Session 2233

The Artificial Sky Laboratory at Oklahoma State University

Khaled Mansy, Ph.D.

Assistant Professor, Oklahoma State University

Abstract

Utilization of daylight is one of the most cost-effective energy-efficient strategies to design and engineer low-energy buildings. Integration between daylighting and electric lighting systems in commercial buildings results in a significant reduction in annual energy use and operating cost. As in other engineered systems, quantification of the performance of daylighting systems should dictate their design. In the US however, the majority of students of architectural engineering and architecture; architectural engineers; and architects currently use inaccurate rules of thumb and/or over-simplified methods to design and predict performance of daylighting systems. The Architectural Engineering Program at OSU is in the process of adopting and implementing the approach of testing daylighting scale models, which has proven to be able to accurately predict and quantify the performance of daylighting systems. With the support of the National Science Foundation (NSF), the school is currently in the process of building a cutting-edge daylighting laboratory, i.e., the **Artificial Sky Dome**. The new laboratory will help integrate the engineering of daylighting systems into the school's curriculum, with the anticipation that this will nurture the scientific background and design skills of undergraduate students. The secondary mission of the laboratory is to disseminate the same knowledge and/or skills between graduate students, faculty, and practicing professionals. The laboratory will also be an effective venue to integrate teaching and research. The specific outcome expected from this project is to enable OSU' students, and consequently OSU' graduates to effectively incorporate daylighting systems into the design of buildings, which should result in the conservation of energy used to operate buildings, and the mitigation of related negative environmental impacts. The paper reports on the need of daylighting laboratories and their relevance to achieve a sustainable future through the design of low-energy buildings. The paper also reports on the existing tools currently being used in the USA to test daylighting scale models. The design challenges of building the new laboratory that assures accurate testing and results will be discussed.

1. Scope of Interest

Integration of daylight into buildings saves energy directly and indirectly. As published by the Energy Information Administration [1], an average of 44% of the electricity consumption in office buildings in the US is consumed by artificial lighting systems. Furthermore, thermal load from electric lighting systems appears as a component of the internal thermal loads in conditioned spaces, which contributes to higher cooling loads and consequently higher cost of air conditioning. That is why minimal use of electric light is considered a fundamental strategy to minimize the use of purchased energy in commercial buildings. Utilization of natural light in lieu of or integrated with electric light in commercial and institutional buildings should result in a significant reduction of energy use and operating cost. Accurate evaluation of the performance of daylighting systems promotes improved design and allows the potential energy savings to take place while designing new buildings or retrofitting existing buildings. Optimum design of daylighting systems admits only the minimal amount of needed daylight without an "over-design" of the system that may admit much more daylight than needed, which may cause visual discomfort and/or unnecessary high solar heat gain in perimeter spaces.

1.1. The Problem

Building design community, namely architectural engineers, architects, and design students currently use over-simplified methods, i.e., rules of thumb and approximate mathematical methods as tools to size and design sidelighting (windows) and toplighting (skylights) systems. As explained below in section "1.2", each of these approximate methods ignores the impact of some fundamental variables that affect the performance of daylighting systems. The variables ignored include location, orientation, different sky conditions, location of openings (windows), ground reflection, and special designs like the incorporation of external reflectors (light-shelves) that reflect light deep into interior spaces. Although there are many computer programs that may assist in the design of daylighting systems, these programs are seldom used by building designers because of the significant time and effort spent to build 3D models in a digital environment. Besides, these programs require expertise that is normally hard to find and/or expensive to hire. Neither the simplified design methods nor computer programs are accurate when their results are compared to real measurements. On the other hand, the test of scale physical models to predict daylight performance proved to be the most accurate method of analysis, design, and evaluation of daylighting systems, especially when these systems are designed for special or irregular architectural forms [2], [3] & [4]. Results, from testing scale physical models, are proven to be the most credible and meaningful to evaluate both quantitative and qualitative aspects of daylighting. As part of the design process, the majority of architectural engineering and architectural students; and firms usually build accurate scale models, especially for their special and irregular designs. A common practice in architectural design is to use models to visualize ideas, forms, and explore alternative designs. The same models could be used to predict the performance of daylighting systems. The problem testing models is currently facing is that the test requires a carefully controlled luminous environment.

