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Performance of Tubular Daylighting Devices

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Tubular daylighting devices (TDDs) can economically admit natural light into areas of buildings that do not have windows or skylights. This Update outlines the features and characteristics of TDDs and presents research findings that will improve the ability of manufacturers to design and rate their products. It will also help specifiers select best-performing products for particular locations and installation geometries.

Tubular daylighting devices are used to collect and channel daylight through the roof of a building into interior spaces (Figure 1). Compared to conventional skylights, they have the advantages of energy savings (small area relative to the amount of useful light they can admit), lower solar heat gains, and relative ease of installation. Straight TDDs are common but non-linear light guides with bended sections are sometimes needed to suit the geometry of a building.

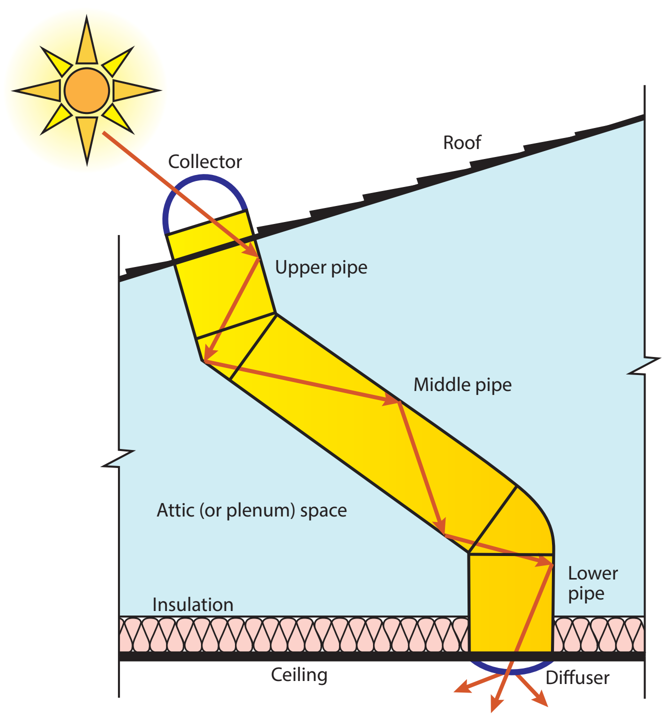

Figure 1. Typical tubular daylighting device

The daylighting of indoor spaces helps reduce the use and cost of artificial lighting. The glare-free daylight provided by TDDs contributes to the visual comfort, health and well-being of building occupants.

The lighting performance (light output) of a TDD varies according to time of day, outdoor daylight availability, building location, roof orientation and exposure, and tube length-to-diameter ratio. A typical device can illuminate an area of 14 to 28 m^2 (150 to 300 ft^2). The area of coverage is dependent on the height of the ceiling—the higher the ceiling the more widely the light will be uniformly distributed.

TDDs collect solar heat and carry it indoors. The solar heat gain is desirable in winter for reducing the heating load, but in summer it increases the cooling load. In addition, TDDs may lose indoor heat to the outdoors through their roof openings. These aspects have an influence on the energy performance of a TDD and hence on the ability of a building to comply with energy codes and standards.

TDD technologies have been evolving rapidly to meet high standards of energy efficiency in buildings and the need for glare-free lighting. The energy-saving potential of TDDs is well recognized, and their use is increasingly encouraged and sometimes mandated, particularly in commercial buildings.

Features

TDDs typically consist of three parts: a collector on the roof to gather sunbeam light and diffuse sky light, a hollow pipe guide in the plenum/attic space to channel light downwards, and a diffuser at ceiling level to spread light indoors (see Figure 1).

Collector

The collector is usually a single or multiple-layer transparent glass or plastic dome projecting above the plane of the roof. The collector may embody various geometric shapes or contain optical features such as prisms, reflectors or diffusing elements to enhance the lighting output of the TDD, especially at low sun altitude angles (Figure 2).

