SIMULATION OF TUBULAR DAYLIGHTING DEVICES AND DAYLIGHTING SHELVES IN ENERGYPLUS

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ABSTRACT

Tubular daylighting devices (TDDs) and daylighting shelves are two methods for bringing natural exterior daylight into the hard-to-reach, interior spaces of a building. Recently two models to simulate these devices were added to the EnergyPlus whole-building energy analysis program. In addition to modeling their daylighting effects, solar gains and conductive/ convective heat transfer are also integrated into the zone heat balance. This paper presents an overview of the concepts and algorithms implemented in EnergyPlus to simulate TDDs and daylighting shelves. Preliminary testing efforts are also described.

INTRODUCTION

Tubular daylighting devices (TDDs) and daylighting shelves are two methods for bringing natural exterior daylight into the hard-to-reach, interior spaces of a building. TDDs, also known as tubular skylights or light pipes, channel the daylight incident on an exterior dome to an interior diffuser via multiple internal reflections in a pipe. Daylighting shelves, or simply light shelves, are composed of an inside shelf and/or outside shelf which divides a typical window into an upper and lower portion. The inside shelf diffuses daylight from the upper window onto the ceiling. The outside shelf acts as a reflector, changing the amount of daylight incident on the upper portion of the window.

The strategic use of daylighting devices in a building design can reduce the electric lighting load and result in energy savings. However, daylighting devices also have a thermal impact. A building with too much fenestration, for example, can actually increase the overall building energy usage because of greater solar gains and greater heat losses. A daylighting analysis must be combined with a whole-building energy analysis to determine the overall energy impact of daylighting devices.

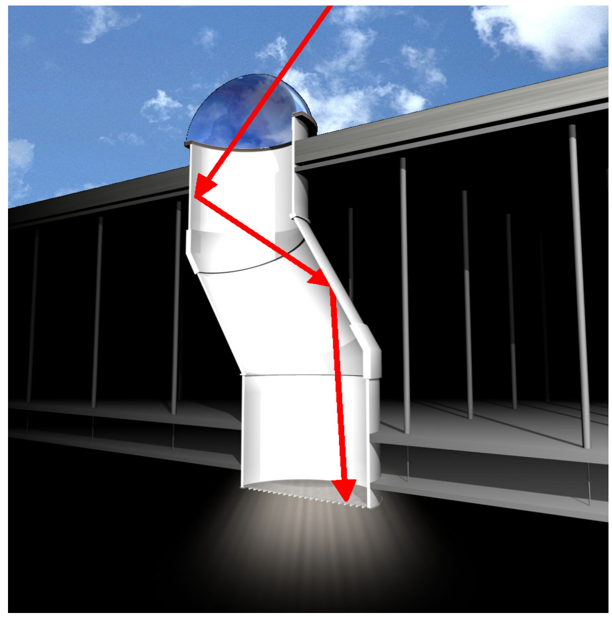

Figure 1. Tubular daylighting device.

EnergyPlus is one recent program that is capable of both daylighting and energy calculations for a building. The daylighting model is derived from the DOE-2.1E daylighting algorithm (Winkelmann et al. 1985). Daylight factors are calculated to determine illuminance levels at locations in a zone. Direct beam illuminance is calculated by ray tracing. Diffuse illuminance due to internal reflections in the zone is calculated using the split-flux method. The effects of multipane windows and window coverings such as shades or blinds are also simulated. The EnergyPlus model improves on DOE-2.1E by utilizing four sky types (Perez et al. 1990), as opposed to just two sky types in DOE-2.1E. Daylight factors in EnergyPlus are also calculated hourly instead of the 20 representative annual sun positions in DOE-2.1E.

The EnergyPlus energy simulation uses the heat balance method which is based on the law of conservation of energy (Strand and Pedersen 2001). Optical and thermal calculations for window glazing are based on algorithms from the WINDOW 4 and WINDOW 5 programs (Arasteh et al. 1989; Finlayson et al. 1993). Detailed surface geometry is used to calculate shading. Both daylighting and heat balance models are described in detail in the *EnergyPlus Engineering Document* (UIUC and LBNL 2003).

