Luminaire development for hybrid solar lighting applications

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ABSTRACT

Efficient hybrid luminaire development is an integral part of the Hybrid Solar Lighting Program at Oak Ridge National Laboratory. Hybrid luminaires are necessary to blend light from a fiber optic solar source with electric fluorescent lamps. The luminaire designs studied involve a commercially available fluorescent luminaire that has been modified to include optical elements for efficiently dispersing fiber optic solar light sources. Quantitative measurements of optical efficiency and spatial intensity distribution for two luminaire designs are compared.

Keywords: luminaire, fiber optic, solar lighting, hybrid lighting, remote source lighting

1. INTRODUCTION

Oak Ridge National Laboratory (ORNL) is developing an energy-efficient Hybrid Solar Lighting System that uses large-core plastic optical fiber to permit direct utilization of visible solar light for internal lighting[1,2] (see Fig. 1). A major step toward the realization of fiber optic solar lighting for internal lighting purposes is the development of a hybrid luminaire to seamlessly balance electric and fiber optic illuminants. Fluctuations in the intensity of collected solar light, due to changing cloud coverage or solar collector movement, requires rapid compensation by electric lamps to maintain a constant room illumination. If the spatial intensity distribution of a hybrid luminaire's electric lamps does not closely match the spatial intensity distribution of the luminaire's fiber optic illuminants, then the shift between artificial and solar lighting will be noticeable, and potentially distracting, to the occupant. In addition, because this technology is primarily aimed at reducing energy usage (and associated costs), any potential hybrid luminaire designs must maintain high optical efficiencies yet remain cost-effective.

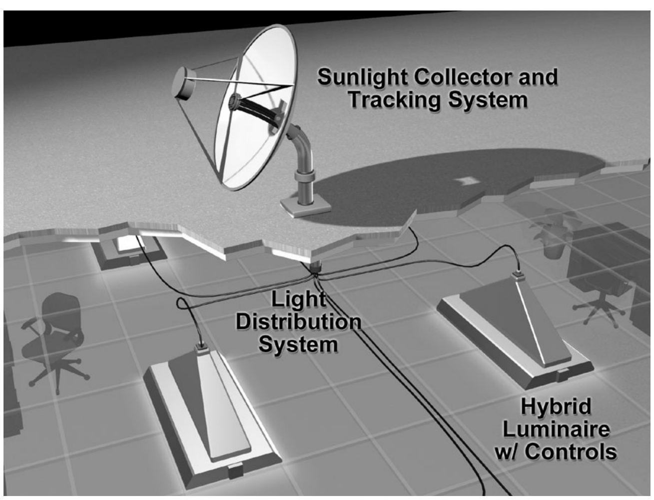

Figure 1: Hybrid solar lighting system.

To develop an optically efficient hybrid luminaire that exhibits a static spatial intensity distribution, regardless of which lighting source dominates, various light dispersing techniques have been developed and studied.[3] Among these techniques, one dispersion optic has been found to be effective and compatible with our luminaire design needs. Thus far, two different designs based on this device have been developed and tested. The evolutionary design process and comparison of resulting performance metrics are the focus of this paper. A more detailed discussion of the development of the original design has been previously reported.[4]

2. SELECTION AND MODELING OF COMMERICIAL LUMINAIRE

A Lithonia four-tube T8 fluorescent luminaire was selected for use as the hybrid luminaire development platform. The Lithonia General Purpose T8 Luminaire (GT8) was chosen because of its high electrical and optical efficiency, relative low cost, and easily integrated design. The GT8 luminaires also use an acrylic diffuser that assists in masking/merging two internal light sources. To aid in the design, construction, and testing of a hybrid luminaire, a high-detail optical model of the luminaire was first constructed using ZEMAX ray-tracing software. This model allowed the luminaire to be simulated under various configurations. The modeled luminaire was simulated within a 6-ft cube, to provide intensity distribution data at various positions and working distances. An example of one such simulation is shown in Fig. 2. This simulation shows the typical illumination pattern on the end wall, side wall, and floor of the 6-ft cube, as predicted by the Zemax model of the GT8 luminaire.

