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Spectrophotometric measurements and ray tracing simulations of mirror light pipes to evaluate the color of the transmitted light

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ABSTRACT

Tubular daylighting systems are designed to guide light to the building's core using a highly reflective pipe. The intensity of the transmitted light is essential for the performance of the system. For the qualitative perception of the provided illumination, the color of the delivered light is also an important aspect. For highly reflective mirror light pipes, spectral variations are generally assumed not to affect the color of the transmitted light. Here, spectrophotometric measurements and ray tracing simulations of mirror light pipes are used to verify this commonly made assumption. The characterization methods employ spectral evaluations for both direct and diffuse incident light. The color properties are evaluated for mirror light pipes with a length to diameter aspect ratio of up to 16, using the CIE chromaticity diagram and CIELAB coordinates. For the *xy* chromaticity diagram, a larger color shift was noted for different illuminants than as a result of the optical properties of the reflective material. Using the CIELAB coordinates, a small color shift was noted for light incident at low solar altitudes. Overall, highly reflective films with spectral variations of a few percent do not markedly affect the color of the transmitted light.

1. Introduction

Tubular light guiding systems are gaining popularity as daylighting devices for installation in both domestic and commercial buildings. The generic system consists of a plastic dome for collection, a reflective pipe for distribution of light, and a diffusing emitter that spreads the light into the room. The performance of the tubular daylighting system is determined by the optical properties of the individual components, and for enhanced light delivery, various improvements of the respective components have been proposed.

For the collector dome, these innovations are generally aimed at reducing the number of reflections in the pipe by using, for example, laser cut panels [1–3] or Fresnel lenses [4]. These light deflecting materials enhance the performance of the tubular light guiding system for beam illumination at low solar altitudes. Furthermore, the use of light diffusing dome materials has been suggested as a method to reduce the occurrence of high intensity light spots on the exit aperture [5]. Although a more uniform light distribution is reported, diffusing domes have not found widespread use.

For the light diffusing emitter, improvements have focused on increasing its transmittance without adversely affecting its light scattering properties. Many manufacturers of tubular daylighting systems offer a range of diffusers for the exit aperture of the pipe. Fresnel diffusers are an example of a commercial product that has been developed for this purpose. These are especially beneficial when the tubular daylighting system is illuminated with direct incident light, but the disadvantages are only moderate in overcast conditions [6]. Furthermore, the use of a two-component diffuser, with a Lambertian center and a clear rim, has been proposed to utilize better the incident light compared to a uniform diffuser [7].

An early design of a light distribution system suggested the use of prismatic materials to guide the light through the pipe [8]. These materials are efficient light redirectors, but they suffer from a narrow acceptance angle that limits their ability to utilize daylight from the entire hemisphere. The market advancement of tubular daylighting systems has instead been driven by the development of highly reflective optical materials. The reflectivity of these dielectric materials is based on constructive interference from a large number of layers and can provide a high reflectance within a well-defined wavelength interval [9]. It is important for the visual aspects of the light guiding system that reflectance be nearly independent of wavelength, since spectral reflectance variations affect the color of the transmitted light [10]. In addition to spectral reflectivity, the magnitude of the color shift depends on the length of the mirror light pipe, the composition of direct and diffuse light, and the angle of incidence. The color change becomes more pronounced for pipes with large length to diameter aspect ratios and direct light at low solar altitudes.

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It is possible to evaluate the effect of spectral variations using methods that predict the transmittance of the mirror light pipe. Zastrow and Wittwer described a prediction method that uses an effective diameter to determine the number of times a ray is reflected in the pipe [11]. The method benefits from its simplicity, and the use of an effective diameter makes it applicable to pipes of different cross-sections. It was, however, concluded that the validity of the method was limited to long mirror light pipes at low incident angles [12]. Swift and Smith extended the approach and provided an integral expression to evaluate the transmittance of light pipes with cylindrical cross-sections [12]. While the expression can be modified to include the angular dependent reflectance of the interior surface, and thereby provide an exact solution, wide scale application is impeded by the integral form. These prediction methods can be used for spectral evaluations and are valuable to obtain the transmittance of the mirror light pipe. However, the effect of small reflectance variations tends to be overestimated by the Zastrow and Wittwer method due to its two-dimensional approach, and the use of detailed optical data for the reflective film has not been disseminated experimentally using the integral expression.

