CHAPTER I

INTRODUCTION

1.1 STATEMENT OF THE PROBLEM

The main objective in designing a modern atrium building is to provide the occupants with a thermally and visually comfortable indoor environment by using the atrium space as a thermal buffer space and daylight collector. Daylighting and sunlighting are key functions of atria, not only to conserve energy in buildings owing to the reduced energy requirements for electric lighting and thermal conditioning, but also to provide occupants with comfortable indoor environments. Proper use of the ample natural light in atria has a great potential to reduce initial costs by allowing smaller thermal conditioning equipment and fewer lighting fixtures. Furthermore, atrium spaces can be used for a variety of activities for extended periods of time over the year owing to the increased thermal and visual comforts.

Good daylighting in atria can be achieved by critically judging lighting design criteria and properly controlling the intensity and distribution of available daylight to meet those design criteria (Navvab and Selkowitz 1984). Previous studies (Boyer 1990; Boyer and Oh 1988; Gillette and Treado 1988; Kim and Boyer 1988; Navvab and Selkowitz 1984) suggested preliminary and general design guidelines relative to daylighting performance levels. The previous studies also identified daylight availability, configurations of fenestration system and atrium well, wall surface reflectance, and light collecting system of adjacent spaces as the most important parameters to be carefully treated. These parameters determine the intensities of incoming daylight and solar radiation and the spatial distributions of the daylight in the atrium space and the adjacent spaces. Improper decisions on these parameters may result in glare problems and solar heat gains within the atrium space during the daytime. Another negative result caused by inappropriate design may be insufficient illuminances for interior trees/gardens and adjacent spaces. Other studies (Boyer and Kim 1988; Degelman et al. 1988) introduced models to predict daylight illuminance levels specifically in atrium spaces based on illuminance measurements inside actual atrium spaces and/or scale models.

The style of this dissertation followed that of ASHRAE Transactions.

Even though the design guidelines suggested by the previous studies can give useful insight to building designers, actual design processes still require more suitable evaluation tools and specific performance data for key design parameters. In addition, many existing prediction algorithms were developed without fully considering the effects of direct sunlight penetrations. Since the direct sunlight almost always penetrates through non-north-facing canopy systems causing greater peak cooling load and glare problems, it is necessary to evaluate impact of direct sunlight when predicting and assessing daylighting performances in atria.

As identified by the previous studies, configurations of atrium well and canopy system are the most important design parameters which have major impact on light intensity and spatial distribution in atria. However, previous guidelines were mostly based only upon the measured and/or calculated illuminances inside atria. The previous studies did not explain how daylight and sunlight were admitted and distributed in the atrium space and finally delivered to the reference points. It was mainly because the complex transmission and distribution characteristics of daylight and sunlight by complex canopy structures and glazing systems could not be evaluated by previous daylighting evaluation tools. Measurements using photometric sensors may record illuminances at the reference points, which are the final products of direct illuminations and interreflections among the surfaces inside atria. By this method, however, it is impossible to explain how the daylight and sunlight behave within atria after being transmitted through the canopy systems. On the other hand, computer models based on lighting physics and empirically obtained algorithms are good vehicles to predict average daylighting performances throughout the year for geometrically simple atria. However, actual situations often involve highly complicated geometric configurations of both atrium canopy systems and wells which might be far beyond the capabilities of computer models. Furthermore, the complicated transmission, reflection and absorption characteristics of transparent, tinted or translucent glazing materials for canopy systems and interior windows are more difficult to analyze using computer models.

In order to properly address the effects of key design parameters on atrium daylighting, not only measurements and/or calculations of illuminances, but analyses of luminance distributions on interior surfaces must be conducted. In this respect, the current study focuses on developing instrumentation systems suitable for atrium daylighting studies and on deriving the daylighting and sunlighting performance data of various atrium canopy systems from parametric scale model measurements.

1.2 BACKGROUND

Throughout history daylighting has been an important factor in the design of buildings, because daylight has been the primary source of light, supplemented by burned fuels. In addition to interior illumination, daylight has been symbolic of cleanliness, purity, knowledge, and heaven (Moore 1986). Indeed, the form of a building was substantially influenced by the decision about the role of daylighting. As a means of admitting daylight into the space, windows have always held a special place in architecture. For example, Gothic architecture developed the fenestration as part of the whole structural system; and Renaissance architecture can be characterized by the rhythmic repetition of elaborate window units (Bell 1973).