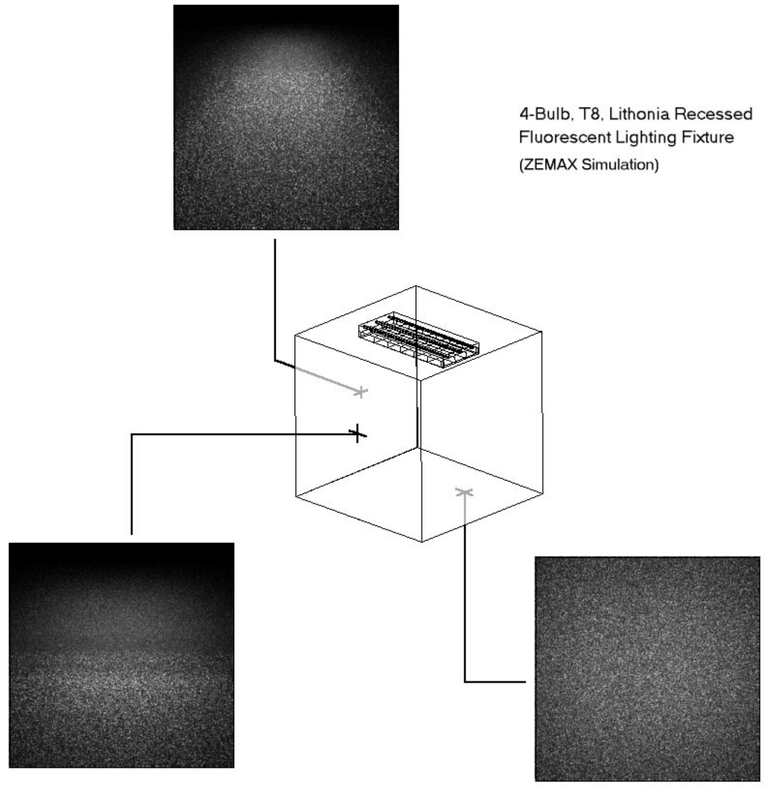

Figure 2: Spatial intensity distribution of selected commercial fixture.

3. ILLUMINATION CELL DETAILS

To characterize the hybrid luminaires' performance, it is necessary to measure the efficiency, spatial intensity pattern, and spectrum. This must be done independently for each sub-system (fluorescent lights and fiber illumination) so that the compatibility of the two can be evaluated. An illumination cell was constructed to conduct these tests.

ORNL's Illumination Cell is a 6-ft cube equipped with mounts in the ceiling for attaching a luminaire (see Fig. 3). The walls and floor of the cell are uniformly black, and the ceiling is open. A relocatable, spectrally neutral, white wall within the cube can be placed on any of the four walls or on the floor to enable the distribution pattern and flux at that location to be measured. A Prometric CCD colorimetry system allows the intensity and color distribution, incident on the white wall, to be precisely mapped. The integrated flux from the four walls and the floor are used to determine the optical efficiency of the luminaire.

Figure 3: ORNL illumination cell.

4. HYBRID LUMINAIRE DESIGNS

A luminaire design was sought that would provide a simple means of seamlessly combining the light from the fluorescent and fiber optic sources. Typically, the sunlight exiting the optical fibers produces a conical distribution pattern that is not compatible with the pattern produced by fluorescent lamps. To make the intensity distribution pattern more compatible with that from the fluorescent tubes, it was necessary to transform the light from the fiber into a more cylindrical geometry. Various attempts were tried to construct nonimaging optical components to achieve this goal. Ultimately, the best results were obtained by using a cylindrical, side-emitting diffusing rod developed by 3M. The 3M Side-Emitting Rod (Part #: LF180EXN), is shown in Fig. 4. Two versions of this optic were used in initial tests: the S version, designed for single fiber illumination via one end, and the D version, intended for use with two illuminating fibers. The best linear uniformity of the emitted light was obtained by using the D version with the illuminating fiber at one end of the rod and a reflecting element at the other.

