Design of a Multiple-Lamp Large-Scale Solar Simulator

A simple solution to the conflicting constraints of providing uniformity and collimation of irradiance in multiple-lamp solar simulators is proposed. As proof of concept, irradiance measurements obtained in a simulator comprised of 28 1-kW mercury-iodide gas discharge lamps and capable of irradiating a 1.22 m-by-2.44 m collector plane are given. The design is based on preventing a portion of the light from each bulb reaching the collector plane. Light blockage is achieved by placing a "shadow board" 1.02 m from and parallel to the plane of the lamps. Lamps are arranged in an hexagonal pattern with 4 columns of 7 lamps at a lamp-to-lamp spacing and column-to-column spacing of 0.45 m. Lamp-to-collector plane distance is 3.05 m. The design is determined from measurements of the spatial distribution of radiant energy from a single lamp. Irradiance from an array of lamps is then simulated. Measurements of irradiance in the full-scale simulator confirm that uniformity and collimation conform to the American Society of Heating, Refrigerating and Air Conditioning Engineers' standard. Average irradiance is 1080 W/m². Maximum irradiance is 1190 W/m² and minimum irradiance is 980 W/m². Every point on the plane of the collector receives 100 percent of radiant energy from an area on the lamp array contained within a subtended angle of 20 deg.

Introduction

Using lamps to simulate the sun is not a new concept. A crude solar simulator was used nearly 50 years ago to test solar air collectors (Löf, 1992). Worldwide, more than 30 large-scale simulators were in use in 1983 (Tanemura, 1983). Unfortunately, the four original large-scale simulators in the United States have been decommissioned. Although it is possible to construct a simulator capable of irradiating 4 m² using a single argon arc lamp, cost of the lamp is $250,000 (McClenahan, 1993). The objective of this work is to provide a lower cost alternative using multiple light sources. The problem of using multiple lamps is the difficulty of simultaneously satisfying specifications of uniformity of irradiance and light collimation as stated by ASHRAE (American Society of Heating, Refrigerating and Air Conditioning Engineers) in standard 93 (1986). The simulator is intended to test flat-plate collectors and water heating systems such as integral storage and thermosiphon systems.

The ASHRAE standard sets minimum average irradiance at 790 W/m². Maximum and minimum values of irradiance must be within ten percent of the average. Average irradiance is based on values measured in a uniform rectangular grid at intervals ≤0.15 m. Spectral distribution of light over 0.3 μm ≤λ≤ 2.6 μm must "reasonably" match that of natural sunlight defined by air mass 1.5 (American Society for Testing and Measurements, ASTM, 1987). Average radiant energy should not vary by more than ±3 percent. Collimation must be sufficient to ensure that ≥90 percent of the energy received at any point on the collector test plane emanates from a region of the solar simulator contained within a subtended angle of 20 deg. Infrared irradiance (3.5 μm ≤λ≤ 50 μm) should not exceed that of a theoretical blackbody at ambient temperature by more than 50 W/m².

The objective in designing a low-cost large-scale simulator is to minimize the number of lamps and place them in an area not substantially larger than the test plane. Prior multiple-lamp designs have used either hundreds of low-power tungsten-halogen lamps in combination with fresnel lens or higher powered gas discharge lamps (typically xenon or mercury-iodide) placed near the perimeter of the irradiated area. Placing the lamps away from the center portion of the irradiated plane significantly reduces any collimation provided by the lamp reflector but can facilitate obtaining uniform radiant energy. The xenon discharge lamp has good spectral qualities but requires water cooling and complex controls (Krusi and Schmid, 1983). The most reasonable lamp choice is the mercury-iodide gas discharge lamp (called Compact Source Iodide, CSI, by the manufacturer). The CSI lamp is a sealed beam unit with the bulb placed in front of a parabolic reflector. In the bulb, iodide is combined with mercury gas to produce light which has a spectral output very similar to AM-1.5. The iodide reduces evaporation of mercury and thus extends bulb life and produces greater useful output (Keitz, 1971). The lamps were originally developed for use in stadiums to improve color television filming (Krusi and Schmid, 1979). Lamps are easy to
control, have a 1000 hour life, and require no special cooling. They cost approximately $1000, including ballast, ignitor, socket, lamp and variac. To keep total cost below $30,000, it was desired to use less than 30 lamps.