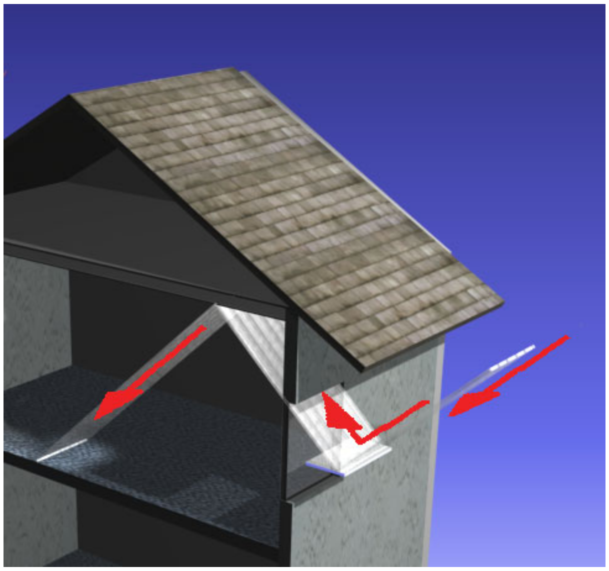

Figure 2. Daylighting shelf.

The capability to simulate TDDs and light shelves was added to EnergyPlus in version 1.1.1. The simulation of these devices is tightly integrated into both the daylighting and heat balance models. This paper gives an overview of the EnergyPlus models for daylighting devices in the context of a whole-building energy analysis.

TUBULAR DAYLIGHTING DEVICES

Tubular daylighting devices (TDDs) are constructed of three components: a dome, a pipe, and a diffuser. The dome is typically a hemisphere made of clear plastic. It allows daylight into the pipe while keeping exterior weather out. The pipe is assumed to be a smooth cylinder with a highly reflective inside surface. The surface is usually either bare polished metal or a special reflective sheet adhered to the inside. The pipe passes through one or more transition zones, channeling the daylight from the dome to the diffuser via multiple internal reflections. The diffuser is typically a prismatic or frosted plastic cover. The diffuser evenly distributes the daylight to the zone.

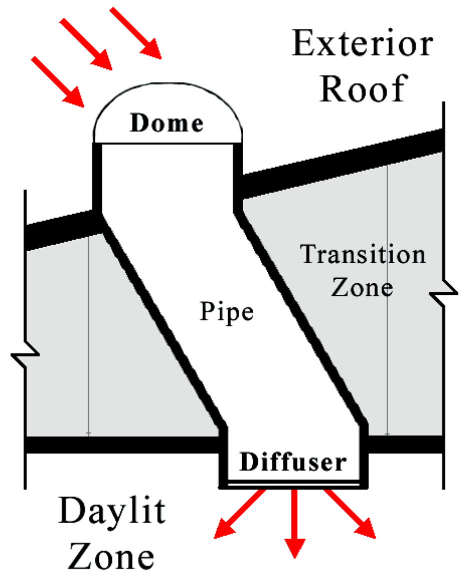

Figure 3. Tubular daylighting device diagram.

In EnergyPlus the TDD model includes three distinct, but related, phenomena:

- Daylighting
- Solar gains
- Conductive/convective gains

Solar gains and conductive/convective gains are simulated by the zone heat balance while daylighting is simulated independently.

For both daylighting and heat balance simulations, the dome and diffuser components are treated as special window surfaces to take advantage of many of the standard EnergyPlus daylighting and heat transfer routines. Together the dome and diffuser become "receiver" and "transmitter", i.e. radiation entering the dome ends up exiting the diffuser.

The pipe is simulated by a separate code module. While several different measures for characterizing TDD performance are in use (Zhang et al. 2002; Harrison et al. 1998), using the transmittance of the TDD is most compatible with the existing EnergyPlus daylighting and heat balance code. Calculation of the transmittance of the pipe component and the overall TDD for different types of radiation is fundamental to all phenomena covered by the model.

Pipe beam transmittance

The transmittance of a beam of collimated radiation is derived from the integration of the transmittance of many parallel rays. The transmittance of a discrete ray through a pipe is dependent on the reflectivity of the inside pipe surface, the aspect ratio of the pipe, the incident angle of the ray, and the point of entry into the pipe.