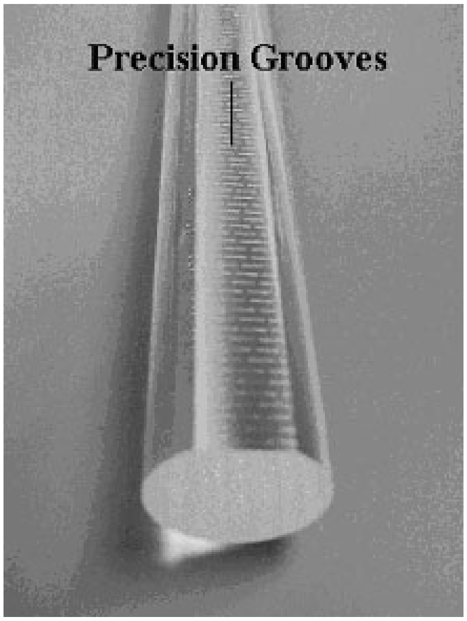

Figure 4: 3M side-emitting rod design.

The grooves in the flat surface of the 3M side-emitting rod serve to reflect light out the opposite side of the rod. Ideally, all of the light would be reflected out the side of the rod by the time the last of the rays reached the far end of the rod. In practice, however, a significant portion of the light exits the end of the rod instead of the side. To further improve the efficiency of the side-emitting rod, various reflectors were attached to the end of the rod. Ultimately, a concave spherical mirror (produced by aluminizing the curved side of a plano-convex lens) seemed to produce the best results. The mirror served to reflect and diverge any coaxial light that was not scattered on an initial pass through the rod. The rod was mounted within a custom-machined acrylic holder that allowed a large-core optical fiber to mate with one end of the rod.

In the initial design, two assembled rods were mounted within a four-tube fluorescent fixture, as shown in Fig. 5. The two side-emitting rods were located on each side of the ballast cover, directly between the two corresponding fluorescent tubes. The side-emitting rods were mounted so that the light was projected toward the acrylic diffuser and out of the fixture. This dual-rod design was selected to provide good spatial distribution match to the light from the fluorescent tubes. Unfortunately, the design required the use of a high-quality splitter (low-loss, 50:50 split) to divide the light from a single fiber into the two light tubes.

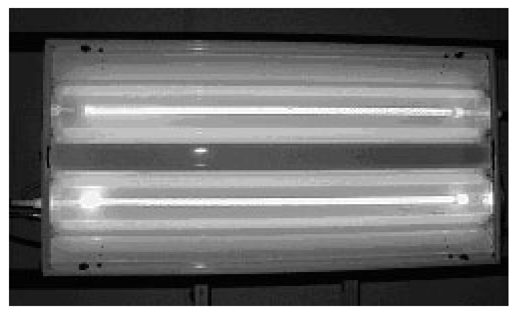

Figure 5: Hybrid luminaire with two side-emitting rods (diffuser removed).

The hybrid luminaire was mounted and tested within ORNL's Illumination Cell (see Fig. 3). Instead of using a splitter, two separate optical fibers sources were used. Thus, the measured efficiency did not reflect the additional losses that would be contributed by the connection losses and inherent internal loss associated with using a splitter.

The initial tests of the hybrid luminaire indicated that coupling losses from the fiber to the side-emitting rod were high, leading to reduced efficiency. Design enhancements to the luminaire were added to stabilize the position of the side-emitting rods and improve coupling efficiency. The enhanced version of the dual-rod design was tested to measure the improvement in performance.

To further improve efficiency and lower the cost of the luminaire, a design was proposed that would use only one side-emitting rod. By using only one side-emitting rod, the need for a splitter would be obviated, eliminating the connection losses into and out of the splitter as well as the inherent loss within the splitter itself. In addition, the cost of the splitter and the additional side-emitting rod would be eliminated. However, the use of a single side-emitting rod would require two major modifications to the luminaire design. The rod would have to be mounted in the center of the luminaire to maintain symmetry in the intensity distribution pattern, and it would have to be rotated 180° to broaden the intensity distribution pattern.

To enable the side-emitting rod to be centrally mounted, the standard ballast and ballast cover were removed, making the central portion of the luminaire available for development. A compact (16.5-in. × 1.25-in. × 1-in.), four-bulb, dimmable ballast was obtained from Advance Transformer (Mark 7 IntelliVolt series, product number IZT-4S32) and installed on the rear of the luminaire housing.