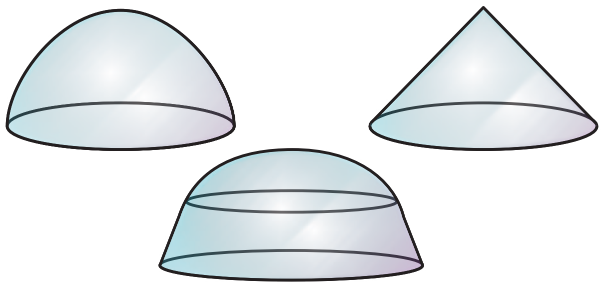

Figure 2. Typical collector shapes

Tubular light guide

The tubular light guide can be straight-rigid, elbow-rigid, or flexible, and is usually made from an aluminum sheet. The interior surface of the aluminum guide is usually coated with special materials to highly reflect the visible component of sunlight and absorb the infrared component so that mainly visible light gets into the indoor space. Coating materials with a light reflectivity up to 99% are commercially available. Depending on the building type and building (fire and energy) code requirements, the exterior surface of the pipe may have a section covered by insulation at the ceiling level (e.g., attic space of residential buildings) or roof level (e.g., plenum space of commercial buildings), or the entire pipe surface may be covered by insulation.

Pipe diameters normally range from about 250 to 560 mm (10 to 24 in.). The ratio of the length of pipe (L) to its diameter (D) is its aspect ratio (L/D). The lower the aspect ratio, the more light will reach the interior space (Figure 3). In general, the practical limit for the aspect ratio is ~25. This means that small-diameter pipes of 25 cm (10 in.) can have a maximum length of 6 m (20 ft), while large-diameter pipes of 53 cm (21 in.) can span up to 13 m (44 ft).

Figure 3 illustrates how the amount of sunlight is transmitted through a straight pipe (without the roof collector, ceiling diffuser and any elbow) as influenced by the pipe aspect ratio, reflectivity of the interior pipe surface, and the angle at which sunlight strikes the pipe opening surface (the angle of incidence). The light transmittance of vertical pipes decreases with increasing incidence angles. For example, on summer days, vertical pipes transmit more sunlight than in winter days. Furthermore, the lower the aspect ratio, or the higher the pipe reflectivity is, the more sunlight gets transmitted through the pipe to the indoor space. In addition, the effects of the pipe reflectivity and aspect ratio are more pronounced at mid- to high-incidence angles (> 25 degrees; e.g., at sunset/sunrise, or on winter days in the northern hemisphere). In other words, long pipes should be combined with high reflectivity to efficiently transport sunlight to the indoor spaces.

It should be noted that the results of Figure 3 are indicative for the vertical pipe transmittance only. Adding a complex collector (with prismatic structures) on the top of the pipe, or multiple elbows will modify the profile of the pipe transmittance of Figure 3, especially at high incidence angles (or low sun altitude angles).

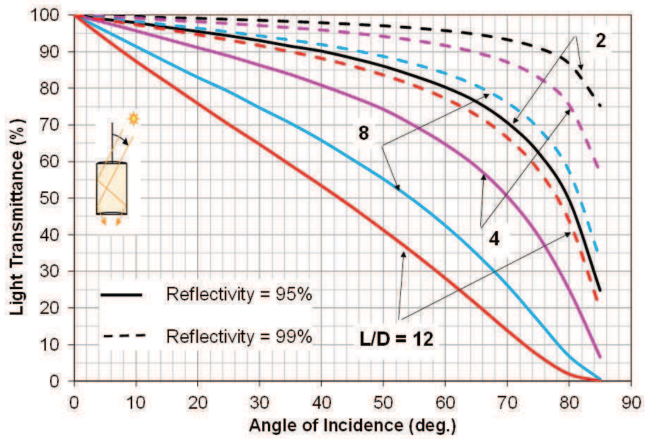

Figure 3. Visible (light) transmittance of a straight pipe (without any elbow) as influenced by the pipe aspect ratio (L/D), reflectivity of the interior pipe surface and the angle of incidence.

