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Optical characterization of fritted glass for architectural applications

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ABSTRACT

Fritted glass is commonly used as a light diffusing element in modern buildings. Traditionally it has been used for aesthetic purposes but it can also be used for energy savings by incorporating it in novel daylighting systems? To answer such questions the light scattering properties must be properly characterized.

This paper contains measurements of different varieties of fritted glass, ranging from the simplest direct-hemispherical measurements to angle-resolved goniometer measurements. Modeling the light scattering to obtain the full bidirectional scattering distribution function (BSDF) extends the measured data, making it useful in simulation programs such as Window 6 and Radiance. Surface profilometry results and SEM micrographs are included to demonstrate the surface properties of the samples studied.

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1. Introduction

Fritted glass is used in building design for its privacy properties and aesthetic values. Inquiries have been made with regards to how this material could be beneficial for daylighting or energy saving purposes. Today there are no standards for the rating of light-scattering products for these purposes. This lack of method is locked in a stalemate between input data not being produced and the fact that building simulation programs do not handle light scattering data. The stalemate situation is currently being unlocked as programs such as Radiance [1], EnergyPlus [2], and BC/LC [3], are all getting full scattering data capabilities. At the same time the need for complete scattering distributions are being observed by the measurement community and full data sets are being produced.

The parameter to use for describing the scattering properties is the bi-directional reflectance/transmittance distribution function (BR/TDF) that was originally defined by Nicodemus [4]. For samples with both reflecting and transmitting properties it is common practice to use the term bi-directional scattering distribution function (BSDF) to simplify the discussion. This parameter describes the relation between the incident irradiance and outgoing radiance in a specific solid angle. In that sense it is only slightly different from the traditional concepts of reflectance and transmittance; the difference being the need to define the solid angle of the outgoing scattered light. A BSDF value is commonly described as dependent on incident and outgoing angle (two pairs of spherical angles), but in reality the value generally depends on wavelength and polarization, just like the classical parameters reflectance and transmittance.

At first glance it would seem that incomplete data sets could be used to simulate many cases. For example, only a limited number of incident angles are needed for direct sunlight incident on a window. Full BSDF data sets for materials are needed for computations of the effects from multiple reflection between a diffusing material and other layers. Then information about all incident and outgoing angles will be needed. Tools for calculating such properties have previously not been available and so far any simulation would have to be through raytracing of any multi-layer system which had a scattering layer in it. This is impractical and would require the raytracer to have the scattering probability function of the scattering layer; information that is complex to obtain.

There are many characterization problems included in studying scattering samples such as fritted glass. These range from design compromises in the instruments to lack of standard procedures and reference characterization methods. This is somewhat surprising, considering that the material is both homogeneous and without

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rotational preference. The International Commission on Glass (ICG TC-10) is currently conducting an inter-laboratory comparison (ILC) on scattering samples to improve the methodology for characterizing such samples. A previous ILC they carried out in this field was inconclusive [5].

An integrating sphere is designed only for direct-hemispherical outgoing data and commonly only for normal angle of incidence. It is, however, possible to obtain BTDF data for homogeneous samples using an integrating sphere [6], but the common method is to use a goniometer type instrument that has a detector scanning the outgoing hemisphere and measuring the angle-resolved scattering. The only organized inter-laboratory comparison of goniometer type instruments [7] showed that different instruments are not always in agreement, sometimes strongly disagreeing. All these measurement problems and lack of comprehensive standard methods force the results of data acquisition to include a verbose description of how it was carried out.

Without the possibility of obtaining a complete set of experimental data a model is needed to complete the information while using as much of the available data as possible. A good model also guarantees that energy is conserved and that no unphysical values are produced. The ABg-model [8] is a general empirical model for producing a fairly simple scattering distribution.

When all the pieces finally come together it will be possible to get quantifiable results to determine how good or bad light-scattering products perform for daylighting and energy conservation.

The aim of this paper is to present a procedure to produce a complete BSDF of fritted glass samples, both pigmented and unpigmented. The report includes as much information as possible about the different experimental methods and procedures that were employed in the process of obtaining the BSDF data sets, as well as intermediary results such as direct-hemispherical properties. The purpose of the verbosity describing our intermediary findings is two-fold; the procedures used are not included in standards and have not been published in a single publication describing the path from the different experiments to complete BSDF. Secondly, previously published material on the topic of fritted glass is limited and therefore even the partial results are worthy of consideration.