Since the built-in reflector on the CSI lamp does not produce uniform, collimated light, this paper presents a simulator design based on use of a "shadow board" which blocks a portion of the light emitted from each lamp from the plane of the collector. Figure 1(a) shows a typical horizontal centerline irradiance distribution of a single lamp located so that light reaches the collector test plane at normal incidence. The solid lines in Fig. 1(b) show irradiance distributions of two lamps placed 0.45m apart. The dashed line represents total output from two lamps.

Hot spots are produced as the "tail" of the distribution from lamp 1 adds to the irradiance peak of lamp 2, and vice versa. In a full-scale simulator, uniformity is even harder to achieve since the point on the collector directly underneath a lamp is affected by as many as six other lamps. Increasing the spacing between lamps decreases maximum irradiance, but creates cold spots.

It was hypothesized that by reducing the area on the test plane affected by each lamp, uniformity could be improved. Figure 2 is a sketch of the geometric effect of the shadow board concept. The detrimental effects of multiple lamps are minimized by blocking some light from each bulb so that at the point of maximum flux from one lamp there is minimal added irradiance from surrounding lamps. To restrict the irradiated area to a circle of radius 'Y', measured from the centerline of the lamp, an opaque plane with a hole of radius 'x' is located distance 'z' from the lamp. Lamp-to-test plane distance ('z'), can be varied depending on the desired irradiance at the collector. Dimensions 'x' and 'z' are arbitrary as long as the ratio of 'x'/z' equals Y/z.

Methodology

Light uniformity and collimation depend on configuration of the lamp array and shadow board. To ascertain the effects of lamp-to-lamp and lamp-to-shadow board spacings, irradiance flux maps of a single lamp were measured and then radiant energy output of 28 lamps was simulated. Experimental parameters include: distance from the lamp to collector test plane, lamp orientation, lamp power setting, and shadow board geometry. Lamp-to-lamp spacing and geometric pattern were considered in numerical simulations of the entire irradiated plane.

Measurement Procedure. Global radiant energy was measured with a Licor 200SA calibrated against an Eppley PSP.

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Nomenclature

- \( G \) = irradiance, W/m²
- \( G_a \) = average irradiance, W/m²
- \( p \) = power setting of lamp, W
- \( X \) = column-to-column spacing of lamp array, m
- \( x, y \) = coordinates along test board, m
- \( x' \) = radius of shadow board hole, m
- \( Y \) = lamp-to-lamp spacing in each column of array, m
- \( Y' \) = offset between alternate columns in lamp array, m
- \( z \) = lamp-to-test plane spacing, m
- \( z' \) = lamp-to-shadow board spacing, m
- \( \lambda \) = wavelength, m
To obtain a stable mean value, the signal from the pyranometer was sampled with a 12 bit A/D board at 200 Hz for five seconds. Response time of the silicon photodiode is 10 ms. Measurement accuracy is limited by a 0.5 percent of gain offset (± 6 W/m²). Assuming a calibration accuracy of ± 3.5 percent, total uncertainty is ± 4 percent, including the error of conversion between the two instruments. Resolution of the data acquisition system is 0.73 W/m². An Eppley Precision Infrared Radiometer was used to measure infrared radiation (IR). The measurement procedure developed by Albrecht and Cox (1976), which includes a correction for heating of the silicon dome, was used.

Simulation. The objective of the numerical simulations was to investigate many possible lamp configurations to determine the lamp array pattern which best meets requirements for uniformity and collimation. The output of 28 lamps was predicted from the output of a single lamp with a spreadsheet. The spreadsheet simply adds the radiant energy from the lamps based on the measured spatial distribution of intensity of radiation from a single lamp. Data were obtained at 0.056 m intervals over a 1.06 m by 1.06 m area. Average irradiance of the simulated output of 28 lamps over a 1.22 m by 2.44 m test area was calculated and areas of irradiance greater than ± 10 percent of the average were used to specify the degree of uniformity. Figure 3 shows the geometric parameters of the array. Approximately 100 different combinations of X, Y, and Y' were tried in each simulation. The values of X and Y ranged from 0.34 m to 0.56 m and the value of Y' ranged from 0 m to 0.28 m.