A second major design modification was necessary to achieve an acceptable intensity distribution pattern from a single emitting rod. To achieve a pattern of sufficient width, the direction of the rod would have to be reversed, directing the light onto the reflective housing of the luminaire and allowing the diffuse reflection to exit the acrylic diffuser, rather than projecting the light directly onto the acrylic diffuser. If the light from the single rod were projected directly onto the acrylic diffuser, the intensity distribution pattern would be unacceptably narrow in comparison to that from the fluorescent lamps. To improve the efficiency and intensity distribution characteristics of the new design, a diffuse reflective film was used in conjunction with the side-emitting rod. A “Light Enhancement Film” from 3M (Scotchcal 3635-100) was placed on the luminaire housing in the area directly behind the side-emitting rod. This film provided a more diffuse reflection and higher reflectivity than the reflective paint in the luminaire (94% vs 90%). The single-rod luminaire design is shown in Fig. 6.

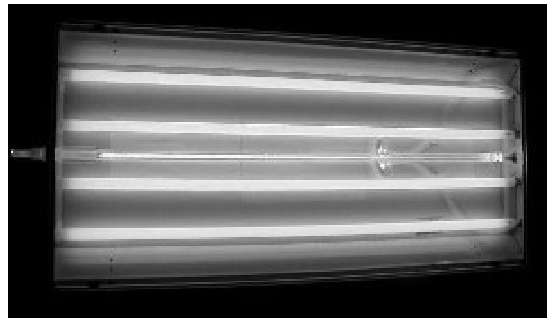

Figure 6: Hybrid luminaire with one side-emitting rod (diffuser removed).

One additional feature was added to the single-rod design to further enhance the optical efficiency. Previous designs had used a reflector at the end of the side-emitting rod to direct the coaxial light back through the rod. Though the intention was to force all of the light to eventually be emitted out the side of the rod, some light was suspected of traveling back up the source fiber where it could not be used for illumination. An alternate concept was tried in the single-rod design. Rather than attaching a reflector to the end of the side-emitting rod, a bundle of small optical fibers was attached to the end of the rod and routed back into the central portion of the luminaire. Coaxial light that was not emitted from the side-emitting rod would enter the bundle of fibers and be redirected into the luminaire where it would add to the side-emitted light from the rod. For the proof-of-principle prototype, the fibers were simply routed around the ends of the fluorescent tubes and back toward the center of the luminaire where the exiting light was scattered off of the 3M light enhancement film. It was anticipated that while the efficiency should show improvement, this simple arrangement of the fiber bundle might perturb the intensity distribution pattern. In future prototypes, the fibers could be arranged to achieve a more uniform contribution to the overall intensity distribution.

5. TEST METHODOLOGY

Each of the hybrid luminaire designs was mounted in the illumination cell for testing. Cogent high-intensity discharge (HID) light sources were used to supply the “solar” portion of the light via large core (12-mm) optical waveguides. Rather than use a splitter, the dual-rod luminaire design was tested using two HID sources. Each of the Cogent sources was allowed to stabilize for more than an hour before the measurements were begun. The amount of light from the Cogent sources was measured using a Labsphere integrating sphere and associated measurement system. The efficiency of the fiber optic system was measured as the ratio of the total integrated light (with fluorescent sources off) incident on the walls and floor of the cell to the total amount of light delivered from the fiber source(s). Without a good way to quantify the integrated output from the fluorescent tubes, new florescent tubes were used for the tests, and the manufacturer’s rated lumen output was used for the efficiency measurements of the fluorescent portion of the light from the luminaire. The efficiency was measured as the ratio of the total integrated light (with fiber optic sources off) incident on the walls and floor of the cell to the total rated lumen output from the four T8 tubes.

The spatial intensity distribution on each of the five walls of the Illumination Cell was measured using the Prometrics CCD colorimetry system. Because we were concerned with effectively blending two different lighting sources, the distribution measurements of the luminaire were performed twice: once with all fluorescent lighting on and fiber optic lighting off, and once with fiber optic lighting on and fluorescent lighting off. The measurements produced ten intensity distribution maps, which were cropped and normalized so that they could be easily compared. Ideally, the intensity distribution of the fluorescent lighting and the fiber optic lighting would be identical. In such a situation, any rapid change from one source to the other would be virtually imperceptible to the occupant.

