Potential of innovative daylighting and passive cooling systems for achieving luminous and thermal comfort in commercial buildings

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ABSTRACT

This paper presents the analysis and evaluation of innovative daylighting systems and passive cooling techniques implemented in a typical commercial building. The main objectives are the application of innovative daylighting and passive cooling systems to obtain energy savings and to provide thermal and luminous comfort conditions for the occupants. The case study building selected for investigation is located in Mexico City. Assessments of the occupants' perception of the ambient conditions indoors were obtained through interviews and questionnaires, and conducted concurrently with a monitoring stage of the thermal and luminous conditions inside the building. A thermal simulation program was used to compare the existing and new conditions with the design alternatives implemented in the building. The daylighting design alternatives proposed for the case study were tested using 3-D physical scale models for evaluating their daylighting performance.

The results indicated that these alternatives have the potential to reduce the use of electricity whilst providing luminous comfort conditions for the occupants, both quantitatively and qualitatively.

For the thermal behavior, it was shown that the passive cooling techniques investigated can effectively reduce the use of air-conditioned systems whilst providing thermal comfort for the occupants. Therefore, the daylighting and passive cooling systems investigated can offer important benefits when applied massively and to provide also significant advantages, not only from the ambient comfort and economic points of view, but also for the benefit of the environment and the people, as they are aimed at the application of a healthier and sustainable approach in buildings and at the improvement of people's quality of living.

1. INTRODUCTION. INTEGRATION OF BIOCLIMATIC DESIGN WITH SUSTAINABLE TECHNOLOGIES

Contemporary buildings, mainly in urban centers are responsible for a significant consumption of fossil fuels, which in turn provokes the emission of large quantities of pollutants to the atmosphere. This situation causes the consumption of large quantities of energy and thus high running costs for both artificial lighting and air-conditioning, associated with problems of occupants' discomfort, both thermal and visual. Furthermore, most of these buildings incorporate architectural styles and materials that ignore the local climatic conditions as well as the cultural, social and economic interactions. Therefore, the vast majority of these buildings are not only highly dependent on artificial electromechanical systems, but consume also large quantities of energy, coming mainly from fossil fuels for cooling, heating, ventilation, humidification, dehumidification, and for lighting of the architectural spaces, as well as for water heating and cooking. Most of these needs, if not all, can be fulfilled with an integrated approach of the application of bioclimatic design techniques and the use of sustainable technology systems, based on the use of renewable energies, such as solar and wind, with an approach of energy efficiency in all the processes involved in the performance, operation and maintenance of the buildings.

Therefore, it is necessary to modify these trends and to apply corrective measures oriented towards the application of bioclimatic design integrated with sustainable technologies in buildings.

The objective of this work is to assess the potential of several bioclimatic design strategies for daylighting and passive cooling aimed at achieving energy savings and ambient hygrothermal and luminous comfort conditions for the occupants of the case study building, a typical commercial construction.

2. THE POTENTIAL OF DAYLIGHTING TO ACHIEVE ENERGY SAVINGS AND LUMINOUS COMFORT IN COMMERCIAL BUILDINGS

A suitable daylighting design is a key factor for achieving not only energy efficiency, but luminous comfort conditions in buildings, both in quantitative and qualitative terms. In commercial buildings, this objective is even more important, as most of the energy load is for air conditioning and lighting. This is the case of most commercial buildings located in Mexico City Metropolitan Area (MCMA), where the case study building for investigation is located.

If properly used, daylighting can result in substantial energy savings by reducing the need for artificial lighting. The primary aim of daylighting is to provide sufficient and suitable lighting conditions for the occupants under all circumstances for the tasks they perform within a space.

This work presents design strategies for the appropriate use of daylighting in commercial buildings located, suitably integrated with energy efficient electric lighting, meant to achieve energy savings whilst providing visual, luminous and thermal comfort conditions for the occupants. The application of daylighting is particularly useful in commercial buildings as this can lead to a reduction of electricity meant to achieve important energy savings.

