DEVELOPMENT OF ANALYSIS SOFTWARE FOR THE OPTICAL CHARACTERISTICS AND DAYLIGHTING PERFORMANCE OF CONVENTIONAL AND TUBULAR SKYLIGHTS

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ABSTRACT

This paper presents an overview of the development of analysis software for the optical characteristics and daylighting performance of conventional and tubular skylights. The software is useful to skylight manufacturers, building designers and fenestration rating councils. The software development process spans over a four-year period, and includes development of prediction models for optical and daylighting performance of different skylight shapes, experimental and analytical validation of the prediction models, and software design. This paper focuses on the software structure, inputs, outputs and analysis modules. Preliminary results from the prediction models are also shown for the beam transmittance of barrel vault skylights, diffuse transmittance of domed skylights under different sky conditions, and average Daylight Factor on internal room surfaces.

BACKGROUND

The skylight market has been booming in recent years. Skylights are found in many modern or retrofitted buildings. In commercial and institutional buildings, skylights are used to simulate the outdoors and to bring natural light and solar heat into the indoor space. In residential buildings and houses, skylights are used mainly for illumination. Recently, tubular skylights have emerged as a new technology in commercial buildings and houses, potentially eliminating some of the drawbacks of the excessive solar heat gains of conventional skylights and extending the application of skylights in areas not reached by conventional skylights and windows (Bajda and Carter 2000; Salih et al. 2000; Shao et al. 1998). Skylights have the inherent potential to save electrical lighting, cooling and heating energy, beside their psychologically positive effects on building occupant satisfaction (HMG 2001, 1999; Heschong and McHugh 2000; Allen 1997; AAMA 1987, 1981; Cassidy 1986; Treado et al. 1983). However, despite these amenities, skylights integrated in building design may result in high-energy consumption if not properly designed. Skylight manufacturers lack design tools to assess the optical characteristics and daylighting performance of skylight products owing to complex skylight shapes that change with design requirements, and large sizes that impede fitting skylight products into measurement facilities. Furthermore, while measurements on some skylight products are possible, they can not be generalised for other products. In addition, fenestration simulation software such as VISION4 (CANMET 1995) and WINDOW (LBL 1992) deal with only planar geometry, such as windows and flat skylights.

OBJECTIVES

The Institute for Research in Construction, PERD (Panel for Energy Research and Development), and NRCan have started a four-year project to develop software to analyse the optical characteristics (transmittance, absorptance and reflectance) and daylighting performance of conventional and tubular skylights. The project is accomplished through three main tasks. The first task is devoted to developing prediction models for skylight optical characteristics and indoor daylight availability. The second task is the experimental and analytical validation of the prediction models. The third task focuses on the design of the software. The software will enable skylight manufacturers to prototype and characterise skylight designs before building them, and will aid building designers in skylight selection to meet design criteria for energy savings. The software will also help fenestration rating councils to rate the optical and daylighting performance of skylight products. The specific objective of this paper is to provide an overview of the software structure, analysis modules, and input and output parameters with some preliminary results from the first task of the project.

SOFTWARE STRUCTURE

Figure 1 shows a flow chart of the software structure. The main components of the software are the inputs, databases, analysis modules and outputs.

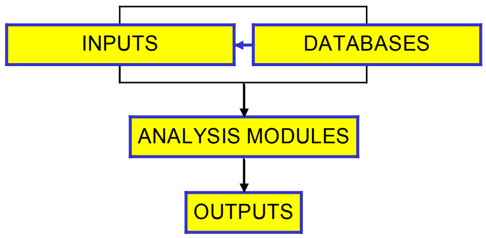

Figure 1 Flow chart of the software structure

INPUTS

The input parameters include general data, sky conditions, skylight system data, and data for the space under the skylight, which include the curb (space above roof), well (space between roof and ceiling) and room (space below ceiling). Databases for glazing optics and climate data are used to simplify the input data process (Figure 2).

General Inputs

The user supplies the site latitude and longitude angles, the ground/surrounding visible and solar reflectances, the simulation day, the floor target illuminance, and the file names for the glazing and climate databases, inputs and outputs. The user may also supply other dummy inputs, which are not used in the computation, such as project identifier, company name, etc.