6. RESULTS

The initial tests of the original dual-rod luminaire design revealed significant differences in intensity distribution between the fluorescent and fiber optic sources. The intensity distribution pattern for the floor of the illumination cell, the wall adjacent to the end of the luminaire, and the wall adjacent to the side of the luminaire were compared for the fluorescent

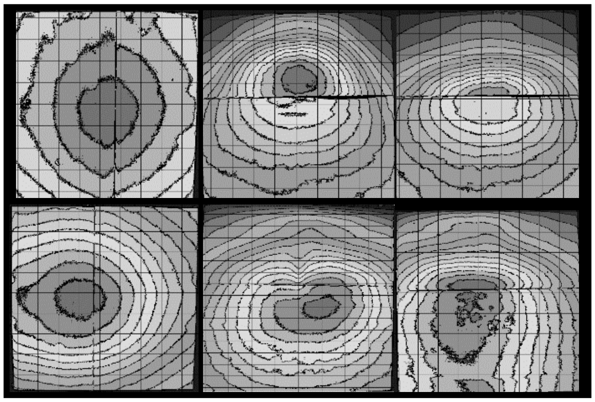

Figure 7: Floor, end-wall, and side-wall intensity distribution for fluorescent (top) and fiber (bottom) emission patterns for initial version of dual-rod luminaire design.

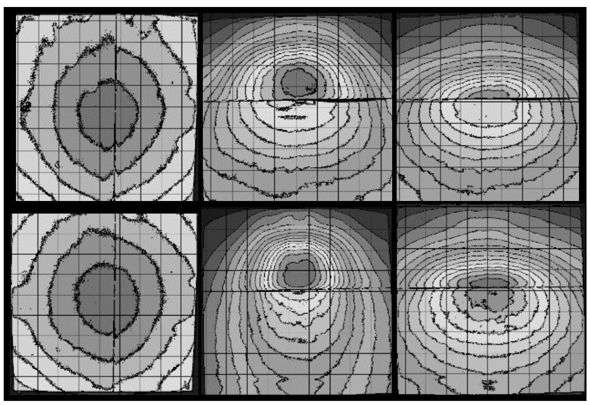

Figure 8: Floor, end-wall, and side-wall intensity distribution for fluorescent (top) and fiber (bottom) emission patterns for improved version of dual-rod luminaire design.

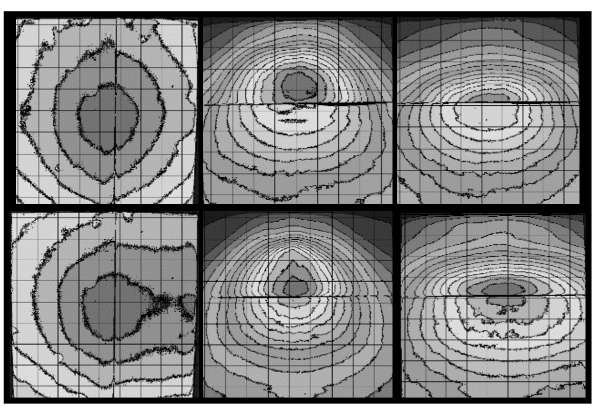

Figure 9: Floor, end-wall, and side-wall intensity distribution for fluorescent (top) and fiber (bottom) emission patterns for initial version of single-rod luminaire design.

and fiber sources. The significant variations in the intensity patterns for the fluorescent and fiber illumination portions of the luminaire are shown qualitatively in Fig. 7. An horizontal line in the data for the end and side walls resulted from a mismatch in the two sections of the white wall used in the measurements.

A more quantitative analysis of the data revealed that the maximum intensity variations were on the floor of the illumination cell. Intensity variations of 20% were observed over large areas, with peak variations as high as 27%. In addition to the intensity pattern differences for the two sources, the measured efficiency of the fiber optic portion of the luminaire was only 58%.

