Advances in Daylighting and Artificial Lighting

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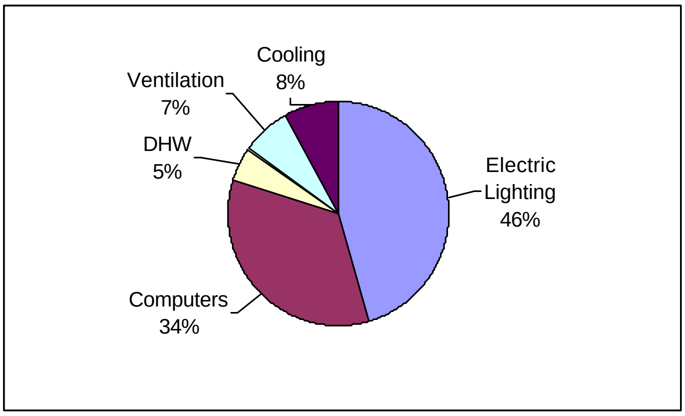
ABSTRACT: A more intensive use of daylight, with a view to minimizing electricity consumption for lighting and reducing heating and cooling loads, has become an important strategy in the effort to improve the energy efficiency of non-residential buildings. Advances in artificial lighting technology are moreover leading to the use of light sources with higher luminous efficacy as well as more efficient lighting fixtures. A successful integration of the two lighting approaches through “intelligent” building design and control can lead to significant improvement of the users’ visual comfort and amenity, while simultaneously reducing the environmental impact of buildings. An overview of recent progress in research and development in daylighting and artificial lighting technologies is given in this paper, with some emphasis on the integration of both lighting techniques by means of advanced building control strategies.

1 INTRODUCTION

The growing World concern about global warming, triggered by the serious perspective of climate change (UN 1992) (UN 1997), has increased building designers’ interest in sustainable development strategies (CSD1997).

Electric lighting in non-residential buildings (offices, industrial and commercial buildings) is responsible for a large part of the electricity consumption of European buildings (see Figure 1), despite the growing electricity demand for other building services (computers, ventilation, air conditioning etc.). In the case of buildings with advanced envelope technologies (energy conservation measures, passive solar techniques), energy consumption for lighting and electrical appliances sometimes even exceeds the corresponding figure for heating: e.g. 42 MJ/m^2·year and 114 MJ/m^2·year versus 76 MJ/m^2·year for the LESO solar experimental building on the EPFL campus (Altherr & Gay, 2002).



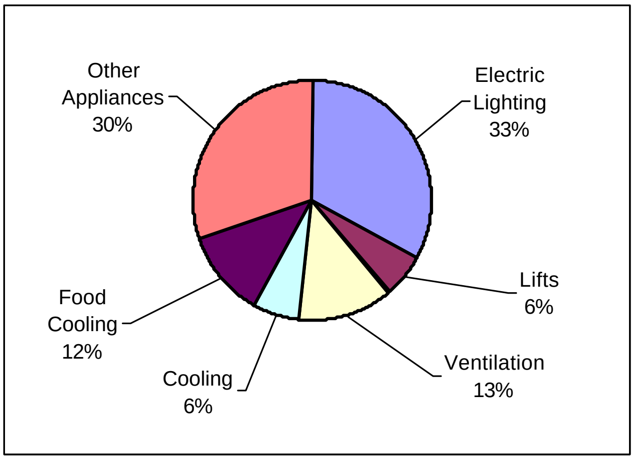


Figure 1. Typical distribution of electricity consumption of a Swiss office building (left: $I_{heating}$= 460 MJ/m^2·year, $I_{electricity}$ =240 MJ/m^2·year) and a commercial retail center (right: $I_{heating}$= 460 MJ/m^2·year, $I_{electricity}$ =730 MJ/m^2·year).

Fossil fuels play an important role in the European electricity production: they are responsible for the major part of greenhouse gas emissions in the UCPTE electricity mix (168 g·CO_2 equ/MJ electricity). Applying energy efficient lighting techniques within buildings could consequently lead to an estimated reduction of carbon emissions comparable to the target of the Kyoto protocol for the European countries (-8% of 1990 CO_2 emissions) (UN 1997).

A more intensive use of daylight within non-residential buildings has become an important strategy to improve energy efficiency by minimizing electricity consumption for lighting and by reducing heating and cooling loads of buildings through a better management of solar gains (IEA 2000). Advances in artificial lighting technology are moreover leading to the appearance in the market of light sources with higher efficacy (see Table 1) as well as more efficient lighting fixtures (see Par. 3). By combining natural and electric lighting in an appropriate manner, through 'intelligent' lighting design and control strategies, significant improvement of visual comfort and amenity can be reached while reducing the environmental impact of buildings.