Sky Conditions

Sky conditions affect the skylight optical characteristics and indoor daylight availability. The user may input a variety of sky conditions, varying from luminance-based to illuminance-based sky conditions. In the luminance-based sky conditions, the sky luminance pattern is known. The user may specify standard skies that are site-independent, or dynamic real skies that change with daytime. Standard sky conditions may be uniform overcast, CIE overcast, CIE intermediate, IES partly cloudy (IESNA 1993), CIE clear with polluted air, CIE clear with clean air (CIE 1990), or dynamic real (Perez et al. 1993). In the illuminance-based sky conditions, the hourly horizontal diffuse illuminance is known. The sky conditions may be uniform overcast, CIE overcast, or dynamic real. In the dynamic real skies, the sky luminance pattern has to be modelled. The model of Perez et al. (1990) is used for this purpose.

Conventional Skylights

Inputs for conventional skylights include the skylight shape and the glazing type. Conventional skylights are classified into four basic classes - dome-Like, vault-like, cone-like, and flat (Figure 3). Skylights with any other shape are converted to the class representative shape through the use of the concept of the Shape Parameter developed by Laouadi and Atif (2001a) and Laouadi et al. (2001). The representative shape for dome-like skylights is a hemispherical dome characterised by its truncation angle and radius. Skylights falling under this class include hemispherical domes with different profiles, segmented domes, square-based bubbles or any other similar shape. The representative shape for vault-like skylights is a barrel vault characterised by its truncation angle, orientation with respect to the south direction, radius and length. The gables (end walls) may be opaque, or glazed with different glazing types from that of the cylindrical part of the skylight. Skylights falling under this class include barrel vaults with different profiles, segmented barrel vaults, ridges, hip ridges, double pitch, rectangular-based bubbles or any other similar shape. The representative shape for cone-like skylights is a circular cone characterised by its cone angle and height. Skylights falling under this class include circular cones, polygons, pyramids, or any other similar shape.

Skylight glazing may be transparent or translucent. When the glazing is transparent, the optical properties (transmittance and front and back reflectances) for the visible and solar spectrums are read from the attached glazing database. When the glazing is translucent, however, the user has to input the diffuse optical properties of the flat sheet the skylight is made of for the visible and solar spectrums.

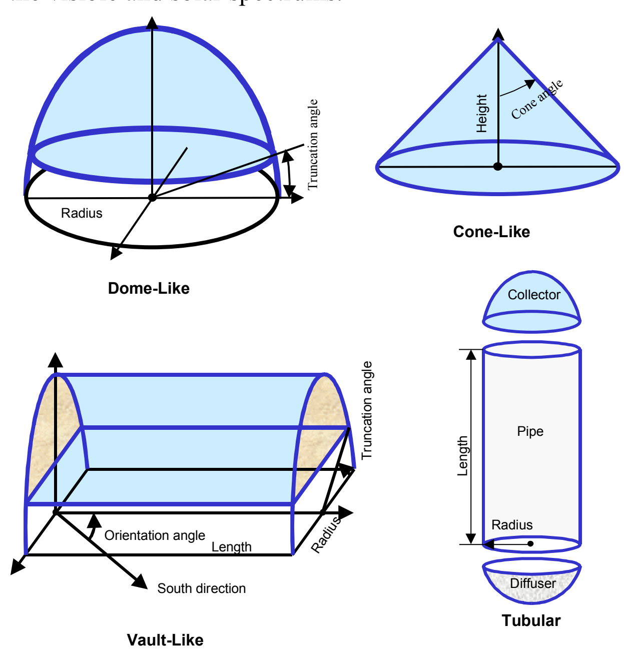

Figure 3 Skylight shape classes

Tubular Skylights

Tubular skylights are made of three components: collector, tube/pipe and diffuser (Figure 3). The collector is a hemispherical clear dome that collects solar rays. Inputs for the collector include the Shape Parameter and the glazing type. The glazing type is supplied from the attached glazing database. The tube or pipe channels solar rays (both beam and diffuse rays) downwards to the indoor space using a highly reflective lining. Inputs include the tube radius, length and surface reflectance. The diffuser is translucent and may take different shapes (flat, dome, rectangular, or other shape). Inputs include the Shape Parameter and the diffuse optical properties of the flat sheet the diffuser is made of.