Although the reflectance of the dielectric films can be close to 99% [9] with a variation of only a few percent in the visible wavelength range, simple prediction methods indicate a color shift of the transmitted light [12]. The aim of this paper is to quantify experimentally the commonly made assumption that small reflectance variations exhibited by dielectric films do not affect the color of the transmitted light. The evaluations are based on spectrophotometric measurements of mirror light pipes under both direct and diffuse irradiation. The measurements emulate reality by illuminating the entire aperture of the light pipe and were performed as a function of both wavelength and angle of incidence. To broaden the extent of the evaluation, the measurements were used to validate a ray tracing method. Using this simulation tool, it is possible to obtain detailed optical data and evaluate mirror light pipes of other dimensions.

2. Outline of work

Section 3 describes the spectrophotometric methods that are used to characterize the optical properties of the reflective material and evaluate the spectral transmittance of the mirror light pipes. This section, furthermore, describes the ray tracing methodology implemented in a commercial software package. The optical properties of the reflective dielectric film are determined for a flat sample and presented in Section 4. These data are used as input to the ray tracing model together with a geometric description of the pipe. The results of the spectrophotometric measurements and the ray tracing simulations are presented in Section 5, which also includes an evaluation of the color of the transmitted light.

3. Methods

3.1. Spectrophotometric methods

The specular and the total reflectance of the reflective film were evaluated using three integrating sphere detectors [13]. The characterizations were performed for a flat sample and as a function of incident angle. The integrating sphere detectors share a common light source, a 250 W tungsten-halogen lamp with a grating monochromator combined with a filter assembly to obtain monochromatic light. The specular reflectance was determined using a 50 mm diameter integrating sphere with an oblong entrance port that is approximately 25 mm long and 8 mm high. The integrating sphere is positioned on a movable arm and can be repositioned for measurements at variable angles of incidence.

For the total reflectance measurements, the flat sample was mounted in the center of a 200 mm diameter integrating sphere [13]. This sphere was used exclusively for reflectance measurements and has one 14 mm diameter port for incident light. The detector is mounted underneath the sample holder and faces the bottom of the sphere. Hence, the detector field of view is shielded from the integrating sphere port and the sample. Furthermore, a Perkin-Elmer Lambda 900 spectrophotometer equipped with an integrating sphere accessory was used to show the film's reflectance at near-normal angle of incidence. Although, these data are not employed for the ray tracing simulations, they are included to illustrate the diffuse and the specular reflectance of the film in the solar wavelength range.

The transmittance of three scaled mirror light pipes was evaluated using a single beam spectrophotometer with a 200 mm diameter integrating sphere detector [13]. The previously described light source was utilized and two mirrors, a parabolic and a plane mirror, were used to redirect the light towards the integrating sphere detector. The interior of the sphere is coated with $BaSO_4$, and a VIS–NIR detector is positioned at the top of the sphere and shielded from direct light. The spectrophotometer was configured for characterization of the light pipes using both direct and diffuse illumination, as illustrated schematically in Fig. 1. A thin aperture was used to adapt the port of the integrating sphere to the diameter of the measured light pipe. The modification was introduced to reduce port losses when the pipe was positioned flush with the integrating sphere. In addition to the aperture, a light diffusing film was positioned across the sphere port to reduce the effect of non-uniform sphere response [14,15]. Incident angles between 0° and 70° were measured in 10°-increments by rotating the integrating sphere and the mirror light pipe. Furthermore, the integrating sphere was mounted on rails so that the center of rotation could be repositioned between the sphere port and the pipe aperture for the reference and measurement scans, respectively. The repositioning of the integrating sphere ensures that the intensity distribution and size of the incident beam are identical for the two scans, but it makes the alignment of the set-up critical.

For characterization of the system under diffuse illumination, a second integrating sphere was connected in series with the

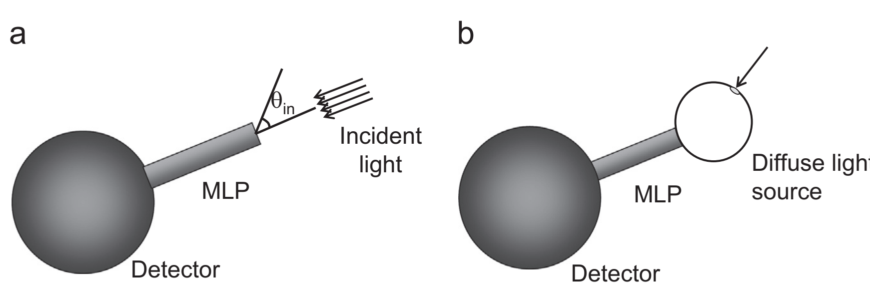

Fig. 1. Schematic illustration of the measurement set-up for characterization of a mirror light pipe (MLP). Shown in (a) for beam illumination and in (b) for diffuse illumination of the pipe.