The use of the direct component of solar radiation can lead to the use of a great number of design alternatives for taking advantage of the natural light in its greatest potential. Taking advantage of natural light by means of the direct component of solar radiation is a promising alternative to solve the dichotomy to maximize the provision of natural light whilst minimizing the external heat gains. This approach is particularly useful in commercial buildings located in hot climates.

The consumption of electricity in buildings located in MCMA has been reported recently and is shown in Figure 1 (SE, 2004).

3. THE POTENTIAL OF PASSIVE COOLING TECHNIQUES TO ACHIEVE ENERGY SAVINGS AND THERMAL COMFORT IN COMMERCIAL BUILDINGS

The hygrothermal comfort conditions available in a building are strongly related to the psycho-physiological functions of the occupants, and these in turn affect their efficiency and productivity. The "desirable" hygrothermal comfort conditions within a building interior can be achieved "naturally" by means of the application of passive cooling techniques. This is a suitable alternative to air-conditioning (AC) as it has a potential for reducing both capital and energy running costs, and for improving indoor comfort conditions of people as well as for supplying air quality in their indoor spaces, whilst providing the basis for preserving the environment. This approach is particularly useful and applicable in commercial buildings, as the main energy load is for air-conditioning and lighting.

The passive cooling techniques are based the use of the four natural environmental sinks: Air, Water, Sky and Earth. Previous studies have identified passive cooling techniques as a very

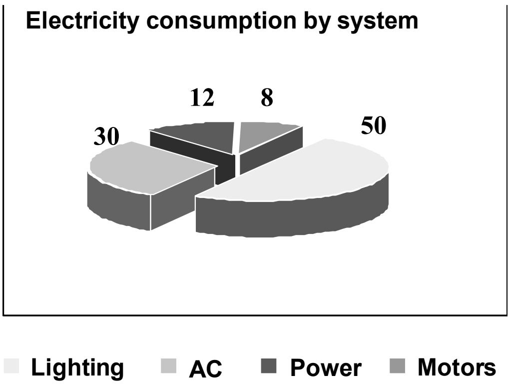

Figure 1: Electricity consumption in buildings n MCMA.

promising alternative for reducing the energy consumption for air-conditioning and to provide the occupants with comfortable hygrothermal conditions in buildings (García Chávez, 2000).

4. CASE STUDY BUILDING

The case study building of this project is a typical commercial building located in MCMA, a prevailing temperate climate (Figs. 2 and 3). The architectural features of this project are as follows:

- Floor area: 392 m^2
- Occupancy: 42 people
- Schedule: 8-14 hrs and from 16-18 hrs. Monday to Friday
- Main orientation: East

5. METHODOLOGY APPLIED

During the first stage of this research work, the consumption of electricity for all the equipment and lighting fixtures was estimated. Subsequently, interviews with the occupants to assess their perception of the ambient conditions were conducted through questionnaires. Concurrently with this stage, monitoring of the dry bulb temperatures and illuminance levels were carried out in nine representative points of the space investigated, during a 10 days period of a typical overheating period in May. During the same monitoring period, the external conditions, including dry bulb temperatures, relative humidity and solar radiation data were recorded. The results were analyzed, interpreted and alternative solutions inferred, meant to determine the most suitable beam daylighting and passive cooling design alternatives to be applied in the building investigated. The conditions of the resulting luminous and thermal design alternatives were simulated with computer software and the use of 3D physical models to compare them with the existing conditions, validated with the on-site monitoring results. During the next stage, the cost benefit of the systems applied and the payback period were assessed. Finally, the last stage consisted of an integral assessment of the contribution of the design alternatives implemented from the thermal and luminous comfort points of view as well as the energy savings and the level of improvement, cost benefit and payback period estimates, and potential benefits on the natural environment.