ANALYSIS MODULES

These are the modules necessary to compute the output parameters (Figure 2). These modules are grouped into three categories: Optics modules, daylighting modules, and sky models.

Optics Modules

The skylight industry employs sophisticated glazing technologies. Most skylights have laminated glazing required for safety raisons. Tinted or solar reflective-coatings are usually employed in conventional skylights to reduce excessive solar heat gains. Low-e coatings are also used to reduce thermal heat loss. Therefore, optics modules have to accommodate all these technologies. These modules compute the optical characteristics of the glazing assembly, conventional skylights and tubular skylights. Glazing optics modules compute the optical characteristics of a composite pane (substrate and coating) and glazing assembly (set of composite panes separated by an air/gas space) at a given incidence angle. Optics modules for conventional/tubular skylights compute the overall optical characteristics of the skylight system under beam and diffuse lights for both solar and visible spectrums.

Daylighting Modules

Daylighting modules compute the outdoor and indoor daylight availability. These include modules to compute the outdoor horizontal illuminance for both beam light and diffuse light under different sky conditions, skylight well efficiency, Daylight Factor (for diffuse light), and indoor illuminance distribution at floor level and normal to walls (for combined beam and diffuse lights).

Sky Models

These modules compute or model the sky luminance patterns for the luminance-based or illuminance-based sky conditions. Sky conditions affect the optical characteristics of skylight and daylight availability. The considered sky models correspond to the sky condition inputs mentioned in Figure 2.

OUTPUTS

The software is used to analyse the optical characteristics and daylighting performance of skylights. The software is also used to produce rating data for a given skylight product under standardised conditions. The optical outputs include the skylight optical characteristics (transmittance, absorptance and reflectance) for beam light as a function of the incidence angle on a horizontal surface, and the optical characteristics for diffuse light as a function of daytime under a given sky condition (Figure 2). The software may also be used to output the optical characteristics of windows and flat skylights. Daylighting outputs include the skylight well efficiency, average Daylight Factor (for diffuse light) at room floor level and at different levels normal to walls, indoor illuminance distribution on the room floor, ceiling and walls (for combined beam and diffuse lights), and outdoor horizontal illuminance for beam and diffuse lights. Rating outputs include beam skylight transmittance at normal incidence angle; diffuse skylight transmittance under CIE overcast, IES partly cloudy and CIE clear sky conditions at noontime in a given location; Solar Heat Gain Coefficient (SHGC); and the ratio of the illuminated floor area to that of the skylight opening under CIE overcast, IES partly cloudy and CIE clear sky conditions at noontime in a given location.

PRELIMINARY RESULTS

Typical outputs of the software from the developed prediction models (project task 1) will be shown. These include transmittance of barrel vault skylights under beam light, transmittance of domed skylights under diffuse light from different sky conditions, and the average Daylight Factor on floor level and normal to walls. Other outputs and details are found in the references: Laouadi and Atif (1998), (1999), (2001a), (2001b), and (2001c).

Figure 4 shows the profile of the equivalent transmittance of barrel vault skylights as a function of the incidence angle on a horizontal surface for relative azimuth angles (difference between the sun and skylight azimuth angles) varying from 0° (sun parallel to the skylight axis) to 90° (sun perpendicular to the skylight axis). The equivalent transmittance is defined as the ratio of the incident light flux to the transmitted flux that reaches the skylight base surface. The skylight length-to-radius ratio is fixed at L/R=2, and truncation angle = 0°. The top surface of the skylight is grey-tinted with double glass (outer pane is grey and inner pane is clear). The gable surfaces are glazed with double clear glass. The transmittance profile of a flat skylight with double-grey glass is also plotted in the figure. Skylights with tinted top and clear gables gather substantially more beam light at high incidence angles (i.e., low sun altitudes) than do flat skylights. At incidence angle $\theta_z = 70°$, vault skylights may transmit between 122% to 293% more beam light than do flat skylights with similar top glazing, particularly when the sun is parallel to the skylight axis. The equivalent transmittance for incidence angles $\theta_z < 85°$ may reach up to 83% higher when the sun is parallel to the skylight axis (relative azimuth = 0°) than that when the sun is perpendicular to the skylight axis (relative azimuth = 90°).

