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Core Daylighting: A New Approach for Non-Residential Buildings

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NOTICE

PROJECT SUMMARY

Project Title:

Core Daylighting: A New Approach for Nonresidential Buildings

Performing Institution:

Solar Energy Research Institute
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Project Manager:

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Project Objectives:

To establish an analysis method to be used by design professionals and researchers in analyzing the performance characteristics of basic heliostat systems.

Project Status:

The project work in FY 1984 proceeded with an empirical and analytical investigation of three basic heliostat types:

- Azimuth tracking/fixed altitude system. In this system the primary mirror continuously tracks the solar azimuth while maintaining a constant altitude angle which is usually equal to the latitude.
- Altitude tracking/fixed azimuth system. In this system the primary mirror continuously tracks the solar altitude while maintaining a constant azimuth angle which is usually due south.
- Altitude/azimuth tracking system. In this system the primary mirror continuously tracks both the solar altitude and azimuth.

To thoroughly define the performance of a heliostat system requires an investigation of the lighting characteristics and distribution system of the heliostat as well as the lighting and thermal characteristics of the entire system.

Plans and Objectives for FY 1985:

The project team will continue to investigate the performance characteristics of heliostats by expanding the effort to include the distribution system's performance characteristics as well as the lighting and thermal energy performance characteristics. The final result of this effort will provide the researcher and the professional with the capability to analyze a heliostat system considering both lighting and energy issues.

Major Publications Related to Project:

Robbins, C. L., Hunter, K. C., 1984, A Method for Determining the Performance Characteristics of Daylighting Heliostat Systems, SERI/TR-254-2301, Solar Energy Research Institute.

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CORE DAYLIGHTING: A NEW APPROACH FOR NON-RESIDENTIAL BUILDINGS

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ABSTRACT

There is a considerable amount of research currently being conducted on a variety of advanced core daylighting concepts, although much of the effort is still in the early experimental stages. This research encompasses a wide variety of advanced concepts ranging from selective glazing materials to direct beam daylighting and includes innovative interior distribution systems such as optic fibers and "light pipes" [1,2,3]. This paper focuses on only these advanced concepts, daylighting heliostats, because there is sufficient research to report and because some heliostat systems are already being used to illuminate the interior of buildings.

Another new concept for daylighting buildings that is similar to heliostats is a polar axis rotating Fresnel lenses [4]. Concepts that are quite different and do not track the sun include holographic optical elements [5], wide angle nontracking lenses with image collapsing subreflectors and reflective cylinders [6]. An advantage of the nontracking systems is that they usually require less moving parts; however, all of these systems in one form or another concentrate or reflect direct illuminance into the building by imaging the solar disc.

DAYLIGHTING HELIOSTATS

Daylighting heliostats consist of either a primary reflector that directly illuminates the interior of the building or a combination of a primary reflector that tracks the sun in some fashion, and a fixed secondary reflector to reflect the sunlight into the building. This paper outlines a method developed to analyze the performance characteristics of heliostat systems that use a primary and secondary reflector system. Although there are several different heliostat systems that can be used for solar thermal applications, there are only three developed that use a primary/secondary reflector system for daylighting purposes. These are [7]:

- Azimuth tracking, fixed altitude systems
- Altitude tracking, fixed azimuth systems
- Altitude/azimuth tracking systems.

In azimuth tracking, fixed altitude heliostat systems the primary reflector continuously tracks the solar azimuth, but the slope of the reflector is fixed at a specified angle (usually equal to the latitude) and cannot track the change in solar altitude. In the altitude tracking, fixed solar azimuth systems the primary reflector continuously tracks the solar altitude but is fixed to a specific solar azimuth, usually due south. In altitude/azimuth tracking systems the primary reflector continuously tracks both solar altitude and azimuth. In all of these systems the secondary reflector is fixed in position. Further, to continuously track altitude, azimuth, or both, it is necessary for the heliostat to have an automatic control system, not a manually driven system.

The direct sunlight $E_{S,H}$ reaching a station point from a daylighting heliostat can be expressed as:

$$E_p = E_{S,H}C_a \,, \qquad \text{(lux)} \qquad (1)$$

where $E_{S,H}$ is the direct sunlight reflected into the aperture from the heliostat and C_a is a coefficient representing the maintenance characteristics of the glazing and the room. On a clear day, $E_{S,H,c}$ is determined from:

$$E_{S,H,c} = L_{out}CU \qquad \text{(lux)} \qquad (2)$$

and on an overcast day the interior illuminance is approximated by:

$$E_{S,H,o} = 0.85\ E_{SE,o} \,. \qquad \text{(lux)} \qquad (3)$$

The $E_{SE,o}$ variable can be determined using the lumen (daylight factor) or flux transfer methods as applied to overcast skies. The opening at the ceiling line is considered to be an unobstructed aperture.