1.2. Simplified Design Methods

Rules of thumb, currently used to incorporate daylight into architectural design, give general recommendations such as: within a depth of 15 feet from the window wall system daylight is sufficient, and within 30 feet from the window wall system daylight provides 50% of required illumination level! In another rule of thumb, to a depth equals 250% of the difference in height between the workplane and the top of the window daylight is sufficient! Rules of thumb fail to take into account the impact of fundamental variables that include, but not limited to: size, design, and placement of windows; building location and orientation; hour in the day; target illumination level; and occupancy schedules. Simplified mathematical and graphical methods are based on pre-calculated data, which were previously obtained from testing physical models. Description of these models may not apply to other cases [4]. The simplified lumen method does ignore the impact of the design and placement of windows. The protractor method, first developed for the overcast conditions in the UK, does not give accurate results when used under clear sky conditions because it assumes an average uniformly distributed sky luminance, which is unrealistic. Using the protractor method is a very time consuming process. The high level of uncertainty, associated with the use of simplified mathematical and graphical methods, results in their limited use, if used at all.

1.3. Testing Models

The use of scale models is the most accurate method to analyze, design, and evaluate daylighting systems. It is simply due to the fact that in the model all the geometric variables that affect performance could be incorporated, i.e., size and placement of openings, light shelves, wall reflectances, inside and outside obstructions, and ground reflectance. Other advantages include:

- Accurate quantitative results, even when crude models are used.
- Ease of parametric analysis by changing a single design component every time.
- Familiarity of most designers with constructing and using scale models.
- Opportunity for qualitative evaluation (such as identification of potential glare problems) through visual observation or photography.

The use of scale models guarantees accurate results only when tested under an accurate simulation of sky conditions. The subject of sky conditions is discussed in section “1.4” below.

1.4. Sky Conditions

A major concern when testing scale models is that they should be tested under an accurate simulation of sky conditions. Under overcast skies, the relatively larger water particles diffusely refract/reflect all wavelengths equally in all directions. This results in a white-colored sky, about three times brighter at the zenith (directly overhead) than at the horizon (Figure 1). On the other hand, under clear sky conditions the sky light becomes a diffuse light resulting from the refraction and reflection of sunlight as it passes through the atmosphere, and the sky becomes darkest 90 degrees from the sun and brightest near the sun (Figure 2). Sky luminance becomes a function in the position of the sun in each hour, in each day, in the year [5]. An artificial sky dome is needed to simulate these different sky conditions. Currently, methods of sky conditions simulation, being used in American universities, do not provide accurate sky simulation. Next section “1.5” will discuss these methods.

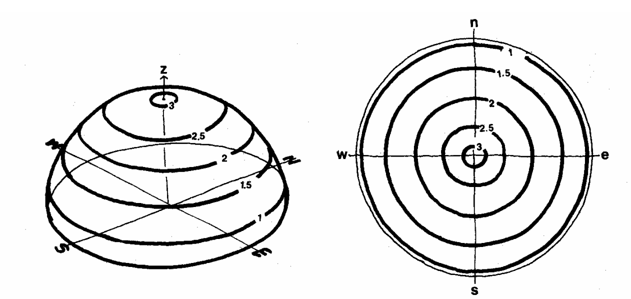


Figure 1: Overcast Sky Conditions

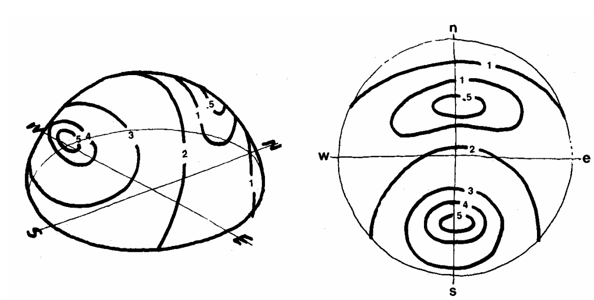


Figure 2: Clear Sky Conditions

1.5. Simulation of Sky Conditions

In American universities, different versions of the "Sun Emulator", also known as the "Heliodon" are used (Figure 3) and (Figure 4). The Heliodon simulates apparent solar movement in the sky and does not combine that with the effect of the Sky Dome, that is why it can only be used to evaluate impact of solar control strategies, but not to evaluate performance of daylighting systems. Using the Heliodon to simulate overcast sky conditions is impossible [6] & [7]. To simulate the overcast sky conditions, the "Luminous Ceiling in a Mirrored Box" can be used [8]. However, using the "Luminous Ceiling in a Mirrored Box" to simulate a combination of sky component and direct beam is impossible.

Testing scale models in the outdoor under real sky conditions proved to be impractical because of the ever-changing luminous intensities and the inability to test models under variety of sky conditions in a reasonable time frame.

Testing scale physical models should be performed under a controlled (indoor) luminous environment that can simulate the three components of daylight, i.e., direct sunlight, diffused sky, and ground-reflected.