Results
Lamp-to-test plane distances from 2.75 m to 3.35 m were considered. The minimum distance was chosen to keep the peak irradiance at approximately 1000 W/m². The maximum distance is limited by ceiling height. Lamp orientation refers to the position of the lamp face and was varied by rotating the lamp ± 15 deg from the manufacturer's suggested position. Power setting was varied from 60 percent to 110 percent of the lamp's nominal level of 1 kW. Different shadow board hole diameters were tested in an effort to improve uniformity of irradiance.

Spectral Output. Irradiance as a function of wavelength for the CSI lamp and for AM-1.5 is plotted in Fig. 4. Data for the CSI lamp were obtained from the manufacturer. Although the spectral output curve of the CSI lamp falls below that of AM-1.5, neither the xenon nor tungsten lamp completely satisfies the ASHRAE requirement for solar spectrum (Krusi and Schmid, 1983). According to the manufacturer, spectral characteristics of the CSI lamps change below 70 percent of rated power.

Irradiance. To determine lamp performance as a function of power setting, the pyranometer was placed 3.35 m from the lamp and power level of the lamp was decreased from 1.1 kW to 0.7 kW (the lamps should be turned on near full power). Below 0.7 kW, gases within the bulb condense and spectral output is altered. Above 1.1 kW there is risk of lamp failure. Irradiance versus power level is

$$G = -0.74 + 2.33p - 0.81p^2 \text{[kW/m}^2\text{]},$$

where p is in kW. All subsequent irradiance measurements were obtained at 1 kW with the collector test plane located in the vertical plane.

Another variable which affects the output of the lamp is bulb alignment. To ensure proper lamp performance, the tail of the bulb must be pointing directly toward the lowest point on the rim of the reflector. The maximum output of the lamp is reduced by up to 14 percent when the lamp is rotated as little as 15 deg.

Figure 5 is a plot of normalized irradiance measured at the geometric center of the lamp and at z = 3.35 m. Irradiance is normalized by average irradiance over the five-hour testing period. Stability of the lamp is within ± 5 percent. This deviation from the standard ± 3 percent should have little effect on average quantities, but could affect instantaneous measurements.

Three lamps were randomly chosen to assess lamp-to-lamp variations. The maximum variation at the point of maximum flux is five percent. In the simulations, all lamps are assumed identical.

Figures 6 and 7 show a vertical asymmetry in the output of the lamps. The most likely cause of this asymmetry is interference by the bulb tail with light reflected from the built-in parabolic reflector. (The asymmetry is in the vertical direction since the lamps are tested with a vertical collector test plane. Gravity has no effect.)

To determine if the CSI lamps can be placed so that the ASHRAE specifications of light uniformity and collimation are satisfied, nearly 100 lamp-to-lamp distances and geometric patterns were simulated for lamp-to-collector plane test distances of 2.89 m, 3.05 m, and 3.35 m. Neither a rectangular
nor an hexagonal pattern creates adequate uniformity of irradiance. The best configurations are obtained with a lamp-to-lamp spacing of 0.45 m. The best rectangular grid has four columns of seven lamps with lamp-to-lamp and column-to-column spacing of 0.45 m. Average irradiance is 1190 W/m². Maximum irradiance is 17 percent above the average, and minimum irradiance is 14 percent below the average. Thirteen percent of the area receives more than 110 percent of the average irradiance, and three percent of the area receives less than 90 percent of the average irradiance.

The best hexagonal grid also has four columns of seven lamps. The 2nd and 4th columns are offset 0.225 m to form an hexagonal pattern. Column spacing and lamp-to-lamp spacing remain at 0.45 m. This configuration yields a predicted average irradiance of 1200 W/m². Maximum irradiance is 16 percent above the average, and minimum irradiance is 16 percent below the average. Ten percent of the area received more than 110 percent of the average irradiance, and four percent of the area receives less than 90 percent of the average irradiance.