Figure 5 shows the daily profile of the ratio of the diffuse equivalent transmittance (absorptance) to that of a flat glazing for double-clear, fully hemispheric domes during a typical summer day (June 24) in Ottawa, Canada. Transparent domes transmit (absorb) about 18% (80%) more than do similar flat skylights under uniform overcast skies, and 11% (58%) more under CIE overcast skies. The luminance-based models predict that transparent domes transmit (absorb) about 28% (47%) more than under standard CIE overcast skies under standard CIE clear skies, and 15% (25%) more under IES partly cloudy skies, particularly at low sun altitudes. The dynamic sky model predicts the equivalent transmittance and absorptance close to that under the IES partly cloudy skies, which was the case on June 24.

Figure 6 shows a comparison of the average Daylight Factor (DF) at floor level predicted using a newly-developed model and existing models under isotropic overcast skies for a square atrium with a 100% glazed roof. The skylight transmittance is fixed at 0.66. The floor and wall reflectances are fixed at 0.2 and 0.45, respectively. The developed model predicts the average DF values very close to the local DF values at the center of the floor predicted by the model of Liu et al. (1991). The developed model also yields average DF values close to those predicted by the model of Tregenza (1997), particularly for shallow atriums (Well Index, WI<1). Models based on physical scale measurements in artificial skies (Neal and Sharples 1992; Kim and Boyer 1986) overestimate the DF by up to 45% for atriums with WI<3 compared to the developed model. For atriums with WI>3, physical scale models yield approximately similar results as the developed model.

Figure 7 shows a comparison between the local DF normal to walls computed using the developed model, and the finite element method and scale-model measurements of Boubekri and Anninos (1996) under isotropic overcast skies. The well index of the sample atrium is fixed at WI=1.4 (length=31.25 ft, width=52.5 ft, and height =105 ft). The skylight transmittance is fixed at $\tau_{eq} = 0.7$. The floor and wall reflectances are fixed at 0.3 and 0.5, respectively. The predictions from the developed model compare very well with those from the finite element method and physical scale-model measurements, with a maximum difference of 13% occurring at the bottom level of the wall.

CONCLUSIONS

The paper presents an overview of new analysis software for the optical characteristics and daylighting performance of conventional and tubular skylights. The paper focuses on the software structure, input and output parameters, and analysis modules. The software will enable users to vary skylight shape, dimensions and glazing types, sky conditions, and characteristics of the indoor space below the skylight. The software will provide skylight designers with optical characteristics (transmittance, absorptance and reflectance) of the skylight system for direct sunlight and diffuse light, and the indoor daylight availability (Daylight Factor, or illuminance on the floor and normal to walls). The software development process spans over a four-year period, and addresses the development of prediction models for the optical and daylighting performance of different classes of skylight shapes, experimental and analytical validation of the prediction models and design of the software. Preliminary results from the developed models demonstrate their accuracy and utility.

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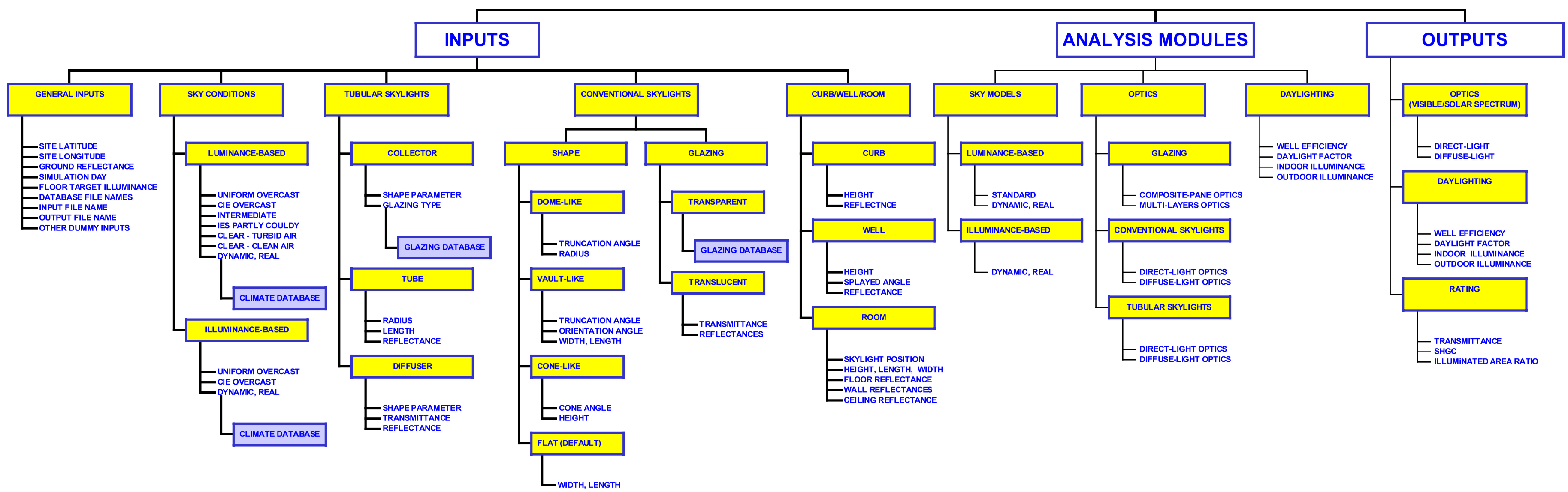