An overview of recent progress in research and development in daylighting and artificial lighting technologies is given in this paper, with some emphasis on the integration of both lighting modes through advanced control strategies.

Table 1. Typical luminous efficacy of light sources (incl. Auxiliary equipment)

Light sources		Luminous efficacy η[Lm/W]
Incandescent Filament lamps	Classical lamps	10 – 20 Lm/W
	Halogen lamps	20 – 30 Lm/W
Low Intensity Discharge lamps	Fluorescent tubes	50 – 100 Lm/W
	Sodium Low Pressure	60 – 150 Lm/W
High Intensity Discharge lamps	Sodium High Pressure	60 – 120 Lm/W
	Mercury vapor	60 – 100 Lm/W
	Metal halides	50 – 100 Lm/W
Daylight	Dawn, sunset	60 – 80 Lm/W
	Cloudy & clear sky	110 – 140 Lm/W

2 DAYLIGHTING SYSTEMS AND COMPONENTS

Throughout the history of mankind, daylight has been the primary source of light in buildings, supplemented by burning fuels. In addition to its contribution to the illumination of indoor spaces, daylight was used as a symbol of purity and knowledge, as in the Great Temple of Ammon (Karnak, 1530 – 320 B.C.) where roof slits and window openings filtered sunlight in a variable manner (Moore 1995).

In modern times, the use of daylight in buildings was encouraged for sanitary and hygienic purposes in large industrial cities. At present, evidences of the human behavior within office spaces show how much daylight is desirable in the day-to-day life. It fulfills at least two basic human requirements: a) the achievement of visual tasks thanks to the illumination of the working space and b) the experience of environmental stimulation through visual information.

Daylight provides high illuminance compared to artificial light sources (110,000 Lux outdoors under clear sky) and offers excellent color discrimination for objects lit by natural light (daylight is a reference source for color rendering assessment). A high visual performance can thus be achieved in the working environment providing that an appropriate distribution of daylight is achieved by windows or daylighting strategies.

Through a better distribution of daylight in spaces, daylighting systems and components integrated into building envelopes can substantially reduce the energy consumption by substituting artificial light with daylight. A large variety of novel daylighting systems and components have consequently been developed over the last 10 years as a way to foster the use of daylighting technology in non-residential buildings (Littlefair 1990, Miloni et a. 1997). Different approaches were used for that purpose, based on the principal physical phenomena altering light propagation, including scattering and diffusion (aerogels, Dengler & Wittwer 1994, capillary structures, Okalux 1996), specular reflection (reflective lamellae, Köster 1989), total internal reflection (light redirecting window, Federmann 1996, sun-directing glass, Müller 1996), optical refraction (prismatic panels, Siemens 1996, prismatic films Withehead et al. 1982) and optical diffraction (holographic optical elements, Müller 1994).

Most of these components show real capabilities of improving lighting conditions when properly installed in the upper part of a window opening: they capture sunlight under clear and/or intermediate sky conditions and re-orient the direct component of daylight toward the room ceiling fraction closest to the window.

Figure 2 shows a view of the sun-directing glass (Müller 1996), attached above the normal viewing window and redirecting sunlight to the ceiling. The component is made of concave acrylic elements stacked vertically within a double-glazed window pane. Such an element shows reasonable thermal insulation characteristics ($U = 1.3$ [W/m^{2}k]), and a rather large solar heat gains transmission figure ($g = 0.36$).

Figure 2. Sun directing glass attached above a normal viewing window (ADO office building Germany) (IEA 2000)