However, during the 1960s, as high-efficiency electric lighting systems and centralized air-conditioning systems were developed and energy costs were relatively low, those once graceful skills were ignored or forgotten. Extreme cases included buildings that produced occupant satisfaction which was due solely to electrically and mechanically controlled visual and thermal environments.

The oil embargo in 1973 and the subsequent large increases in energy prices forced every sector of the economy to reevaluate its energy use practices (Selkowitz and Griffith 1986). In the architectural field, building designers began to make every possible attempt to reduce energy consumption in nonresidential buildings. Lighting was a major target of this action because electric lighting in nonresidential buildings consumes 25 to 60% of the electric energy utilized (Stein and Reynolds 1992, p. 966). Consequently, architects initiated ways to utilize plenty of good quality daylight for interior illumination. Sawtooth roofs, skylights, clerestories, double- and triple-lighted rooms, tinted glass, and all sorts of techniques were tried in an effort to utilize the daylight where it was thought to be needed (Evans 1981, p. 2).

Now this trend is well reflected by the increasing number of atrium spaces which represent major design features in newly constructed non-residential buildings. There are hundreds of recently constructed atrium buildings comprising office, institutional, civic, housing, hotel, retail and mixed-use buildings (Bednar 1986, p. 140). Designers now widely acknowledge that atrium spaces serve many functions in a variety of building types. Even though the existing atrium buildings might be initiated with different design approaches such as daylighting, thermal and/or urban designs, the buildings are still symbolized by plentiful daylight, visually interesting sparkling sunlight patches continuously moving throughout the day from day-break to dusk, and cool water fountains and green plants in the atrium spaces.

Economically, it may cost more to build an atrium building, because there is more roof area with expensive skylights and the need for fire and smoke control systems. In addition, an atrium building requires more site area because of the larger footprint. However, these negative economic arguments are offset by the high rental rate and marketability (Saxon 1987, p. 2). In other words, atrium buildings are more attractive to office tenants, shoppers, hotel guests, or apartment residents. Another important economic aspect of an atrium space is the inherent energy potential of this spatial type. An atrium can contribute to passive heating and always allows more daylight to the spaces which surround it.

The glass and metal canopy systems invented in the 19th century permit the modern enclosed atrium space to provide desirable light and view but protect it from undesirable effects of climates. The development of canopy systems has progressed very rapidly in recent years, expanding design possibilities while solving difficult technical problems. Consequently, the design criteria for canopy systems have also grown more stringent as the design possibilities have continued to expand (Bednar 1986, p. 113).

The atrium space itself should provide sufficient illuminance for pedestrian circulation and casual tasks, because modern atrium spaces are frequently used as hotel registration area, cocktail lounge, and leisure spaces. The recommended illuminances for the general circulation areas range from 50 lux to 200 lux (IESNA 1993, p. 460; Stein and Reynolds 1992, p. 938). However, interior plants and even small trees require a much higher illuminance range from 700 lux to 2000 lux over a substantial period of hours each day (Boyer 1990; Saxson 1987, p. 150; IESNA 1981, pp. 19-32).

In addition, occupants inside the atria often prefer sparkling sunlight patches to totally diffuse daylight, because small areas of sparkle do not cause glare but add visual interest to objects in the space and attract attention (IESNA 1993, p. 610; Lam 1986, p. 162).

1.3 OBJECTIVES

The goal of this study was to provide building designers with significant daylighting and sunlighting performance data for sunlit atria with different well configurations and different canopy systems which can be referenced during the early stages of an atrium design. This study focused on parametric evaluations of the effects of atrium canopy systems with different geometric structural configurations and glazing options on illuminance levels and luminance distributions. To achieve this goal, the specific objectives of this study were defined as follows:

1) To develop instrumentation systems which can overcome the limitations of conventional evaluation tools for effective assessment of atrium daylighting and sunlighting design options.

2) To investigate the effects of atrium geometry on illuminance levels falling on the atrium floor and luminance distributions on the walls without canopy for different sky and sunlight conditions.