Diffusers

TDD ceiling diffusers are usually hemispheric or flat, and are made of single-, or multi-layer glass or plastic. Typically they employ one of three types of glazing: prismatic, diffusing or lensed.

Prismatic glazing (Figure 4A) consists of arrays or layers of micro-replicated shapes (conical prisms, ridges, wedges, etc.), which reflect, refract and redirect the incoming light based on the angle of incidence. Normally these diffusers are made of acrylic or polycarbonate sheets with conical prisms.

Figure 4. Diffuser with prismatic glazing (A), diffuser with diffusing glazing (B), diffuser with lensed glazing (C)

Diffusing glazing (Figure 4B) consists of very fine particles, pigments or films applied to clear glass or plastic sheets to make the glazing look opal (white). The diffusing or scattering properties depend on the refractive index and the size of the microstructures used in the elements applied. (The refractive index is a measure of how much light is bent, or refracted.)

Lensed glazing (Figure 4C) is composed of arrays of diverging lenses that are very thin and therefore very little light is lost by absorption.

Recent developments

While TDDs have been available for more than two decades, manufacturers have not had reliable calculation methods and design tools to allow them to economically predict their lighting and energy performance. Both performance issues are important. Building owners and users need to know what elements constitute an optically efficient TDD—one that delivers maximum light—while energy considerations play a role in helping a building meet requirements of energy codes and standards.

On behalf of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), NRC Construction carried out research to address the shortcomings associated with this technology. Researchers developed models for determining the optical and thermal performance of TDDs with and without bends. The models were successfully validated using third-party public data, measurements and simulations.

Sample results from computations using the models

Some specific results of the computer calculations are provided in Table 1. The table shows the computed optical and thermal characteristics of a typical TDD made up of a 3-mm acrylic collector and a 3-mm polycarbonate diffuser with a standard pipe length-to-diameter aspect ratio of 2.14. The inside surface of the pipe is coated with a polymeric film with a reflectivity of 99% for the visible sunlight and 76% for the non-visible (infrared) sunlight to maximize light output with reduced solar heat gains indoors. (Note: see sidebar for definition of terms.) Table 1 shows that while the number of layers in the collector or diffuser has only a small effect on the visible (light)

Table 1. Characteristics of a typical TDD (transmittance and SHGC are calculated at an angle of incidence of 50 degrees)

Glazing of Collector/diffuser	single/single layer	double/double layer	double/single layer	single/double layer	single/triple layer
Visible (Light) Transmittance (%)	77	63	72	66	58
SHGC (%) (insulation at ceiling)	32	24	27	28	24
SHGC (%) (insulation at roof)	34	33	32	35	34
U-Factor ($W/m^2\,°C$) (insulation at ceiling)	3.54	2.16	3.53	2.17	1.55
U-Factor (insulation at roof)	7.62	4.70	4.70	7.60	7.58

transmittance (and therefore the luminous output of TDD), it has a significant effect on thermal performance as indicated by the SHGC and U-Factor. The table does not show any best arrangement, but provides information that can help a designer select an arrangement best suited to a particular application in either a residential or commercial building.

Guidelines

NRC research produced several outcomes helpful to manufacturers, specifiers and installers:

- The lighting performance of TDDs (particularly VT, NID, and DAC) with bends depends on the geographical location of the building, and on the time of day and year. The optical models developed by NRC can be used to optimize the design for a specific location.
- The presence of elbows in TDDs can significantly affect (reduce or increase) their optical characteristics (VT as a function of angle of incidence). Light transmittance of a TDD is optimized by proper placement and orientation of elbows and pipe connection sections during installation to maximize the collection of sunlight during the operating daytime hours.
- Vertical pipes without bends are more efficient than bended guides (with two elbows) for low incidence angles (< 60°; e.g., noon time in summer), and less efficient for higher incidence angles (> 60°; e.g., noon time in winter).
- Bended guides facing north result in the lowest transmittance for low incidence angles (< 32°) and highest transmittance for intermediate incidence angles between 32° and 60° (e.g., noon time at shoulder seasons). Guides facing south result in reversed trends to the north direction.
- Light guides oriented towards the east or west provide average results between the north and south orientations.