The initial luminaire design was evaluated to identify factors contributing to the poor performance. The mounting structures for the side-emitting rods appeared to be the dominant source of performance problems. A lack of rigidity in the side-emitting rod assemblies was allowing the rods to rotate, affecting the alignment of the light distribution pattern. In addition, the mounting structures were not maintaining a solid connection of the fibers with the side-emitting rods. Without rigid coupling of the fibers to the rods, light losses were degrading the intensity distribution as well as the overall efficiency.

The mounting structures were redesigned to include a rotational alignment feature and to ensure rigid connection of the fiber to the side-emitting rod. In addition, an optical index matching gel (Nye OC431-A) was added between the fiber and the rod to reduce the Fresnel reflection losses.

The enhanced version of the dual-rod design was retested with much more encouraging results. The spatial intensity distribution pattern for the enhanced design was virtually identical for the fluorescent and fiber optic sources, as shown in Fig. 8. The efficiency of the fiber optic portion of the luminaire was also increased to 66%.

The single-rod luminaire design was tested in the illumination cell and showed a significant improvement in efficiency of the fiber illumination system in the luminaire. In addition, the light distribution was comparable to that from the fluorescent light portion of the luminaire, as shown in Fig. 9.

The light distribution characteristics and overall efficiency for each of the luminaire designs are compared in Table 1. Note that the actual amount of light used in the comparisons of the fiber optic systems varied considerably. When illuminated by sunlight, the lumen input to the fiber portion of the luminaires is expected to be between 4500 and 5000 lumens. However, the percentage distribution of the light among the walls and floor

Table 1: Light distribution and efficiency comparisons for each of the luminaire configurations

Fluorescent lamp system		
Position	Lumens	Percent of total
End-wall 1	1772	18
End-wall 2	2073	21
Side-wall 1	1756	18
Side-wall 2	1661	17
Floor	2438	25
Total lumen input 12000		
Luminaire efficiency 80.8%		
Initial dual-rod luminaire		
Position	Lumens	Percent of total
End-wall 1	319	13
End-wall 2	511	21
Side-wall 1	292	12
Side-wall 2	252	10
Floor	1071	44
Total lumen input 4240		
Luminaire efficiency 57.6%		
Enhanced dual-rod luminaire		
Position	Lumens	Percent of total
End-wall 1	583	17
End-wall 2	592	17
Side-wall 1	582	17
Side-wall 2	507	15
Floor	1203	35
Total lumen input 5250		
Luminaire efficiency 66.0%		
Single-rod luminaire		
Position	Lumens	Percent of total
End-wall 1	456	26
End-wall 2	338	20
Side-wall 1	274	16
Side-wall 2	264	15
Floor	397	23
Total lumen input 2200		
Luminaire efficiency 78.6%		

should not change. The characteristics of the fluorescent lamp system were essentially identical for the three cases and thus are presented only once.

The efficiency of the luminaires shows consistent improvement, with the single-rod luminaire providing almost 79% efficiency. This is very comparable to the 81% efficiency of the fluorescent portion of the luminaire. The light distribution for the single-rod luminaire is comparable to that of the fluorescent system as well, noting that the dual-rod designs placed a higher percentage of the incident light on the floor of the illumination cell. The only undesirable feature of the single-rod luminaire is an uneven distribution of light between the different walls of the illumination cell. In particular, the scattering characteristics of the side-emitting rod in the inverted configuration tended to increase the light on one end-wall of the illumination cell. This is considered to be within the bounds of acceptable variation, but efforts will be made to further equalize the distribution from this design.

7. CONCLUSIONS

The hybrid luminaire development to date has achieved optical efficiency and light distribution performance that is approaching that of a conventional high-quality fluorescent luminaire. The most recent luminaire design, based on the use of a single side-emitting rod appears to require limited additional development to achieve the optimum light distribution that is desired for the Hybrid Lighting System installations. The availability of this particular side-emitting rod from 3M is in question for future applications, so additional alternatives are being pursued. However, a sufficient number of these components are available to enable development, testing, and installation of the luminaires needed for the first several installed demonstration systems.

8. ACKNOWLEDGMENTS

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