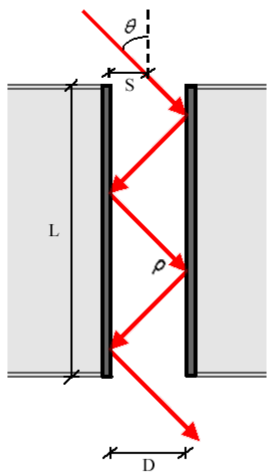

Figure 4. Discrete ray in a pipe.

For an opaque surface, the reflectivity is:

$$\rho = 1 - \alpha \tag{1}$$

where α = surface absorptivity. Visible (i.e. daylighting) and solar absorptivities of the pipe material are specified in the input file. These yield visible and solar reflectivities, respectively. Measured reflectivities for commercial TDDs range from 0.90 to 0.99. Although the actual surface reflectivity is slightly dependent on the incident angle, the model assumes a constant reflectivity for all angles.

The full analytical expression for the transmittance of a beam of light in a highly reflective pipe has been developed by Swift and Smith (1994) and verified by experiment. By integrating over all rays incident on the pipe entrance, they find the transmittance of a beam of collimated radiation to be:

$$\tau = \frac{4}{\pi} \int_{s=0}^{1} \frac{s^2}{\sqrt{1-s^2}} \rho^{INT[a\tan\theta/s]} \left(1-(1-\rho)\left(a\tan\theta/s - INT\left[a\tan\theta/s\right]\right)\right) ds \tag{2}$$

where

a = L/D, the aspect ratio of the TDD

ρ = surface reflectivity

θ = incident angle

s = entry point

INT[x] = a function returning the integer part of x

This integral does not have an analytical solution and must be calculated numerically. It was found that a large number of points (100,000) were necessary to achieve an acceptable accuracy. Since the integration is time consuming and the transmittance of the pipe must be utilized many times at every timestep, values are calculated once over a range of incident angles during an initialization procedure and then stored in a table. The tabulated values are interpolated to rapidly give the transmittance at any incident angle. A polynomial fit was also considered but it was found that interpolation gave superior results.

During initialization of each unique TDD, the program integrates and tabulates values separately for the visible and solar transmittance of the pipe. The results are subsequently used in the daylighting simulation and heat balance simulation respectively.

The effect of bends in the pipe on beam transmittance is not included in this model. Recent research (Zhang et al. 2002) has suggested that a 30 degree bend has a 20% loss in transmitted light. If the effect of bends must be simulated, it can be approximated by the user by appropriately decreasing the transmittance of the diffuser material.

TDD beam transmittance

The beam transmittance of the TDD takes into account the dome and diffuser transmittances in addition to the pipe transmittance.

$$\tau_{TDD}(\theta) = \tau_{dome}(\theta)\tau_{pipe}(\theta)\tau_{diffuser} \tag{3}$$

where

$\tau_{dome}(\theta)$ = beam transmittance of the dome glazing at the incident angle

$\tau_{pipe}(\theta)$ = beam transmittance of the pipe at the incident angle, as described above

$\tau_{diffuser}$ = diffuse transmittance of the diffuser glazing

The dome transmittance is based on the EnergyPlus calculation for a regular flat window. The model does not take into account refraction due to the curvature of the dome surface.

Diffuse transmittance is always assumed for the diffuser component because multiple internal reflections in the pipe scatter the beam with a diffusing effect. Although the light exiting the pipe is not isotropic, it can be approximated as diffuse. The use of a prismatic or frosted diffuser on the TDD, however, ensures that the light delivered to the zone is very close to isotropic diffuse.

The calculation of TDD diffuse transmittance is considerably more complex and is handled differently in daylighting and heat balance simulations. The details are discussed in the following sections.

Daylighting

The daylighting simulation of the TDD treats the diffuser surface as a regular window illuminated from the outside by sun, sky, and ground reflections. However, the TDD model replaces the window glazing transmittance with the appropriate overall TDD transmittance and converts all transmitted light to diffuse.

The illuminance due to the direct beam of the sun is found using the TDD beam transmittance $\tau_{TDD}(\theta)$ as described above. The incident angle θ is relative to the dome surface.

