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A low cost high flux solar simulator

Daniel S. Codd *, Andrew Carlson, Jennifer Rees, Alexander H. Slocum

Department of Mechanical Engineering, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, United States

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Abstract

A low cost, high flux, large area solar simulator has been designed, built and characterized for the purpose of studying optical melting and light absorption behavior of molten salts. Seven 1500 W metal halide outdoor stadium lights are used as the light source to simulate concentrating solar power (CSP) heliostat output. Metal halide bulbs and ballasts are far less costly per-watt than typical xenon arc lamp solar simulator light sources. They provide a satisfactory match to natural sunlight; although 'unfiltered' metal halide lights have irradiance peaks between 800 and 1000 nm representing an additional 5% of measured energy output as compared to terrestrial solar irradiance over the same range. With the use of a secondary conical concentrator, output fluxes of approximately 60 kW/m^2 (60 suns) peak and 45 kW/m^2 (45 suns) average are achieved across a 38 cm diameter output aperture. Unique to the design of this simulator, the tilt angle and distance between the output aperture and the ground are adjustable to accommodate test receivers of varying geometry. Use of off-the-shelf structural, lighting and electrical components keeps the fabrication cost below $10,000.

Keywords: Solar simulator; Concentrating solar power; Metal halide lighting; Volumetric receiver; Molten salts

1. Introduction

Solar simulators are invaluable for solar energy research. Commercial off-the-shelf simulators are designed to provide small areas of uniform, nearly collimated light, matched to terrestrial solar spectra for photovoltaic (PV) cell testing. Typical flux output intensities are a few 'suns' (1 sun = 1 kW/m^2); thus they do not usually provide the high intensities required for concentrating solar power (CSP) testing. Custom made solar simulators have been built to provide the intensities necessary for CSP research, ranging from 30 to 100 kW/m^2 (30–100 suns) and upward, but have cost hundreds of thousands of dollars. These research simulators utilize high power xenon arc lamps, precision engineered optical elements and active cooling circuits (Hirsch et al., 2003; Jaworske et al., 1996; Kuhn and Hunt, 1991; Petrasch et al., 2007).

This paper describes the design, development, and testing of a low-cost solar simulator, and plans for its construction are provided in the Appendix. The goal for this project was to design and build a solar simulator for under $10,000 that would offer similar testing capabilities to more expensive, high-flux research simulators. The only drawback is that the light is not well collimated with the simple concentrating optics that are employed. Although the unit is designed for CSP thermal testing, specifically to study the absorption behavior of volumetric molten salt receivers, it could be utilized for concentrated PV testing provided collimated light was not needed.

Abbreviations: CSP, concentrating solar power; FLC, flow line concentrator; NEMA, National Electrical Manufacturers Association; NREL, National Renewable Energy Laboratory; MH, metal halide.

* Corresponding author. Tel.: +1 617 253 1953; fax: +1 617 258 6427.
E-mail addresses: codd@mit.edu (D.S. Codd), acarlson@mit.edu (A. Carlson), jrees@mit.edu (J. Rees), slocum@mit.edu (A.H. Slocum).

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Nomenclature

α	thermal diffusivity	g	gravitational acceleration
α_{solar}	solar absorptivity	h_m	convection coefficient
β	volumetric coefficient of thermal expansion	k	thermal conductivity, air
θ	cone half-angle	k_{Al}	thermal conductivity, aluminum
σ	Stefan–Boltzmann constant	L	characteristic length
ε_n	normal spectral emissivity	T	absorber temperature
v	kinematic viscosity	T_m	mean air temperature
a	secondary concentrator exit (aperture) radius	T_∞	ambient temperature
A	absorber area	V	absorber volume
C	secondary concentrator entrance radius	q	heat flux
D	diameter		

2. Detailed design

The design of the solar simulator can be broken down into three subsystems: light source; adjustment structure; and concentrator. Table 1 lists the primary functional requirements and associated specification targets for the solar simulator. Fig. 1 shows the completed simulator.

2.1. Light source

Xenon arc lamps, favored by commercial solar simulator manufacturers, can be filtered to have an emission spectrum closely matching that of terrestrial sunlight. They are available in high power single bulb configurations which can be coupled with a single ellipsoidal mirror, resulting in a tightly controlled spot size (Petrasch et al., 2007). However, high power xenon arc lamps and their associated drive electronics are expensive products, with nearly 10 times the costs-per-watt than commodity light sources.

Metal halide (MH) lamps were determined to be the most practical light source due to the significant price difference. However, MH lamps come with quite a few drawbacks worth mentioning, although they were determined not to be detrimental to our CSP testing needs. The ‘unfiltered’ emission spectrum of does not match the emission spectrum of sunlight as closely as that of xenon arc lamps (see Fig. 7 in Section 3). Also, the long ‘filament’ in large MH bulbs does not lend itself to precise focusing – resulting in an increased minimum achievable spot size relative to xenon arc lamps.

MH lamps are widely used in industrial and sports lighting applications, and are thus readily available and inexpensive. Common MH outdoor stadium lights utilize 1500 W BT-56 bulbs and NEMA standardized spun-aluminum ellipsoidal reflector geometries. Light distribution is described by NEMA 1–6 type ratings: Type 1 is a narrow beam (10–18°); Type 6 is a wide flood (100–130°) (Benya et al., 2003). Fig. 2 shows the luminous intensity distributions for the most common types, NEMA 3 and 5. NEMA 3 reflectors were chosen for their narrow, high intensity output beam.

Seven off-the-shelf (Complete Lighting Source: p/n SP1500MHMT) 1500 W outdoor MH units with integral ballasts, adjustable mounts and NEMA 3 reflectors are utilized for the solar simulator. The lights are arranged in a hexagonal array with the seventh light in the center. The simulator is configured for two 30 A/208 V power sources with fused safety cut-off switches and individual circuit breaker and in-line fuse protection.

2.2. Adjustment structure

The frame must be easy to assemble, stiff, and support the weight for the MH lights, ballasts and secondary concentrator – about 160 kg. The frame also must be designed for ease of adjustment, disassembly and short-range mobility so it can be moved within the lab, or between laboratories.

2.2.1. Base

Perforated steel tubing was chosen for its strength, stiffness, availability, low cost, and ability to safely set components at different heights with positive engagement pins. For portability, the frame is designed to separate into two A-frame style halves. The frame footprint measures

Table 1
Functional requirements and design specifications.

Functional requirement	Design parameter	Specification
Emulate solar heating	Metal halide lights with metal reflective concentrating optics	Output flux $\geqslant$ 50 kW/m^2
Adjustable for different receivers	Aperture height adjustability via nested perforated tubing	0 $\leqslant$ Aperture height $\leqslant$ 1 m
Tiltable for non-normal incidence	Aperture rotation pivot	0° $\leqslant$ Aperture angle $\leqslant$ 90°
Large output spot	Conical concentrator	Aperture diameter $\geqslant$ 20 cm
Low cost	Commercially available and simple components	Cost < $10,000