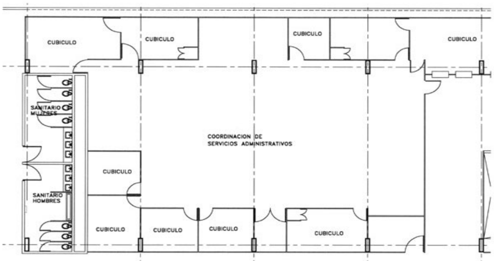

Figure 2: Architectural floor plan of case study building.

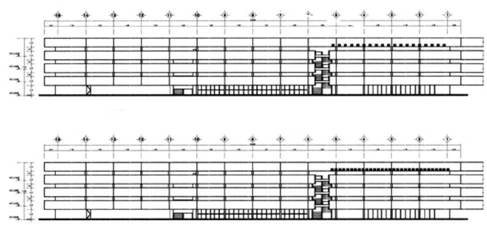

Figure 3: Facades of the case study building.

6. ANALYSIS AND INTERPRETATION OF THE RESULTS

The estimate of the electricity consumption confirmed that the case study investigated is a typical building with a large consumption pattern and this is mainly due to the lack of a suitable response of the building to the external climate and to the inappropriate building internal conditions. The large thermal load of the space, due to the excessive external gains and to the internal gains of the equipment and electric lighting fixtures, and people, provokes an intense and continuous operation during the working hours of a variety of electromechanical systems to counteract the unbearable conditions inside (Fig. 4). This situation was confirmed by the perception of the occupants during the interviews and questionnaires and by the on-site monitoring. From the luminous point of view, most areas of the space showed unsuitable illuminance levels for the visual tasks of occupants. This in turn provoked that their efficiency and productivity were affected, and eventually also the competitiveness of the institution.

During the monitoring period of the ambient conditions the dry bulb temperatures inside the space were located above the upper limit of the

Figure 4: Internal view. Intensive use of lighting fixtures and electromechanical equipment during daytime working hours.

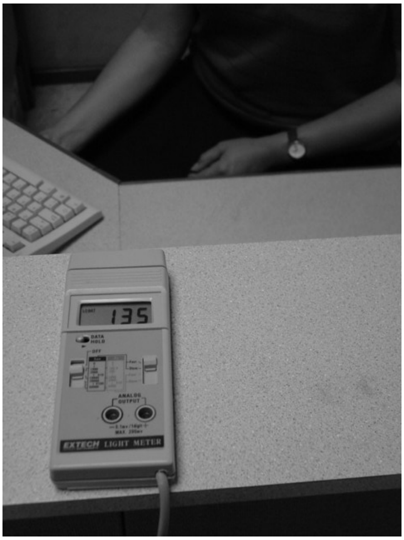

Figure 5: Inadequate low illuminance levels on working areas of the space.

comfort zone for this particular building and location. These results were also consistent with the perception of the occupants reported in the questionnaires. From the luminous point of view, the results clearly indicated quantitative and qualitative problems. In some areas, even though the electric lighting fixtures were on, the illuminance levels measured were below the international light level requirements for this type of space and visual tasks of the occupants (IESNA, 2001). This situation affects the efficiency and productivity of the activities and visual tasks of the occupants exposed to these conditions (Fig. 5). The main reasons for this are: The lack of consideration in the arrangement and design of the building of the potential of daylighting; the utilization of inappropriate lighting luminaries and their lack of maintenance. For example, some fixtures are using an obsolete lighting technology of T12 lamps with low efficiency electromagnetic ballasts.

Apart form this situation; the lamps in some luminaries located in the same unit have different Color Rendering Index (CRI) and Color Temperature (CT), and this provokes qualitative problems in the occupants´ subjective perception of the conditions of the visual tasks and the space itself (Fig. 6).

To sum up, the perception of the occupants of the space indicated dissatisfaction with the hygrothermal and luminous conditions and they feel these affect their efficiency, productivity and eventually, their health. They are worried about finding a rapid and an effective solution to this problem.