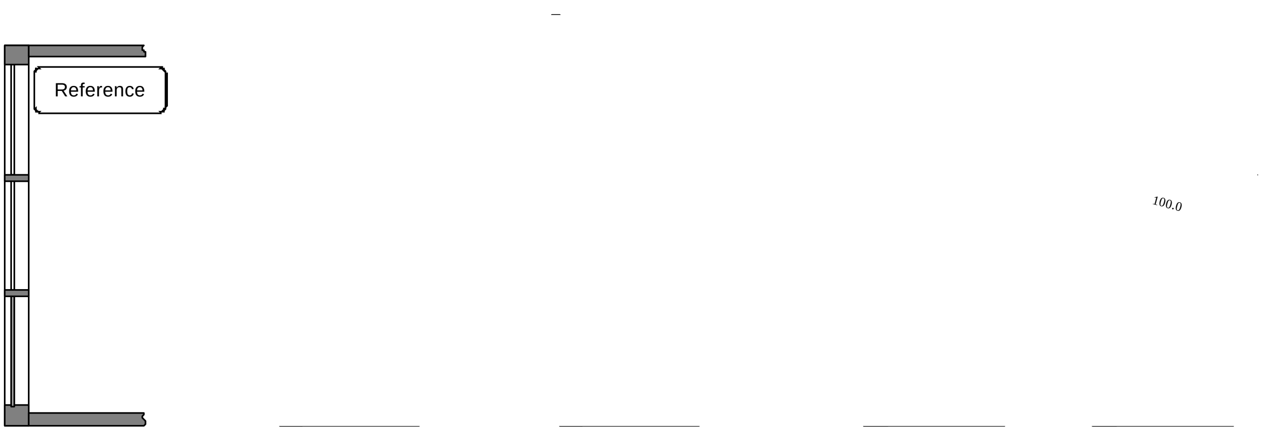


Figure 3. Cross-sections of several daylighting components studied during IEA Task 21 (Michel 1998)

A comprehensive description of a large variety of daylighting components, as well as their sunlighting features, is given in reference (IEA 2000). Figure 3 gives an overview of the most novel components considered during the international scientific program “Daylighting in Buildings” (IEA Task 21). It comprises a light guiding shade, holographic optical elements and reflective light shelves. A plain insulated double glazing façade was considered as well in this program, as a reference system.

Recent progress in photogoniometry, made by means of novel digital imaging techniques (Scartezzini et al 1997), allowed setting up new experimental devices, which are able to assess the directional transmission properties of daylighting components in a very efficient way (Andersen 2002). These transmission features are provided for each component by the Bidirectional Transmission Distribution Function BTDF [sr^{-1}] (CIE 1977) and can be used to optimize its integration into the building envelope. Daylighting simulation programs use these photometric data moreover in order to achieve a reliable modeling of the propagation of daylight through advanced daylighting systems.

The next two figures illustrate the BTDF data, assessed experimentally for two daylighting components by means of this novel bi-directional photogoniometer (Andersen 2002). Figure 4 shows the transmission features of a laser cut panel, produced by making laser cuts in a thin panel of clear acrylic material. Figure 5 illustrates a mirrored reflective blind, designed for an optimal spreading of sunlight toward the indoor space (Köster 1989). Both components show a pronounced redirecting of sunlight in the upper direction, as in the case of the sun-directing glass (cf. Figure 2). The reflective blind is characterized however, by a larger reflected daylight flux despite the diffusion of sunlight (apparent “rounding” of BTDF instead of a “spiky” shape).

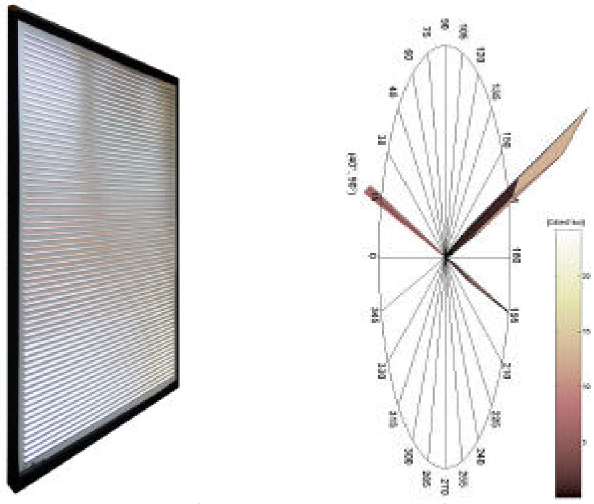


Figure 4. View of a laser cut panel (left) and corresponding BTDF data (right)

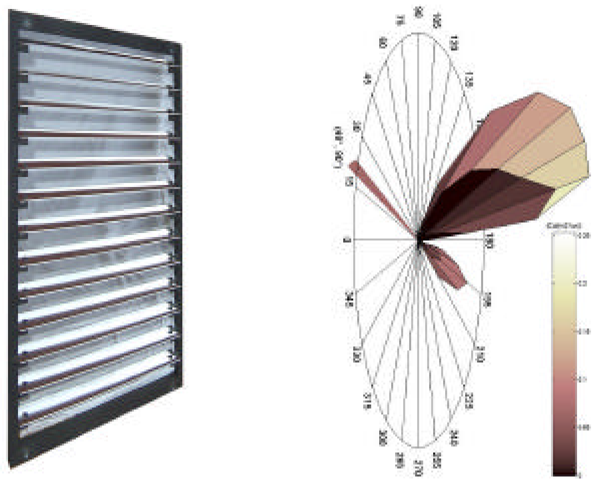


Figure 5. View of a mirrored reflective blind (left) and corresponding BTDF data (right)

Experimental monitoring of daylight factors within scale models (Michel 1998) and test modules (IEA 2000), equipped with the corresponding daylighting components (cf. Figure 3), showed values in the room lower than those obtained with a conventional double glazing façade (2% at a distance of 6 meters from window). As a consequence, the associated daylighting provision on a work plane placed at this distance is nil, which leads to an excessive use of electric light (even for a 300 Lux required work plane illuminance).