2. Theory

The approach in this paper to obtain the complete BSDF for a sample follows three steps:

(1) Measurement of as much information as possible about the sample.
(2) Fitting of a scattering model to the experimental results.
(3) Generation of a full BSDF according to the scattering model.

The first step is carried out using a goniophotometer and integrating sphere spectrophotometers to obtain both angle-resolved scattering properties and direct-hemispherical information. Limitations created by the instruments and samples make it impossible to obtain full data sets from experiments. Typically, data for retro-reflection directions as well as large angles of incidence are hard to obtain. The word full in this context denotes that scattering data are available for both the whole incident and outgoing hemispheres.

The second step makes use of the incomplete experimental data set to find parameters of a scattering model. This is done by minimizing the mean square error between the parametric model and the scattering data.

Once the parameters have been obtained, it is possible to calculate the full BSDF from the model.

2.1. Measurement methods

2.1.1. Integrating spheres

The most commonly available characterization tool for scattering samples is a spectrophotometer with an integrating sphere detector system. Several such systems are commercially available. These instruments measure the direct-hemispherical transmittance and reflectance, in general only at normal angle of incidence. It has been demonstrated how such an instrument could also be used to obtain information the angle-resolved scattering [6].

Even though integrating spheres are designed to measure the properties of light-scattering samples, they are known to have several systematic problems, demonstrated in a recent inter-laboratory comparison of such instruments [5] and demonstrated by raytracing [9]. A large number of papers have been written with regards to integrating sphere theory, and a few examples of corrections that have been suggested are for non-ideal scattering samples [10,11], inhomogeneous sphere response [12], restricting the detector field of view [13], edge effects from the port [14], and losses due to light not entering the sphere in the first place [15,16]. Since a lot of the problems are sample dependent, instrument design dependent, or a combination of the two, it is rare that all corrections are carried out.

The International Commission on Glass (ICG) TC-10 (Optical Properties of Glass and Glass Products) is currently conducting a world-wide inter-laboratory comparison (ILC) between manufacturers, test facilities, and universities. The sample set consists of surface-scattering patterned glass, fritted glass, and bulk-scattering diffuse laminates. One goal is to try to find a measurement method for which all participating laboratories get the same result, and to correctly assess the systematic errors of such a method. For experimentalists trying to characterize scattering samples with integrating sphere instruments it seems like a holy grail to have one method and set of corrections that can be used for all samples. This would greatly simplify comparison of data obtained from different instruments, and most likely result in a smaller difference between them. This approach has been attempted for the direct-hemispherical normal angle of incidence measurements in this paper.

The instrument used was a Perkin–Elmer Lambda 950 spectrophotometer with a Labsphere 150 mm diameter commercial integrating sphere. Two minor, and reversible, modifications were made to the sphere. Firstly the sample holder plate at the transmittance port was completely removed so that the effective size of the entrance port was 26 mm diameter rather than the standard 19 mm, and secondly the reflectance mode sample holder was completely removed to avoid any interference when measuring the reflectance. The next important modification was to use the instrument's common beam mask set to 10% openness for transmittance and 30% openness for reflectance measurements. This resulted in a port diameter to beam spot diameter ratio that was larger than 2, a way to reduce the effects of light loss through side-shift. The reduced intensity due to use of the common beam mask required longer integration times to maintain an acceptable noise level.

Instruments that are capable of measuring direct-hemispherical properties as a function of angle of incidence are less common, but exist in research environments and as specialized accessories from some spectrophotometer manufacturers(e.g. Perkin–Elmer). The instruments used in this paper [17] were single-beam instruments designed only for direct-hemispherical measurements versus angle of incidence. The spheres were 200 mm diameter and coated internally with $BaSO_4$. The light source provides monochromatic light in a wavelength range from 300 nm to 2500 nm. The largest possible angle of incidence that can be measured is determined by the dimensions of the sample and its scattering properties. Reference