3) To investigate the effects of different types and photometric parameters of atrium canopy systems on illuminance levels and luminance distributions in atria for different sky and sunlight conditions.

4) To identify suitable canopy systems for sunlit atria in different geographic locations.

The overall procedure of the current study and the methods to address these objectives will be discussed in the following section.

1.4 APPROACH

1.4.1 Literature Review

At this stage, literature for general information and lighting criteria related with atrium daylighting were reviewed.

First, daylighting design and evaluation issues and conventional daylighting evaluation tools were reviewed. Then, capabilities and limitations of the conventional tools were critically assessed in order to identify what kind of instrumentation system should be developed to address the objectives of the current study.

Second, objectives and criteria of architectural lighting were identified. Then, the criteria of illuminance and luminance ratio in the atrium space were defined for the current study.

Third, general daylighting concepts in atrium buildings were reviewed in order to identify the relative importances of the key design parameters in atrium daylighting and sunlighting.

Finally, the taxonomy of atrium and canopy types were reviewed in order to characterize types of atria and canopy systems. In addition, approximate transmittance data of glazing materials were identified and their optical characteristics were reviewed.

1.4.2 Instrumentation Systems

At this stage, necessary instrumentation systems and computer programs for lighting measurements and calculations were obtained and/or developed.

First, the primary daylighting research facilities were a large sky simulator and an artificial sun at Texas A&M University.

Second, two photometric instruments were obtained. An Illuminance Data Acquisition System (IDAS) consisting of eight photometric sensors and an analog-to-digital signal converter was obtained to measure illuminance values. A spot luminance meter was obtained to measure luminance values at target spots.

Third, a video-based luminance mapping system was developed and calibrated during a pilot research project (Boyer and Song 1991-1993) for this study. This system employs a video-based image capture hardware and a series of customized digital image processing programs. The main use of this system was to determine geometric parameters (configuration factor or sky factor) and photometric parameters (luminance and illuminance) of canopy systems and interior surfaces by mapping and analyzing the luminance distributions inside atrium spaces. The accuracy of this system in determining the luminance and illuminance values was validated by comparing the calculated values with those measured by the spot luminance meter and IDAS.

Finally, an integrating box was constructed to measure hemispherical transmittances of atrium canopy systems under clear and overcast sky conditions.

1.4.3 Experimental Design

First, the schematic approach to lighting measurement was discussed. Second, key research variables to be treated in this study were defined based upon the findings from the literature review.

Third, generic scale models of atria and canopy systems with different geometric and photometric configurations were constructed. To make the scale models represent more realistic conditions, the glass windows of adjacent occupied zones were simulated by clear plastic sheets. In addition, typically used glazing materials having different optical transmission characteristics were used to cover the canopy openings to obtain more realistic daylighting and sunlighting performance data.

Finally, matrices of illuminance measurement cases were developed.

1.4.4 Data Acquisition

At this stage, parametric data of the daylighting and sunlighting performances of various atrium canopy systems were obtained using scale models and the various instrumentation systems.

First, exterior and interior daylight illuminances were measured on the atrium floor by IDAS with all the combinations of the atrium and canopy systems under overcast and clear sky conditions generated by the sky simulator. Then, sunlight illuminances were measured using the artificial sun for noon hours of three different seasons (June 21, September 21, and December 21) at three different geographic locations including Houston, TX, Oklahoma City, OK, and Minneapolis, MN, representing hot, temperate, and cold climates, respectively. Then, the measured illuminance values were converted into Daylight Factors (DF) and Sunlight Illuminance Ratios (SIR). The variations in these two quantities were the primary identifiers of canopy performance for different atrium configurations and different sky and sun conditions.

Second, luminance distributions inside atrium spaces under different sky and sun conditions were recorded using the video-based luminance mapping system. Even though the DFs and SIRs were the primary identifiers of canopy performance, they could not explain why and how the different geometric and photometric configurations of canopy systems affect the illuminance values measured on the atrium floor. Since the measured illuminance value at a point on the atrium floor is the integration of the luminances on the surfaces which can be viewed from that point, the mapped luminance distributions were analyzed to explain the resultant variations in DFs and SIRs.