Figure 2 Flow chart of the inputs, analysis modules and outputs of the software

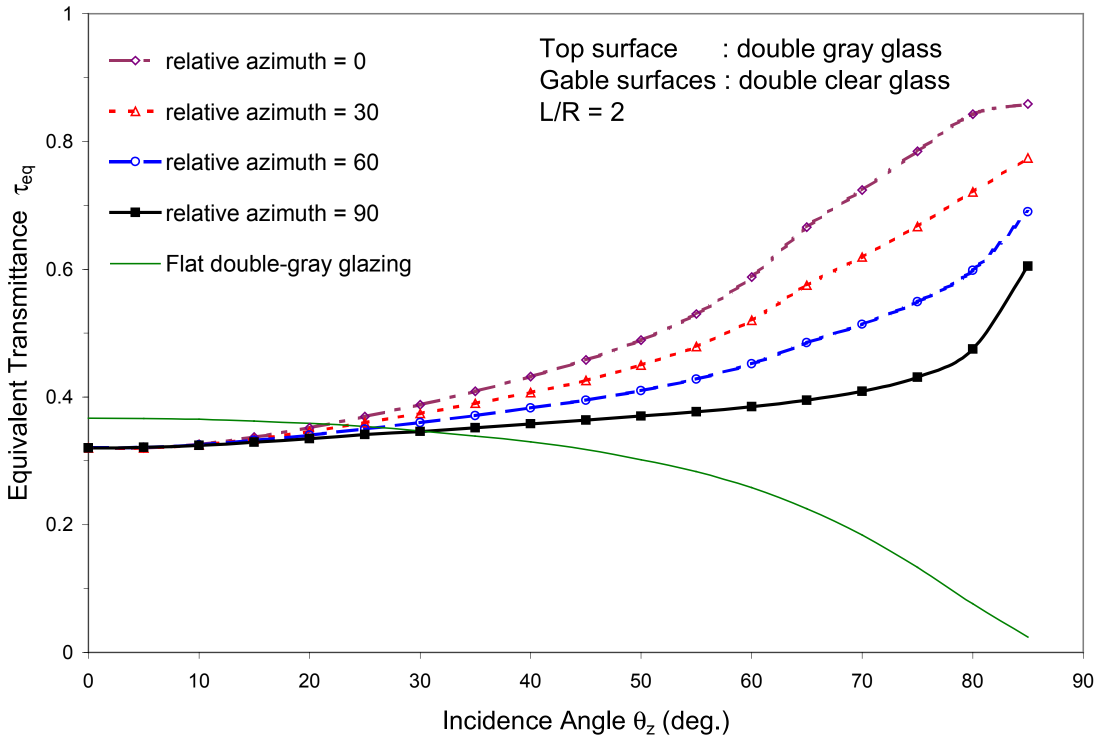

Figure 4 Profile of the equivalent visible transmittance as a function of the incidence angle on a horizontal surface for barrel vault skylights with tinted top and clear gables.