7. RESULTS OF THE THERMAL AND DAYLIGHTING DESIGN ALTERNATIVES PROPOSED

7.1 Passive cooling systems and corrective measures for thermal comfort

According to the results and in order for the building to improve its thermal and luminous performance, the application of a number of

Figure 6: Typical luminaire with different CRI and CT.

corrective design measures and the thermal and daylighting design alternatives include the following:

- Application of waterproof covering on the roof, with an absortance of 0.30 and 0.90 emittance.
- Reduction of the area of skylight from 6m^2 to 3 m^2.
- Replacement of existing 38 watts T12 fluorescent lamps with electromagnetic ballasts and plastic diffuser, for 32 Watts T8 fluorescent lamps with 6000 K and 0.87 CRI with electronic ballast and long life acrylic diffuser.
- Use of a convective cooling technique by means of a combination of openings on the external façade both on the existing vertical fin shading device and on the upper part directly connected with a horizontal plenum existing in the building, and running from side to side of the space on the whole area and then with openings located on the ceiling for exhausting the internal heat gains and assisted with a low consumption extractor fan located by the exist of the plenum. This is a dual system as it is also useful for improving and enhancing the lighting levels into the space (Fig. 7).
- Replacement of existing luminaries fixtures for skylight openings with ventilation to dissipate the heat gains from the inside.
- Open the roof on existing service ducts and upper part of adjacent brick walls associated with air extractors to remove heat gains from the space.

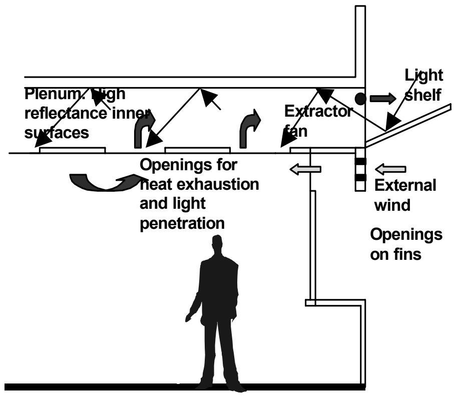

Figure 7: Design alternatives for daylighting and passive cooling.

7.2 Daylighting and electric lighting systems and corrective measures for luminous comfort

The daylighting and lighting systems applied in the project include:

- Replacement of existing 38 Watts T12 lamps and electromagnetic ballasts for 32 Watts T8 fluorescent lamps with 6000 K and 0.87 CRI with electronic ballast and long life acrylic diffuser.
- Use of individual lighting luminaries on working stations to provide the required lighting levels.
- Use of thermal luminous solar duct in the exiting plenum of the building just above the ceiling by means of openings on the external façade on the upper part and running from side to side of the space on the whole area and then with openings located on the ceiling for removing the thermal load due to the internal heat gains and assisted with a low consumption extractor fan located by the two exists of the plenum. This is a dual system because it is also useful for improving ventilation and promoting exhaustion of heat gains and for enhancing the lighting levels into the space (Fig. 7).

7.3 Application of simulation models for assessing the daylighting and thermal performance of the design alternatives

A simulation computer program was applied to assess the performance of the thermal and daylighting design alternatives (Mathews, 2000). As to the existing conditions, the results showed consistency with the real building results, obtained from the monitoring of the thermal and luminous conditions, that is the ambient conditions are not in the comfort zone and provoke the occupants to perceive their space as unbearable (Fig. 8). The simulations for the assessment of the thermal and luminous performance were conducted during the typical overheating period: From the thermal point of view the new conditions with the design alternatives implemented showed that the occupants are located within the comfort zone, for this particular type of building and metabolic rate (Fig. 9).

From the lighting point of view, the simulation was complemented using 1:20 3D physical scale models in an artificial sky and under real clear and overcast sky conditions (Fig. 10).