The quantity of visible flux (lm) entering a building after being reflected from the primary to the secondary reflector and off the secondary into the building is the luminous output L_{out} of the heliostat. Luminous output is a variable used to determine the performance characteristics of most electric lighting systems. The luminous output from any of the three types of tracking heliostat systems is a function of the reflectivity (in the visible spectrum) of the primary and secondary reflectors, the size of the reflectors, and the luminous flux incident on the primary reflector. This can be expressed as:

$$L_{out} = E_i \cos i \, \rho_p \, \rho_s \, A_s \, T_g \, , \qquad (1m) \qquad (4)$$

where L_{out} is the total luminous output of a heliostat, E_i is the available exterior illuminance incident to the plane of the primary reflector of the heliostat, and i is the incidence coefficient. The terms ρ_p and ρ_s are the reflectivity of the primary and secondary reflectors. The area of the secondary reflector is determined by A_s, and T_g is the transmittance of the glazing usually placed between the secondary reflectors and the building. It is assumed that the areas of the primary and secondary reflectors are equal. The location of the glazing can vary depending upon system design. Therefore, the transmission characteristics can also vary; this is discussed in more detail later. The total lumen output of an individual luminaire is used to design the lighting system and establish the number of luminaires, in this case heliostats, needed to illuminate the interior of a building to a desired design illuminance.

Electric lighting systems are usually described in terms of candlepower and the candlepower distribution of the luminaire. These terms are not appropriate for daylighting systems as they describe a point source with diverging light rays. Although the rays leaving a secondary reflector are slightly diverging (2^o), they can generally be described as parallel. The total lumen output L_{out} provides a means to compare and analyze different daylighting heliostats as well as compare heliostat performance to electric lighting luminaires and other daylighting systems.

The performance characteristics of each heliostat system vary primarily with the method chosen to track the sun and the particular view of the sun and sky the primary mirror for each system "sees." These differences are primarily expressed in the incident illuminance term E_i and the incidence coefficient i. Because the view of the sky differs for each system, the thermal gains from the light vary, even though the primary light source is the sun. System performance can also vary depending upon the location of the glazing that separates the heliostat system from the building. For the azimuth tracking, fixed altitude daylighting heliostat the incidence coefficient i varies with the rotation of the primary reflector about a horizontal east-west axis with continuous automatic adjustments of the azimuth angle. The slope angle of the primary mirror is usually set to be equal to the latitude. The incident coefficient for such an arrangement can be described by:

$$\cos i = (1 - \cos^2 \delta \sin^2 \gamma)^{1/2} \, , \qquad (5)$$

where δ and γ are the solar declination and solar time, in degrees of longitude, respectively.

The incident exterior illuminance E_i falling on a primary reflector in this case is described in terms of the illuminance striking a surface of fixed tilt with a constantly changing view of sky. The illuminance from a clear or overcast sky striking a surface of tilt k is:

$$E_{Gk,c} = E_{GH,c} \cos k + E_{GV,c} \sin k \, , \qquad (6)$$

where $E_{Gk,c}$ is the total illuminance striking a surface of tilt k, $E_{GH,c}$ is the illuminance striking a horizontal, and $E_{GV,c}$ is the illuminance striking a vertical surface of a given orientation equal to the solar azimuth at all times.

In the altitude tracking, fixed azimuth system the primary reflector rotates about a horizontal north-south axis with continuous adjustment of the tilt of the reflector to obtain maximum incident light. The incident coefficient i assumes that the azimuth is fixed at due south. The term i can be described as:

$$\cos i = \sin \delta \sin \phi \pm \cos \delta \cos\phi \cos \gamma^{-2} + \cos^2 \delta \sin^2 (\gamma)^{1/2} \qquad (7)$$

where the term ϕ is equal to the solar altitude. The illuminance incident to the surface of the primary reflector E_i is determined by changing the surface tilt k to equal the solar altitude for each calculation.

For the altitude/azimuth tracking system the incidence coefficient i is described by the case in which the primary reflector rotates about two axes (east/west and north/south) with continuous adjustment to keep the surface normal to the incidence illuminance at all times. In this case cos i = 1, and the incident illuminance is approximately equal to the direct normal illuminance E_{DN}.

$$L_{out} = E_{DN}(\rho_s \rho_p) T_a A_s \, . \qquad (lux) \qquad (8)$$

The aperture through which the daylight from the heliostat must pass can typically be located in any of three locations:

- In front of the primary reflector
- Between the primary and secondary reflector
- Between the secondary and the building.

