solar power applications, the standard ASTM E490 [58] is usually applied. The solar spectrum travelling through the atmosphere directly to sea level with a zenith angle of zero (AM1.0) is published by ASHRAE [59]. As solar panels and collectors operate at tilted angles, the solar radiation path is greater than one atmosphere's thickness [55]. Since the world's major solar installations and industry centres are located [60] at mid-latitudes, a specific AM number was defined for a zenith angle of 48.19°. Since the 1970s, AM1.5 has been used for standardisation purposes [61–63] provided by ASTM G173–03 standard; previously ASTM G159-98 [64,65].

The solar spectrum is divided into three main regions: ultraviolet (UV), visible, and infrared (IR) with wavelength ranges of < 400 nm, 400–760 nm, and > 760 nm respectively [66]. According to the International Commission on Illumination (CIE), the UV region can be defined in three bands: UV-A (315–400 nm), UV-B (280–315 nm) and UV-C (100–280 nm) [67,68]. Fig. 2 shows a comparison between different solar spectra and the radiation spectrum of a blackbody at 5800 K. The differences between the spectrum curves in Fig. 2 are attributed to the attenuation and transmission losses of sunlight over its optical path through the Earth's atmosphere. Therefore, the longer optical path shows the least spectral irradiance. However, data plotted in Fig. 2 confirms the assumption of treating the sun as a blackbody radiator at 5800 K.

3. Light sources

Light source selection is the principal step in designing a solar simulator with suitable simulated solar radiation. This light source is required to meet several criteria: spectral quality, illumination uniformity, collimation, flux stability and a range of obtainable flux [70].

Various lamp types have been employed in solar simulators, including carbon arc, metal halide, tungsten halogen, xenon arc, mercury xenon, high pressure sodium vapour, argon arc and light-emitting diode lamps (LED) [33]. The choice can depend on the field of application of the solar simulator. For example, the optimum output current of a PV cell is generated when the incident spectrum matches with the spectral absorption properties of the semiconductor [104] and are more sensitive to the incident light spectrum below 1000 nm for a silicon PV cell [33,71–73]. Multi-junction PV cells are more sensitive to the spectrum of the light source which affects their fill factor and short-circuit resistance [75]. Therefore, researchers tended to use multi-light source synthesis to improve the spectral matching for PV performance testing. These simulators employ either conventional light sources, such as