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Design and commissioning of a virtual image solar simulator for testing thermal collectors

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ABSTRACT

A solar simulator has been designed and built for testing prototype (0.5 × 0.5 m) flat plate thermal collectors. An internally reflecting light tube generates multiple virtual images of the four halogen floodlights to ensure uniform illumination. Ray-tracing simulations were used to choose the tube dimensions and maximum allowable clearance. Illumination measurements agree well with these predictions.

The visible & near IR spectrum appears to follow a black body curve. In the absence of a “cold sky” IR filter there is a secondary, long wavelength IR spectral component that causes heating of the cover glass on a solar flat plate collector. The cover glass temperature can be maintained at typical outdoor levels using a cooling fan. The design would be well suited to LED illumination.

Simulation of solar collector response to this spectrum shows that an efficiency based on pyranometer readings is approximately 1% higher than would be obtained with an AM1.5 spectrum.

1. Introduction

Solar panels are frequently tested indoors under a solar simulator that provides control of illumination levels and allows these to be maintained in a stable environment. When testing PV cells the illumination spectrum is important since the conversion efficiency is spectrally-dependent; this typically requires the use of specialised lamps, for instance high-pressure xenon discharge bulbs (Dibowski and Eber, 2017), metal halide (Meng et al., 2011; Dong et al., 2015) or LEDs (Kohraku and Kurokawa, 2006; Bliss et al., 2009; Jang and Shin, 2010; Bazzi et al., 2012; Kolberg et al., 2012; Plyta, 2015). A combination of quartz-halogen lamps and blue LEDs is a cost-effective way of generating a spectrum covering the IR and visible spectrum (Grandi et al., 2014). Interest in the potential of small, high efficiency PV cells illuminated using concentrating optics has led to the development of high-flux solar simulators (Codd et al., 2010; Kreuger et al., 2013; Sarwar et al., 2014; Ekman et al., 2015). Schubert and Spinner (2016) compares the spectral accuracy of a number of light sources.

The requirements for testing thermal collectors are however much less stringent. Absorbers typically use a selective emissivity coating having high absorbance, over a wide spectral range, for wavelengths present in sunlight and then low absorbance for wavelengths characteristic of black-body radiation at the absorber temperature. The exact spectral distribution is of little interest. The illumination for a thermal panel simulator can therefore be provided by low-cost quartz-halogen bulbs (Shatat et al., 2013). Typically these produce a spectrum with a lower colour temperature than sunlight i.e. a larger infra-red component.

The illumination should be sufficiently uniform that the mean power over the panel area can be easily and accurately determined from a number of point measurements.

Traditionally this has been achieved using an array of lamps covering an area considerably larger than the test section (Simon, 1976). This is inefficient in terms of the laboratory space requirement and heat input in what should ideally be a temperature-controlled area; there is also a risk of a bright spot under each bulb if the bulb to panel distance is small. The simulator described here overcomes these difficulties by using a reflecting light tube.

2. Simulator design

A highly uniform illuminated field may be obtained with a small number of bulbs by using a reflecting light tube that generates multiple virtual images, Fig. 1. The virtual images simulate the appearance of a

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Nomenclature

d	thickness of glass
f	internal transmittance
G_{pyr}	pyranometer measurement of illumination power (W/m^2)
G_T	total illumination power (W/m^2)
k	extinction coefficient
n	refractive index
p	polynomial coefficients
r	normal reflection coefficient at each surface
α	absorbance
ρ	reflectance
τ	external transmittance

much larger lamp array.

A ray-tracing program was written in Matlab to predict the illumination at every point $s(X,Y)$ on a 41 × 41 node grid covering the target area. The program input parameters are defined in Fig. 2 and include a limit on the maximum number of reflections for each ray.

For each lamp in the lamp plane the program calculates the distance to the target point, the number of reflections and the elevation and altazimuth angles of the beam relative to the lamp axis. The process is the same both for “real” lamps providing direct illumination and their reflected (virtual) images. The light tube reflective surface was made from aluminium foil to minimise the weight of the assembly; the foil was attached to the plywood using Spray Mount™ adhesive. The reflectivity of the foil’s more reflective side was assumed to be the nominal level for aluminium (0.88). No correction was applied for variation in reflectivity with angle: it seemed likely that at low angles the reflectivity would increase towards total reflection but that this would be at least partially offset by increased scattering due to roughness of the plywood underneath the foil.

The illumination distribution for a floodlight was measured using a Kipp & Zonen CMP11 pyranometer (Fig. 3). For simplicity the mean of the two profiles was adopted as a radially-symmetric distribution and characterised as a fourth-order curve fit. The power was assumed to follow an inverse square law with distance. The data was obtained over a plane and then (Fig. 3b) scaled to represent illumination on the surface of a sphere of radius 1 m.