The illuminance due to sky radiation and ground reflected radiation is calculated by integrating over the sky and ground within the viewable hemisphere. This is done separately for each of the four sky models. For the TDD, the transmittance of each sky or ground element is also found using the TDD beam transmittance at the incident angle of the sky or ground element relative to the dome.

Solar gains

Solar radiation incident on a window is calculated separately as sun, sky, and ground reflected radiation. A different transmittance must be applied for each type of radiation. For beam radiation, the TDD beam transmittance $\tau_{TDD}(\theta)$ for the solar spectrum is as described above.

For sky and ground radiation, EnergyPlus uses the Perez sky model (Perez et al. 1990). This is an anisotropic distribution modeled as the superposition of three simple distributions: a diffuse isotropic background, a circumsolar brightening near the sun, and a horizon brightening. While the daylighting model is capable of calculating the luminance of any position in the sky, the solar model only calculates the ultimate irradiance on a surface. For this reason it is not possible to integrate over an angular distribution function for sky radiance. Instead the diffuse transmittance for sky and ground radiation is handled piecewise.

$$\tau_{diff,aniso} = \frac{\sum I_{trans,aniso}}{\sum I_{inc,aniso}} = \frac{I_{trans,iso} + I_{trans,circum} + I_{trans,horiz}}{I_{inc,iso} + I_{inc,circum} + I_{inc,horiz}} \quad (4)$$

Substituting in the appropriate transmittances:

$$\tau_{diff,aniso} = \frac{\tau_{diff,iso} I_{inc,iso} + \tau(\theta) I_{inc,circum} + \tau_{diff,horiz} I_{inc,horiz}}{I_{inc,iso} + I_{inc,circum} + I_{inc,horiz}} \quad (5)$$

where

$\tau_{diff,iso}$ = diffuse isotropic transmittance

$\tau(\theta)$ = beam transmittance at incident angle θ of sun

$\tau_{diff,horiz}$ = diffuse transmittance of the horizon

It is important to note that transmittances above are for the overall TDD. The transmittance of the dome and diffuser must be included to account for their angular dependencies as well. The beam transmittance is used as an approximation for all circumsolar radiation. The diffuse isotropic transmittance is found by integrating the beam transmittance over all angles in the hemisphere.

Some solar radiation is inevitably absorbed by the TDD before it reaches the interior zone. Every reflection in the pipe leaves behind an amount of solar radiation that depends on the surface absorptivity. Rays incident at a greater angle make more reflections and leave behind more absorbed solar radiation in the pipe wall.

The total absorbed solar radiation in the TDD is the sum of the following gains:

- Inward bound solar radiation absorbed by multiple pipe reflections
- Outward bound solar radiation absorbed by multiple pipe reflections due to:
  - Reflection off of diffuser surface (inside of TDD)
  - Zone diffuse interior shortwave radiation incident on the diffuser from lights, etc.
- Inward flowing absorbed solar radiation in dome and diffuser glazing

All absorbed solar radiation in the TDD is distributed among the transition zones that the pipe passes through between dome and diffuser.

The complexity of the exact solar distribution in the pipe is not modeled. Instead the assumption is made that transition zone heat gain is proportional to the length of pipe in each zone. Any exterior length of pipe also receives a proportional amount of heat, but this is lost to the outside. Since the user specifies the length of pipe in each transition zone in the input file, there is flexibility for adjusting the lengths, and hence the heat gain, to match a predetermined solar distribution. The user, for example, may be able to estimate a distribution from experimental measurements (perhaps using infrared thermography), or calculate a distribution using an external model when future research makes such available.

Conductive/convective gains

For conductive and convective heat gain, TDDs are treated as one entity with an effective thermal resistance (i.e. R-value) between the outside and inside surfaces. The outside face temperature of the dome and the inside face temperature of the diffuser are calculated as usual by the outside and inside heat balances respectively. Normal exterior and interior convection and IR radiation exchange occurs for both surfaces.

Although little research has been done to measure the thermal characteristics of TDDs, one experiment (Harrison et al. 1998) reports an average effective thermal resistance of 0.279 m^2 K/W for a commercial TDD measuring 0.33 m in diameter by 1.83 m in length. This value, however, reflects a measurement from outside air temperature to inside air temperature. The EnergyPlus model assumes an effective thermal resistance from outside *surface* temperature to inside *surface* temperature.