Finally, Hemispherical Transmittances (HT) of the canopy systems were measured under clear and overcast sky conditions with the specially constructed integrating box. The Hemispherical Transmittance (HT) value is a unique measure of the light flux transmitted through a canopy system relative to the light flux transmitted through the same area of opening without the canopy. It is mainly dependent upon geometric and photometric configurations of canopy systems and exterior sky condition; and is independent of atrium configuration. Even though it was not dealt with in this study, with the HT values and DF values obtained with canopy systems, the Coefficient of Utilization (CU) values can be calculated using the equations of Lumen Method for toplighting provided by IESNA (IESNA 1993, p.373). With the CU values, if the HT value of a designed canopy system is known, corresponding DF values can be calculated for different atrium configurations.

1.4.5 Data Analysis and Results

At this stage, the data obtained from the lighting measurements were analyzed to summarize the findings of this study.

First, the net effects of atrium well configuration on illuminance levels and luminance distributions under diffuse sky conditions were determined by analyzing DF values and luminance distributions obtained with uncovered atria. Then, these DF values were defined as Base Case Daylight Factors (BCDF).

Second, the effects of different canopy systems were determined by analyzing DF values and luminance distributions obtained with canopy-covered atria. For this purpose, Effective Transmittance (ET) values were calculated for every combination of canopy system and atrium configuration by dividing the canopy-covered DF values by the BCDF values. As implied in the term, the ET values represent the effects of canopy systems on daylight illuminances relative to the effects of uncovered atria. Therefore, the ET values can characterize the daylighting performances of various canopy systems. Since existing empirical formulas (Boyer and Kim 1988) and mathematical models (Windows and Daylighting Group, LBL. 1985) can fairly accurately calculate DF values in uncovered aria, one can determine the BCDF values for an uncovered atrium space using those design tools, then can determine final DF values with designed canopy systems by multiplying the BCDF values by the ET values.

Third, the same analyses were performed with the SIR data to examine the effects of atrium well configuration and canopy systems on sunlight illuminance levels and luminance distributions. In addition to the photometric properties (illuminance and luminance) of the sunlight inside atria, the geometric properties (locations and sizes) of sunlight patches were examined for potential glare discomfort and potential visual interest.

1.4.6 Selection of Canopy Systems and Field Application

At this stage, suitable canopy systems were selected for atria with different well configurations in different geographic locations. The selection procedure utilized the conventional Daylight Factors (DF) and Sunlight Illuminance Ratio (SIR) values to maintain recommended interior illuminance levels (1000 lux in this study). In addition, it includes a new qualifier involving geometric properties of sunlight patches on atrium walls for potential glare problems and potential visual interest owing to sparkles.

Then, the instrumentation systems and findings from this study were applied to an existing atrium building (Kleberg Animal and Food Science Center at Texas A&M University) which was examined in a previous study (Kim et al. 1985).

First, a scale model which duplicated major atrium features (such as Well Index, wall reflectance, and the configuration and reflectance of the canopy) was constructed.

Second, the daylighting illuminance levels of the existing canopy and those constructed for the parametric lighting measurements were compared for clear and overcast sky conditions.

Finally, to demonstrate the usefulness of the video-based luminance mapping system in analyzing existing daylighting conditions, an on-site illuminance measurement and luminance mapping were conducted in the building.

Figure 1.1 shows the general procedure of this study as discussed in this section.