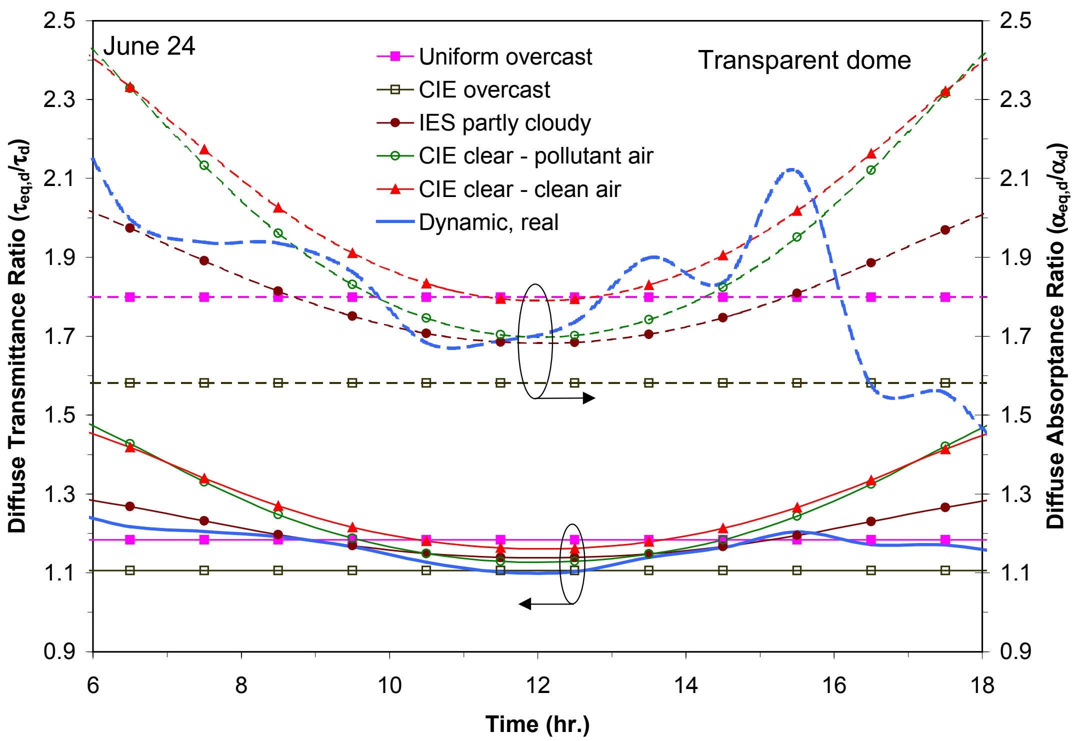

Figure 5 Daily profiles of the diffuse transmittance and absorptance ratios for transparent domes under standard and dynamic sky conditions during a summer day.