The National Fenestration Rating Council (NFRC) has included a method for determining the U-value of TDDs in the latest *NFRC 100* publication (NFRC 2002). Rated TDD U-values for participating manufacturers can be found using the on-line *NFRC Certified Products Directory*. Typical R-values for one product line range from 0.366 to 0.419 m^2 K/W. Again, this value reflects heat flux from outside air temperature to inside air temperature. Care must be taken to subtract off outside and inside surface heat transfer coefficients before using with EnergyPlus.

The heat transfer effects of convection of air in the pipe, including stratification and infiltration, must also be taken into account by the user when estimating the effective thermal resistance. Note that the effective thermal resistance does not take into account any heat transfer between the pipe component and the transition zones through which the pipe passes.

Testing

Preliminary testing of the model has consisted of simulating TDDs for specific cases where the results are well-known. These cases are not meant to take the place of a detailed validation against experimental data or ray tracing simulations, but rather to serve as a check that the results are reasonable. The primary concern is to ensure an energy balance and eliminate programming errors.

The fundamental new feature of TDDs in both daylighting and heat balance models is the algorithm for calculating the beam transmittance of the TDD pipe component. To test the algorithm, interpolated values from EnergyPlus were calculated over a range of aspect ratios and reflectivities for beam radiation at an incident angle of 30 degrees. In the graph below, the EnergyPlus values are compared to the results of ray tracing simulations performed at the Florida Solar Energy Center for the TDD pipe geometry (McCluney 2003).

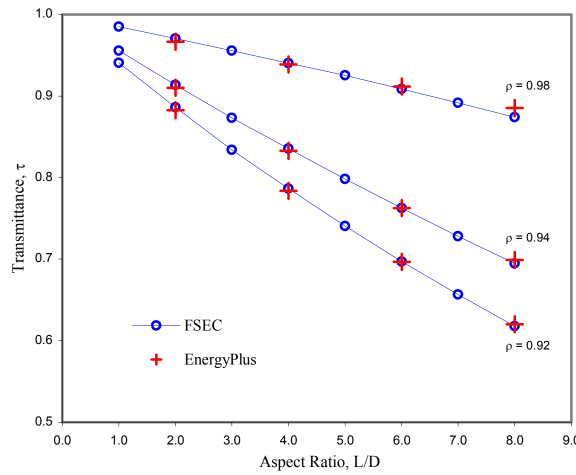

Figure 5. Pipe transmittance comparison.

As shown in Figure 5, the results compare very well. Unfortunately, ray tracing results for incident angles other than 30 degrees were not available for comparison.

The remaining test cases use a side-by-side simulation of two zones: one with a TDD and the other with an equivalent window or heat transfer surface. Other than the TDD or window, the zones have identical geometry and construction and should give the same simulation results. The zones are separated by enough distance in the simulation such that neither zone can shade the other at any time. For daylighting tests, the illuminance map feature in EnergyPlus was used to report a grid of illuminance levels throughout both zones. For heat balance tests, i.e. solar and conductive/convective gains, the total heating and cooling loads of both zones were reported.

A basic daylighting test case was performed to test the receiver-transmitter effect between dome and diffuser and the diffusing characteristic of the diffuser component. The TDD zone consisted of a TDD passing through an attic zone with a flat roof. The TDD received daylight at the north end of the roof and transmitted daylight above the south end of the zone. The reference zone consisted of a window (i.e. skylight) with a diffusing shade on a flat roof with no attic above the south end of the zone. The TDD diffuser and window were identical in size and position relative to the zone. Since the TDD pipe obviously changes the overall transmittance of the receiver-transmitter combination, the TDD transmittance was temporarily modified in the code to match the transmittance of the reference window with a diffusing shade. The final test case simulation showed the illuminance map to be identical for both zones. The TDD daylighting model, therefore, is successfully receiving daylight at the dome surface and transmitting it as diffuse illumination at the diffuser surface.