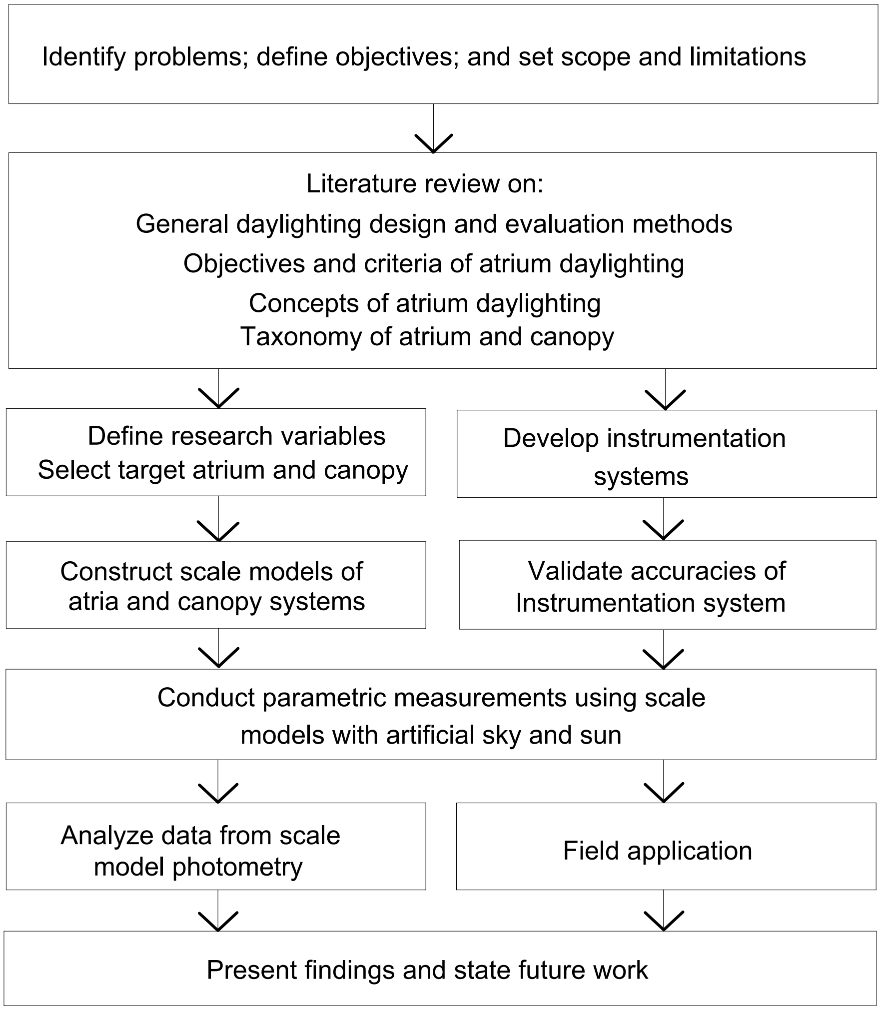

Figure 1.1 General Procedure of the Study

1.5 SCOPE AND LIMITATIONS

This study focuses on the daylighting and sunlighting in the atrium space itself. It does not deal with the daylighting in adjacent spaces which surround the atrium. The lighting and thermal conditioning equipment energy requirements for overall building structures are not included in this study. Since this study focuses upon parametric analyses of the daylighting and sunlighting effects of atrium canopy systems, all measurements are conducted inside scale models with a sky simulator and an artificial sun.

The target canopy systems analyzed in this study are generic types which are constructed to obtain selected parametric values. The scale models of atrium spaces are also generic four-sided square atria which are created by stacks of rectangular boxes made of cardboard sheets. However, one atrium scale model and canopy system of an existing atrium building is constructed to demonstrate field application method.

In order to simulate more realistic atrium spaces, the specular surface texture of the windows of adjacent spaces are simulated by clear acrylic sheets. Also, the openings of canopy systems are covered by typically used real glazing materials for which light transmittance values are specified by the manufacturer. The reason for using the real glazing materials is that not only the transmission, but also the reflection and absorption characteristics of the canopy glazing materials are considered significant.

In this study, the performance identifiers are Daylight Factor (DF) and Sunlight Illuminance Ratio (SIR) which are the ratios of interior daylight and sunlight illuminance levels to exterior daylight and sunlight illuminance levels, respectively.

To examine potential glare problems, a new concept "Luminance Index" (LI) are developed. Luminance Ratios (LR) between two contiguous wall areas (solid wall area and window area in this study) are calculated from the average LI values on the wall areas.

Furthermore, a new method is developed to quantify the geometric properties of sunlight patches on the atrium walls, which can add liveliness and visually interesting sparkles to the atrium space. This method determines Sunlight Patch Locations (SPL) and Sunlight Patch Sizes (SPS) from the digitized video images captured inside sunlit atria.

Finally, the sky conditions for the scale model measurements simulated in this study include completely overcast sky, clear sky without sun, and clear sky with sun. A partly cloudy sky condition is not included because of its infinite variability.