Shadow Board. Since the specification for light uniformity and collimation cannot be met by using only CSI lamps, the shadow board is used with the hexagonal lamp configuration producing the best level of uniformity with lamps only. The hexagonal pattern was selected in preference to the rectangular grid because modification of the final design for off-normal testing is easier. Evaluation of alternate shadow board designs was first conducted with a single lamp. Table 1 lists the shadow board configurations evaluated.

Figure 8 shows irradiance distributions along the x-axis for selected configurations listed in Table 1. Other configurations are omitted for clarity. The lamp face has a radius of 0.10 m. If the hole radius is ≤ the lamp radius, the peak irradiance is lower than if the hole radius is > the lamp radius. A shadow board with hole radius of \( x' = 0.15 \) m is picked for the final design to ensure that the peak irradiance is not reduced.

Figure 9 shows an irradiance distribution along the x-axis for a lamp with and without the shadow board. Lamp-to-
Fig. 9 Centerline irradiance distribution for a lamp with and without the shadow board.

Fig. 10 Simulated irradiance of 28 lamps in an hexagonal array with the shadow board.

Collector plane distance \(z\) equals 3.05 m and the shadow board has dimensions \(x'\) = 0.15 m and \(z'\) = 1.02 m. At \(x = \pm 0.45\) m, the differences in irradiance between the bare lamp and the lamp-shadow board combination are on the order of 25 W/m². With this reduction in irradiance, the maximum flux directly under any lamp can be reduced by nearly 150 W/m², based on all lamps being affected by six neighboring lamps. Decreasing a hot spot by 100 W/m², or ten percent of an average 1000 W/m², is enough to solve the nonuniformity problem.

The shadow board must be designed for specific lamp-to-lamp spacing and test distance. Therefore, exhaustive numerical simulations are not required to optimize the irradiance output. However, simulated irradiance of 28 lamps is still based on output of one lamp. The shadow board, with hole radius \(x'\) = 0.15 m, is placed 1.02 m from the lamps. The numerical simulation for the 1.22 m by 2.44 m test area predicts an average irradiance of 1050 W/m² with a maximum of irradiance six percent greater than the average value and a minimum value nine percent lower than the average irradiance. The irradiance pattern of this configuration, shown in Fig. 10, exceeds the ASHRAE requirements for light collimation.

Final Design

The completed simulator facility consists of a space frame, a light mounting frame and shadow board, and a collector test stand with all necessary plumbing and controls required for testing. Complete details of the design are given by Kenny (1993). A photograph of the complete simulator is shown in Fig. 11. The simulator irradiates a 1.22 m-by-2.44 m test area with an average irradiance of 1080 W/m². The lamp-to-collector plane distance is 3.05 m, and the shadow board is located 1.02 m from the 28 1-kW CSI lamps. The shadow board hole radius is 0.15 m. The array is composed of four columns of seven lamps each spaced 0.45 m apart. The distance between columns is also 0.45 m. The 1st and 3rd columns are offset 0.225 m below the 2nd and 4th columns. The shadow board is constructed of plywood. To prevent overheating of the board, the wood is covered with reflective aluminum on the side facing the lamps. The other side of the board is painted flat gray.

Radian energy measured in the simulator is plotted in Fig. 12. Average irradiance over the test plane is 1080 W/m². The maximum and minimum values differ from the average by +10 percent and –9 percent, respectively. The nonuniformity of the distribution in Fig. 12 could be reduced by finer adjustment of lamp power levels. However, since the variation in radiant energy is not much greater than the time variations, adjustments were not made. Improvements in spatial distribution can also be made by more accurate aiming of lamps. The lamps should be aimed so that the geometric center of the bulb is located along a line perpendicular to the point of maximum flux from that lamp on the collector test plane. Devia-
tions as little as 2 cm can affect uniformity. Average irradiance can be reduced by lowering the power level of each lamp.

Infrared radiation measurements were taken with 28 lamps operational. Ambient temperature was measured in the plane of the collector with a thermocouple in an aspirated radiation shield. The difference between the measured IR and that of a theoretical blackbody at ambient temperature does not exceed 50 W/m² over four hours.

The simulator has been used for extensive testing of an integral storage collector (Mason, 1993). Future challenges are modification of the shadow board and lamp arrangement to allow off-normal testing.

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References

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