To test the TDD heat balance model, solar gains and conductive/convective gains were examined separately. For the solar gains test case, efforts were made to minimize the effects of conductive/convective heat transfer. Both TDD and reference window were set to be highly insulated. The effective thermal resistance of the TDD was set very high and the conductivity of the window material was set near zero. To eliminate radiation heat transfer, the TDD dome, TDD diffuser, and reference window surface were set to have near zero emittance and absorptance. The TDD zone consisted of a TDD passing through an attic zone with a flat roof. The reference zone consisted of a window on a flat roof with no attic. Since the small area of a typical TDD surface makes its thermal impact difficult to detect in a zone heat balance, the areas of the TDD surface and window surface were enlarged to nearly the size of the zone roof in order to exaggerate any discrepancies. Again, as for the daylighting test case, the TDD transmittance was modified to match the reference window. The final test case simulation showed the total heating and cooling loads to be identical for both zones under two different design day conditions. This indicates that the TDD model is correctly adding solar gains to the zone heat balance.

Finally, to test the conductive/convective gains in isolation, a simulation was performed under no solar conditions by setting the sky clearness factor to zero. The TDD zone consisted of a TDD passing through an attic with a flat roof. However, the height of the attic zone was reduced to nearly zero in order for the TDD dome surface and reference surface to be at the same height, which affects the calculation of exterior convection coefficients. The reference zone consisted of a special R-value-only heat transfer surface in place of the reference window on a flat roof. The R-value of the reference surface was matched to the effective thermal resistance of the TDD. Enlarged surface areas where again used for both TDD and reference surfaces. The final test case simulation showed the total heating and cooling loads to be identical for both zones under two different design day conditions. This indicates that the TDD model is also correctly adding conductive/convective gains to the zone heat balance.

DAYLIGHTING SHELVES

Daylighting shelves, or simply light shelves, are constructed of up to three components: a window, an inside shelf, and an outside shelf. The inside shelf acts to reflect all transmitted light from the upper window onto the ceiling of the zone as diffuse light. The outside shelf changes the amount of light incident on the window. All light reflected from the outside shelf that enters the window also goes onto the zone ceiling. The inside shelf and outside shelf are both optional. However, if neither shelf is specified in the input file, the daylighting shelf object has no effect on the simulation.

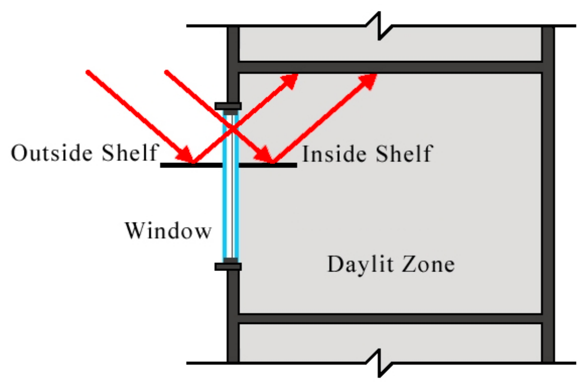

Figure 6. Daylighting shelf diagram.

The window is divided into two window surfaces: an upper window and a lower window. The upper window interacts with the daylighting shelf but the lower window does not, except to receive shading from the outside shelf. Daylighting shelves are simulated separately for daylighting and the zone heat balance. The general model is similar in both cases, but the details vary.

Inside shelf daylighting

In the split-flux method, daylight is "split" into upward-going and downward-going flux. Beam radiation is always considered to be downward-going. A diffusing shade on a vertical window, however, will equally divide the flux into upward-going and downward-going components.

The inside shelf is modeled in the daylighting simulation by converting all light transmitted by the upper window into diffuse upward-going flux. It is assumed that no beam or downward-going flux can pass the end of the shelf regardless of the position or orientation of the shelf. Daylight transmitted by the lower window is not affected by the inside shelf.

Inside shelf heat balance

In the heat balance simulation the inside shelf is defined as an interzone heat transfer surface, i.e. partition. Since it does not have an external boundary condition, it is essentially equivalent to internal mass. Because the shelf surface has two sides that participate in the zone heat balance, the surface area is doubled by the program during initialization. Like regular internal mass in EnergyPlus, the shelf surface is allowed to interact convectively and radiatively with the zone air and other zone surfaces.