If the aperture glazing is located in front of the primary reflector it would mean that the heliostat is inside the building and the performance characteristics must be altered to represent the fact that any illuminance striking the primary reflector has already passed through the building glazing.

In the case of the glazing being placed between the primary and secondary reflector the incident angle i describes the angle between the primary reflector and the secondary reflector rather than between the sun and the reflector. In the case where the glazing lies between the secondary reflector and the building the average glazing transmittance can be used, T_g.

HELIOSTAT COEFFICIENT OF UTILIZATION

The performance characteristics described by the previous equations do not determine the illuminance at the workplane. They establish the total flux output at the ceiling line, which is then multiplied by the heliostat coefficient of utilization to establish the illuminance at a given station point. Table 1 illustrates a set of coefficients of utilization (CU) for a azimuth/altitude tracking heliostat.

These CUs were generated based upon the following assumptions:

- ceiling reflectivity (70%)
- wall reflectivity (50%)
- floor reflectivity (20%)
- interior reflector (70%)
- ceiling heights of 10 ft, 12 ft, 14 ft, 16 ft
- 2.5-ft horizontal workplane height
- station points at 5-ft intervals.

In the table the station point locations are placed at 5-ft intervals, beginning with a station point directly under the interior reflector and in line with the secondary mirror. This is station point 0; the next station point 5' is located 5 ft away, the next 10 ft away, 10'. Since the interior reflector is pyramidal, the resulting distribution pattern of the daylight in the space is in the form of a square with rounded corners. The approximate area daylighted by the heliostat for each station point is noted under the station point number. For example the station point marked 5' is equal to an area of 100 ft^2 that is illuminated to the level represented by the station point. The slope of the light well for the CU values in the table is measured from the horizontal at the ceiling line.

SAMPLE CALCULATION PROCEDURE

To calculate the $E_{S,H}$ it is necessary to use illuminance data in some form [8,9] and determine the E_{DN} term for the appropriate equation. For example 1000 h in June, in Denver, the E_{DN} is 85,950 lux. Assuming primary and secondary mirror reflectivity of 0.87, T_g of 0.75, and A_s of 2.75 ft^2 (0.84 m^2) and the area to be illuminated is 900 ft^2 (90 m^2) with a ceiling height of 10 ft, the luminous output is

$$\begin{aligned} L_{out} &= (85949)(0.87)(0.87)(0.75)(0.84) \\ &= 40{,}985 \text{ lumens}, \end{aligned} \tag{9}$$

and the illuminance $E_{S,H}$ at station points 0, 5', 10', and 15', in any direction on a work plane 2.5 ft above the floor is:

$$E_{p,0} = (40985)(0.021132) = 703 \text{ lux} \tag{10}$$

$$E_{p,5} = (40985)(0.021374) = 791 \text{ lux} \tag{11}$$

$$E_{p,10} = (40985)(0.023841) = 883 \text{ lux} \tag{12}$$

$$E_{p,15} = (40985)(0.014879) = 551 \text{ lux} . \tag{13}$$

These values represent the total absolute illuminance at the station point from daylight from an individual heliostat.

Table 1. Heliostat: Altitude/Azimuth Tracking

Ceiling Height	0	5' 100 ft^2	10' 400 ft^2	15' 900 ft^2	20' 1600 ft^2
Coefficients of Utilization CU: Vertical Light Well					
10'	0.002158	0.003596	0.004676	0.002517	0.001888
12'	0.001579	0.003158	0.003684	0.002632	0.001754
14'	0.001398	0.001849	0.003082	0.002055	0.001745
16'	0.001277	0.001713	0.002739	0.002050	0.001736
Coefficients of Utilization CU: 60° Sloped Light Well					
10'	0.021132	0.021374	0.023841	0.014879	0.014145
12'	0.018122	0.018168	0.020265	0.014357	0.013437
14'	0.015587	0.015892	0.015094	0.013835	0.012516
16'	0.012989	0.013236	0.012578	0.012570	0.011920
Coefficients of Utilization CU: 45° Sloped Light Well					
10'	0.015144	0.018173	0.019687	0.011055	0.010600
12'	0.012872	0.015446	0.016734	0.009940	0.009007
14'	0.010903	0.012721	0.012357	0.009952	0.008632
16'	0.009086	0.010600	0.010298	0.008995	0.008114
Coefficients of Utilization CU: 30° Sloped Light Well					
10'	0.010972	0.014387	0.020345	0.020344	0.013375
12'	0.009526	0.012229	0.017293	0.017239	0.012438
14'	0.009419	0.012184	0.016634	0.016616	0.009570
16'	0.009316	0.011487	0.013862	0.014836	0.009067

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