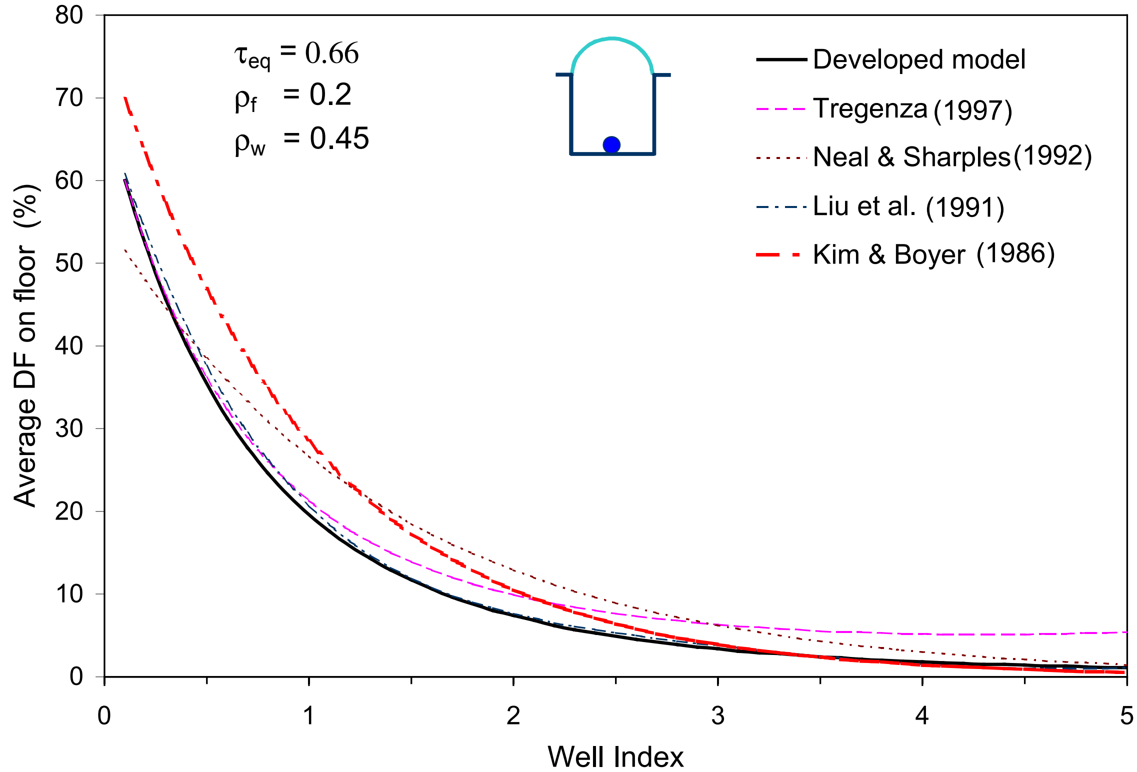

Figure 6 Average Daylight Factor on floor level of an atrium space

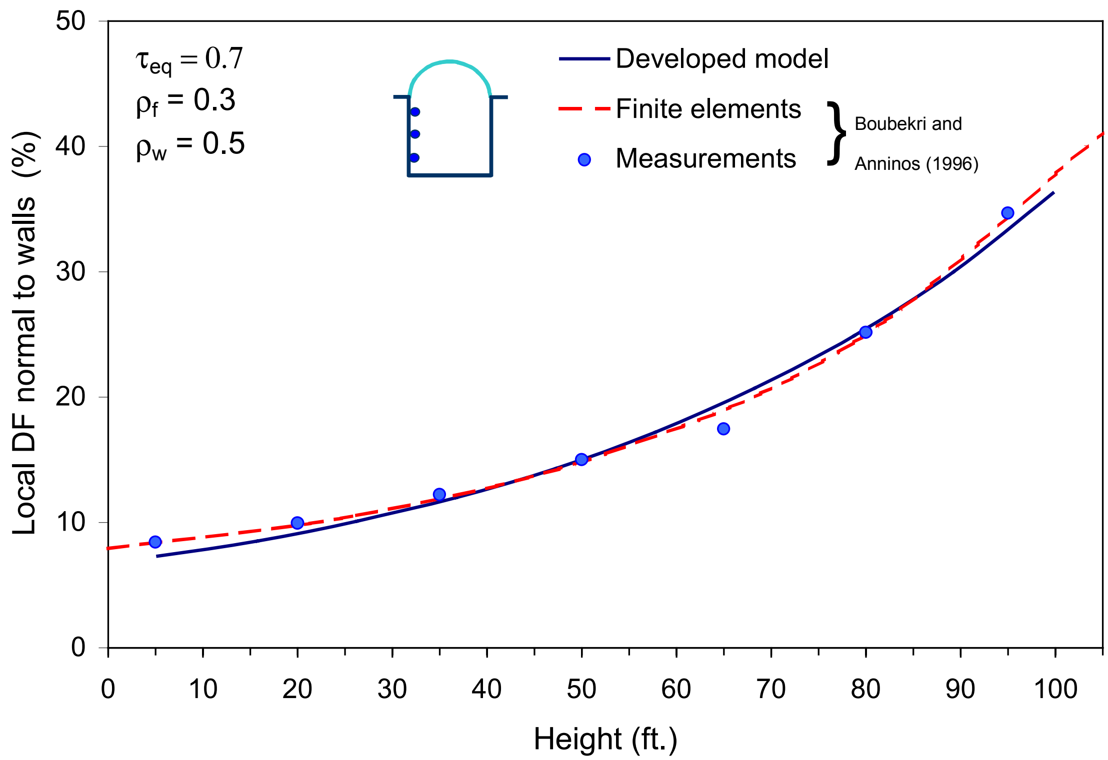

Figure 7 Local Daylight Factor normal to walls of an atrium