The zone interior solar distribution is modified by the inside shelf. Regardless of the solar distribution algorithm selected in the input file, all beam solar radiation transmitted by the upper window is incident on one side (half the doubled surface area) of the shelf surface. The beam radiation that is not absorbed by the shelf is reflected throughout the zone as diffuse shortwave radiation. The treatment of sky and ground radiation is unchanged; both are added directly to the zone diffuse shortwave. The beam, sky, and ground radiation transmitted by the lower window is not affected by the inside shelf.

Outside shelf daylighting

In the daylighting model the luminous flux transmitted by the upper window is determined by integrating over the sky and ground and summing the luminance contribution of each sky or ground element. The luminance of any intervening exterior or interior surfaces is assumed to be zero. Defined as a shading surface, the effect of the outside shelf during the integration is to block part of the view of the ground, thereby reducing the window transmitted flux due to diffuse ground luminance. After the integration is complete, the shelf model calculates the amount of diffuse light that is reflected through the window by the outside shelf and adds it as a lump sum to the upward-going flux transmitted by the window.

The amount of reflected light incident on the upper window due to the outside shelf is determined using a view factor from window to shelf. The program automatically calculates an exact view factor for adjacent perpendicular rectangles based on the dimensions of the window and shelf. If the window and shelf have a different geometry, the user can optionally specify their own view factor in the input object.

Outside shelf heat balance

The heat balance simulation does not do a sky and ground integration. View factors to sky and ground are used instead. Similar to the daylighting calculation, the view factor from window to shelf is also used here to determine the incident reflected solar radiation due to the shelf. The total incident radiation on the upper window is the sum of the beam, sky, ground reflected, and shelf reflected radiation. With the incident radiation determined, the remainder of the window heat balance is calculated normally.

No other thermal effects are considered for the outside shelf. There is assumed to be no conduction between the outside shelf and inside shelf, i.e. no heat fin effects.

Testing

Preliminary testing of the daylighting shelf model was similar to the side-by-side simulation test cases for TDDs. A shelf zone and an equivalent reference zone are simulated and illuminance map and total heating and cooling load results are compared. Inside and outside shelves are tested separately. Only the upper window is defined in the test cases; the lower window is not affected by the daylighting shelf and does not require a test.

The objective of the daylighting test case was to verify that the inside shelf yields diffuse upward-going illumination. The shelf zone consisted of an inside shelf and an upper window in a south facing wall. The reference zone consisted of an upper window with a diffusing shade in a south facing wall. The code was temporarily modified to direct all of the diffuse transmitted daylight from the shaded window upward to match the effect of the inside shelf. The final test case simulation showed the illuminance map to be identical for both zones. The shelf daylighting model correctly converts all daylight to diffuse upward-going flux.

To test both the daylighting and heat balance effects of the outside shelf, the shelf zone consisted of an outside shelf and an upper window in a south facing wall. Adjusting the user-specified view factor from the upper window to the outside shelf to be 0.5, the window viewed the shelf like an artificial ground, stretching infinitely to the horizon. The reference zone consisted of an upper window with a diffusing shade in a south wall. The code modification described above to convert all light to upward-going flux was also used in this case. The ground reflectance was specified in the input file to match the reflectance of the shelf so that both zones should see an expanse to the horizon with the same reflectivity. The final test case simulation showed the illuminance map and total heating and cooling loads to be identical for both zones. The shelf model is correctly adding illuminance and solar gains due to reflection off of the outside shelf.

CONCLUSION

The new TDD and daylighting shelf models add advanced daylighting simulation capabilities to EnergyPlus that are not available in other whole-building energy analysis programs. The models simulate both daylighting and zone heat balance effects, including solar gains and conductive/convective heat transfer.

Preliminary testing indicate that the models are expected to yield reasonable results. A more detailed validation should be undertaken to further verify the accuracy of the daylighting models by comparing EnergyPlus results to experimental data or ray tracing simulations from other daylighting programs.

Many of the simplifying assumptions described for both TDDs and daylighting shelves leave room for future development. In particular, a more comprehensive thermal model of the conductive/convective heat transfer for TDDs is needed to replace the effective thermal resistance approximation. Unfortunately, the thermal behavior of TDDs is not yet well understood. A new model must await additional experimental research results.

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