It is recommended that manufacturers use the models developed by NRC to determine TDD product ratings instead of using costly measurement procedures currently available.

Once manufacturers begin to employ the models, specifiers and builders will be able to select TDDs that will suit a specific building type (residential or commercial) and location and comply with building energy codes and energy efficiency standards (such as ASHRAE 90.1, and ENERGY STAR®).

If the models are adopted by rating fenestration councils, TDD manufacturers will start adding product performance metrics such as U-factor, SHGC, visible transmittance, luminous intensity distribution, and daylight coverage area to their product packaging.

The addition of the TDD models to fenestration design tools or the ASHRAE Load Toolkit will help design professionals select site-specific, energy-efficient products.

Selection of Suitable TDDs

When selecting TDDs, specifiers should consider:

- Visible transmittance: products with the highest visible transmittance should be selected to reduce the number of installed TDDs, or use TDDs with smaller diameter sizes.
- Solar heat gain coefficient: For heating-dominated climates, TDDs should have a medium to high SHGC. Most TDDs have medium to low SHGC (< 40%).

TDD performance and specification terms

Visible (light) transmittance (VT) – the ratio of the luminous amount of sunlight transmitted to the indoor space to the luminous amount of sunlight incident on the TDD pipe aperture, calculated or measured at a standard angle of incidence.

Normalized intensity distribution (NID) – an index treats TDDs as lighting luminaire systems. TDD intensity distribution is important for lighting energy calculation, and spatial arrangement of TDDs.

Daylighting area coverage (DAC) – the portion of the work-plane surface area under a daylight illuminance equal to or greater than the recommended task illuminance under a CIE standard clear sky condition. DAC is an important parameter for TDD product rating and selection, and spatial arrangement that guarantees capital cost reduction (i.e., fewer installed TDDs).

Spacing ratio (SR) – the maximum distance between two pairs of TDDs normalized to the ceiling height of the building. SR is calculated based on the illuminance uniformity criteria (which are usually set by interior lighting standards) on the work-plane surface.

Solar heat gain coefficient (SHGC) – the normalized solar heat gains getting into the indoor space through a TDD system when sunbeam light is incident on the TDD pipe aperture at a standard angle of incidence.

Thermal transmittance (U-factor) – the heat loss from a TDD to the outside per unit surface area and temperature difference between the inside and outside environments.

- U-factor: TDDs should have multi-pane ceiling diffusers when insulation is placed at ceiling level (e.g., residential buildings) or multi-pane collectors when insulation is placed at roof level (e.g., commercial buildings) to reduce TDD heat losses to the outdoor environment.
- Spacing ratio (SR): SR relates to the normalized luminous intensity distribution of TDDs. To minimize capital cost (as few as possible installed TDDs), select TDDs with higher spacing ratios. For ideally diffusing TDDs, SR varies from 1 to 1.5 for illuminance uniformity (ratio of minimum to average work plane illuminance) of 0.95 to 0.8, respectively.

Installation

Installation methods for TDDs vary depending on roof type (asphalt shingles, roof tiles, membranes, metal roofing, etc.). Assemblies must be installed to resist air and water infiltration, and damage due to wind and snow load. Manufacturers' instructions provide specific details. Careful attention to detail is required when re-roofing takes place.

Conclusion

Tubular daylighting devices (TDDs) are an excellent means for admitting daylight to buildings. Their optical performance affects the illumination they provide. Their thermal performance affects heat gain and loss and a building's ability to meet energy code requirements. NRC Construction has completed research, on behalf of ASHRAE, that will greatly enhance the ability of manufacturers to design and rate TDDs in terms of their performance characteristics. Adoption of the models by industry will allow specifiers to select products that will give the best optical and thermal performance for given locations and TDD orientations.

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