Fig. 4 models the illumination achieved when each of the four floodlights is angled to face a collector centreline (vertical or horizontal). This was the configuration chosen for collector testing. The sharp drop-off at the edges demonstrates the effect of the vertical gap between the target and the lower extent of the light tube. Some gap here is desirable for ventilation, for ease of access and viewing the collector whilst testing. The light tube width was made 40% larger than the solar panel so that the panel could sit within the uniform field. The light tube length was constrained by the laboratory ceiling height: a longer light tube would produce greater uniformity.

The mechanical design of the simulator is intended to allow the light tube to be rapidly swung to one side. The tube is mounted on hinges and has a pair of counter-balance weights, Fig. 5. For panel installation it can be raised to a horizontal position, Fig. 5b. The solar collector is typically mounted at an angle of 11° to the horizontal to avoid any risk of bubbles collecting internally against the upper surface.

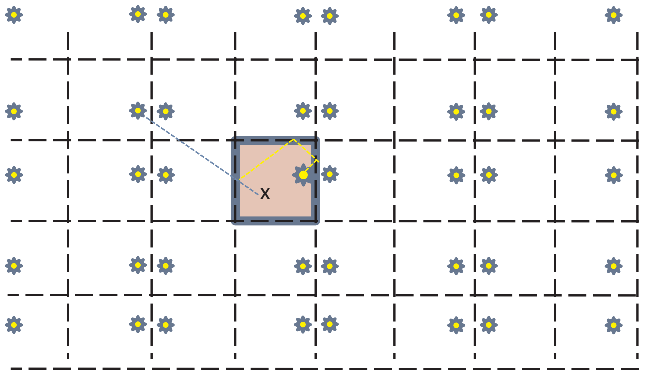

Fig. 1. Cross-section through the lamp array plane, showing one lamp within the light tube area (shaded) and the virtual images of this lamp when reflected in one or more sides of the light tube. Dotted lines show actual (yellow) and virtual (mauve) light path from bulb to a target point X.

3. Simulator commissioning and calibration

The mean power and uniformity of illumination was determined by reading the pyranometer at 25 locations on a 5 × 5 grid. This was done at full power and for various combinations of bulbs: all four, then three, two or just one bulb; for brevity only the four-bulb data is presented here. When reducing power it is preferable to reduce the number of lamps in use instead of running the bulbs at a lower temperature. The latter option can result in reduced bulb life as well as changes to the spectrum.

The illumination over a 0.5 × 0.5 m grid with all four bulbs is shown in Fig. 6. A 4th order surface, Fig. 6(a), was fitted through all 25 data points:

$$G(x,y) = \sum_{j=0}^{4} \sum_{i=0}^{4} p_{ij} x^i y^j$$

The area-averaged mean power was then found by integration. Cross-sections through the central region, Fig. 6(b), are less uniform than was expected from the simulation. This may be due to small errors in the angular alignment of the lights. The degree of uniformity is however sufficient to enable the mean power to be accurately determined when testing solar collectors. The predicted mean illumination is 2.3% lower than measured; the simulation would match the measured illumination if the reflectivity value used were $r = 0.894$ instead of the nominal 0.88.

The observed non-dimensional standard deviation for the data in Fig. 6 is $\frac{\sigma}{\mu} = 0.053$, very close to predicted levels for the lamp tilt angle $\alpha = -5.5°$, Fig. 7. Subsequent analysis indicated that a more uniform illumination could have been achieved with a tilt angle $\alpha \approx +8°$.

The four floodlights are powered by a variable transformer. The maximum illumination is 1340 W/m^2; typically solar collectors are tested up to 1000 W/m^2, with lower powers being achieved by reducing either the voltage or the number of lamps in use. The transformer output power is measured by a Hameg HM115 power meter. To avoid any possible error due to variation in mains voltage over the duration of a test the instantaneous power signal from the Hameg is recorded along with all the solar collector data. The instantaneous power signal (100 Hz) passes through a full-wave operational amplifier rectifier and low-pass filter to provide a recordable DC level. Subsequent testing revealed the 100 Hz signal to be almost entirely positive so the rectifier was not strictly necessary.

Measurements over a wide power range led to an empirical correlation between electrical power and mean illumination, Fig. 8.

4. Investigation into solar collector cover glass temperatures

The simulator has been used to test evacuated flat plate solar collectors: full experimental results will be published in due course. The internal pressure is in the evacuated collectors is typically less than 0.2 Pa and an array of pillars (Fig. 9) supports the cover glass against atmospheric pressure, Henshall et al. (2016). The absorber is black