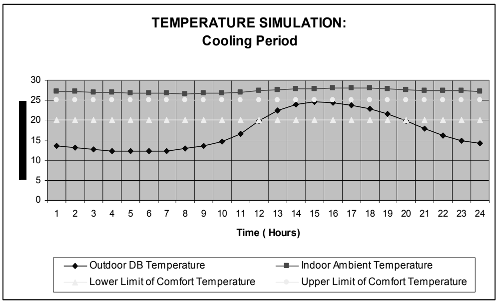

Fig. 8. Existing conditions. Results of the thermal simulation during the typical overheating period.

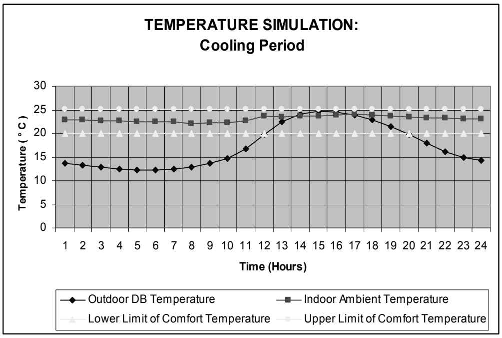

Figure 9: New conditions, with the design alternatives implemented. Results of the thermal simulation during the typical overheating period.

With the simulation software, during the overheating period and under clear sky conditions, the daylighting strategies provided suitable illuminance levels and even under typical overcast sky conditions the average illuminance level recorded in the space was 420 lux, and the uniformity ratio (Ur) maximum to minimum illuminance level was 2.1. According to current international standards, the uniformity ratio, related either to illuminance levels or Daylight Factors, should not be more than 3 (ASHRAE/IESNA, 2002).

The results of the experiments conducted with the 3D physical models showed consistency with those of the computer simulations.

The results of the lighting conditions from the 3D experiments and computer simulations indicate a significant improvement and enhancement of the lighting conditions as well as of the luminous comfort of the occupants inside the space, relative to the existing conditions.

Figure 10: 3D physical model for daylighting, showing the plenum and openings to enhance daylighting and thermal performance.

8. COST BENEFIT ANALYSIS

The additional cost of the implementation of the thermal and daylighting design alternatives and the building corrective measures relative to the annual savings on electricity gives a payback period of 2.7 years. Apart from these advantages, there are other benefits which are not necessarily countable but are very important such as the improvement of the hygrothermal and luminous comfort conditions of the building' occupants and their quality of living.

9. ENVIRONMENTAL BENEFITS

The energy savings due to the implementation of the thermal and daylighting design alternatives and the building corrective measures are directly related to a reduction of the emission of the greenhouse gases to the environment as the electricity used in the building comes from a conventional thermal power plant and therefore, the annual reduction of the emission of the pollutants and water consumption in this type of power plant is as follows:

- 87 Ton of CO_2
- 0.73 Ton of SO_2
- 0.31 Tons of NOx
- 0.04 Tons of dust and suspended particles
- 453, 953 m^3 of water.

10. CONCLUSIONS

The hygrothermal and luminous comfort conditions of the occupants are particularly important in commercial buildings as it is directly related to their efficiency, productivity, and more importantly to their health. In this research work, the factors that have determined the thermal and luminous design alternatives to be implemented are: The visual tasks of the occupants; the internal thermal load due to equipment, lighting system and people; the levels of electricity consumption; the maintenance and functionality of the space, the accomplishment of efficiency and productivity levels; and the health of the occupants. The results of this work have demonstrated that by implementing suitable design alternatives and corrective measures, the consumption of the electricity can be significantly reduced whilst improving the hygrothermal and visual comfort conditions of the occupants as well as their efficiency and productivity and their health. The environment can also be eventually improved due to the reduction of the emissions. It is expected that the results of this research work serve as a demonstrative example for other applications to contribute to generate a multiple cascade effect, not only in existing buildings, but in new architectural projects and constructions likewise. Therefore, the holistic approach of this project is directly and strongly related to sustainability to improve the environment both locally and globally and this is aimed at generating new energy and natural resources cultures oriented to achieve an authentic quality of living for the existing and new generations of the new millennium.

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