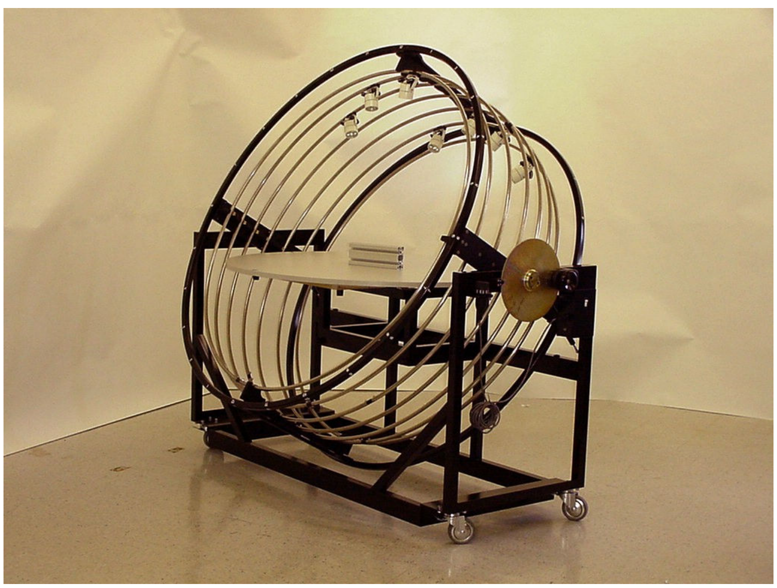


Figure 3: Flat Table Heliodon

Figure 4: Tilting Table Heliodon

The "Artificial Sky Dome" is the right answer to the question of "Simulation of Sky Conditions". The proposed "ARTIFICIAL SKY DOME" is capable of simulating both conditions required for the testing, i.e., overcast and clear sky conditions. The model of artificial sky, as will be described, does not exist in the US. Recently an artificial sky dome was constructed in the environmental laboratory in the Welsh School of Architecture of Cardiff University, UK, funded by the British HEFCW. The dome was opened mid 1999. A modified version of that facility will be built, supported by funding from NSF, in Oklahoma State University.

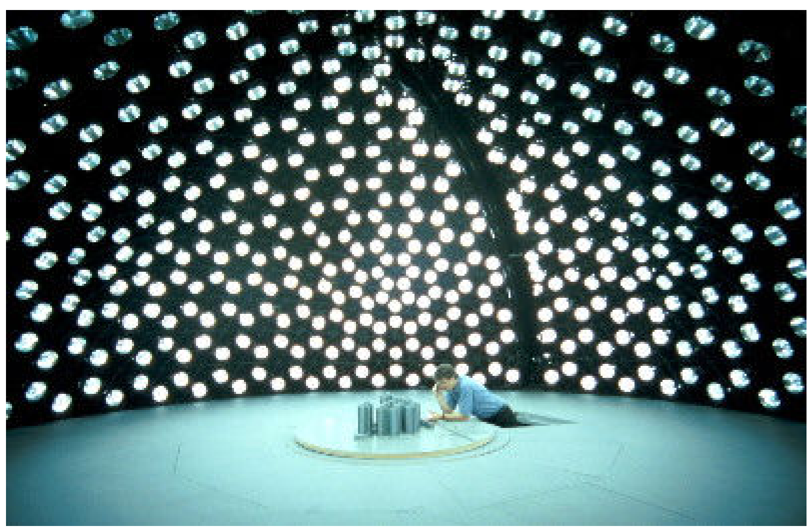
2. Detailed Project Plan

In conclusion, physical models should be tested in a controlled luminous environment that allows simulation of different sky conditions in different geographical locations. The new daylighting laboratory, the "Artificial Sky Dome" is able to provide this possibility of simulating different sky conditions. The Artificial Sky Dome is capable of accurately simulating ambient daylight conditions, due to sun, sky, and reflections from the ground and nearby structures [9].

2.1. Description of the Artificial Sky Dome

The dome contains a number of individual luminaires uniformly distributed over the inside surface of the dome (Figure 5). The luminaires contain lamps, which can be selectively dimmed to model the luminous distributions of different types of sky conditions, i.e., overcast, clear, or mixed. A computer controls the lamps and individually dims them, in a range between 100% and 3%, to model the appropriate luminous distribution. The dome also contains a heliodon, which can move to match the sun position as appropriate for the time, date, and location being studied. One modification is proposed in the design of the new Sky Dome at OSU. The addition of reflectors behind the luminaires to create a more homogeneous illuminating surface will help enhancing the readings taken inside the model. Observations showed that, due to the small size of models and light sensors, a set of readings might show inconsistency if sensors see point sources of light. Diffusers will also be used in front of the luminaires.

Figure 5:
The Sky Dome, as constructed in Cardiff University, UK



2.2. Design and Installation of the Laboratory

During the academic year 2003/2004 the dome and the lab are currently in the design phase. The author, who is the Principal Investigator for the NSF grant, in consultation with structural and power control experts are in the final stages of the laboratory design.

In the academic year 2004/2005, all equipment and instrumentation are expected to be ready for installation. The author will supervise the installation of the equipment, supervise the creation of the laboratory's website, and prepare for the opening of the laboratory including workshops to educate faculty and presentations to inform the design community in the state of Oklahoma.

2.3. Implementation of Testing Models into the Curriculum

The author will administer the laboratory to make it accessible to undergraduate and graduate students; and faculty in OSU. The implementation of testing daylighting models into the curriculum will take place through the following activities:

- Using the laboratory in teaching the two required Environmental Control courses for undergraduate students in the School of Architecture, OSU.
- Using the laboratory in teaching an advanced Environmental Control course that focuses on the design for daylight.
- Using the laboratory in the analysis, design, and evaluation of daylighting systems incorporated into the design work of the students in the upper-level design studios, i.e., third, fourth, and fifth year studios; the comprehensive design studio; and the competition studio. The laboratory will be open to the students on a 24-hour basis with a TA or a faculty available for consultation.

When testing models, students determine the daylight factor distribution by taking readings of the outside and inside illumination levels (Figure 6). The question then becomes "how to translate the readings taken from the model into a quantitative estimation of resulting energy saving?" The procedure, described below, answers this question.

Figure 6: Students at OSU in preparation of a test model.

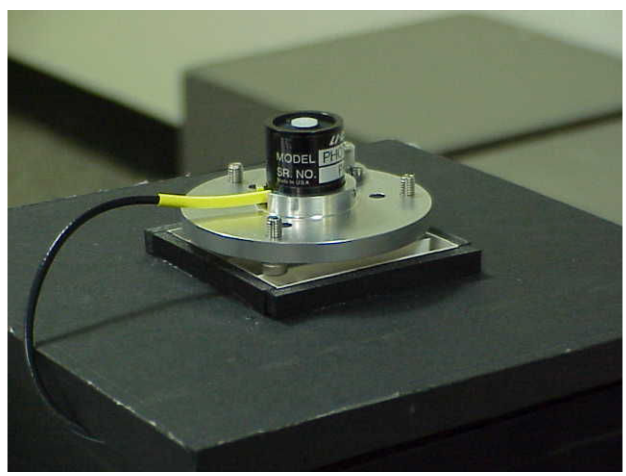


Figure 7: Reading the outside illumination level using a light sensor.

The readings inside the model are taken on a two dimensional grid that has the same height of the workplane. The outside and inside readings are used to determine the daylight factor at each grid point (Figure 7). To calculate interior illumination levels, values of the daylight factor are multiplied by the standard outside illumination level in the target location in the four seasons, i.e., fall, winter, spring, and summer. When actual distribution of illumination level is obtained, the numerical values should then be compared to the target illumination level required for the type of activity performed within the space. Percentage savings due to incorporation of daylight then could be quantified. However, to translate the percentage saving in the light energy into dollar amount, a base case electric light system should be designed for the space in order to calculate the energy cost for that system. For detailed technical information on the calculation procedure, please refer to the article: "Mansy, *A Simplified Method to Quantify Savings due to Incorporation of Daylight into Architectural Design*, Solar 2003, pp. 797-802, Austin, Texas, June 21-26, 2003. In this simplified method, Excel worksheets are used to do the aforementioned mathematical procedure, and proved to be very effective and easy to use and understand by undergraduate students in OSU. The author used the same mathematical procedure in teaching the advanced environmental control course in which the students showed real interest, improved understanding of the subject, and appreciation of the results before hand. The use of a digital camera to document the model and the experiment is highly desired.

3. Conclusion

In conclusion, this Daylighting Laboratory should be considered as a model to be adapted in other parts in the country in other educational institutions. This should allow students and professionals accurately evaluate the quantitative and qualitative aspects of daylighting systems in a way that should eliminate the uncertainty in this field. A better design of daylighting systems in buildings will result in significant energy saving and higher quality spaces to live and work in.

4. Bibliography

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5. Biography

The author is an Assistant Professor in the Architectural Engineering Program, School of Architecture, Oklahoma State University. He earned his Ph.D. from Illinois Institute of Technology, Chicago, 2001, and has 15 years of experience in undergraduate teaching in professional programs in the USA and Egypt.