Achieving an efficient collection and redistribution of diffuse daylight issued from the sky vault, remains as a consequence a challenging objective: it is a key step toward daylighting systems that are appropriate for climatic conditions dominated by overcast skies.

Non-imaging optics, well known for its application in solar concentrators (Welford & Winston 1989), was used to set up a new design approach for daylighting systems. These novel devices, called anidolic systems (an: without; eidolon: image, in ancient Greek) were designed and installed on experimental test modules to monitor their luminous performance and assess their acceptance by users. Reference (Scartezzini & Courret 2002) gives a detailed description of the different techniques used to design these systems (compound parabolic reflectors).

Three different anidolic systems designed for overcast conditions were studied over several years; each of them fulfilled different main functions with regard to diffuse component of daylight: a) a maximal capture of zenithal light (anidolic zenithal collector), b) an optimal collection and distribution of zenithal light (anidolic ceiling) and c) an optimal façade integration (integrated anidolic system).

Figure 6 shows a cross-section view of the anidolic zenithal collector, installed on the northern façade of a 5.4 x 3.4 x 2.7 m test module (Scartezzini & Courret 2002). The device consists of two compound parabolic collectors (CPC) -- an external zenithal collector and an internal “Daylight beam projector” -- placed in front of each other in opposite directions. The overall anidolic system takes advantage of the angular selection of the admitted light rays and the minimal number of reflections to efficiently collect diffuse daylight from the sky vault, as well as of the sharp angular selectivity to reduce glare risks in the room (Compagnon 1993).

Figure 6. Cross-section of the anidolic zenithal collector showing ray-tracing of the diffuse daylight component through the system (rays emitted by the sky vault)

An outstanding daylighting performance was observed for this system in a comparison with an identical room (same photometric and geometrical features), equipped with a conventional double-glazing façade. Daylight factors of 3.3% were monitored in the rear of the room under overcast conditions: this corresponds to a (1.7) multiplication factor in absence of any obstructions on the horizon (rural environment) and a (2.7) multiplication factor in the case of a 40° high obstruction (urban environment). The yearly fraction of daylighting provision reaches 60% in the rear of the room for a 300 Lux required workplane illuminance (instead of nil for the reference facade).

Figure 7 shows the anidolic ceiling, which uses an external anidolic zenithal collector and a light duct integrated into the ceiling, to achieve an efficient collection and redistribution of diffuse daylight deep into the room.

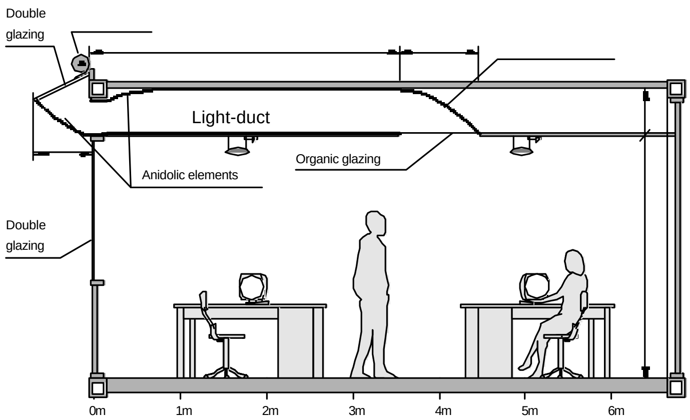


Figure 7. Cross-section of the anidolic ceiling installed on a 6.55 x 3.05 x 3.05 m test module

All the surfaces of the anidolic ceiling were covered with highly reflective aluminum foils ($\rho_r = 0.9$) in order to maximize the efficiency of the overall device (32% efficiency for the whole system). The experimental monitoring of the luminous performance of the anidolic ceiling showed a 4% daylight factor at a distance of 4.5 meters from the façade; this corresponds to a (1.7) multiplication factor for the rear of the room in comparison to a conventional double glazing façade (rural environment). A substantial improvement of daylighting provision for the deepest part of the room is thus achieved (cf. Table 2); energy consumption of the electric lighting over a 6 month long period confirmed the related savings in comparison to the reference façade (32% savings of electricity).

Figure 8 shows outdoor and indoor views of the integrated anidolic system installed on a test module and placed side by side with the reference façade (conventional double glazing). The system fits with the requirements of building refurbishment and reduces the complexity of the setting-up process of the device on a building (protrusion less than 0.3 m, fixed ceiling height of 2.7 m taken into account, lowest point of internal reflector higher than 2 m).

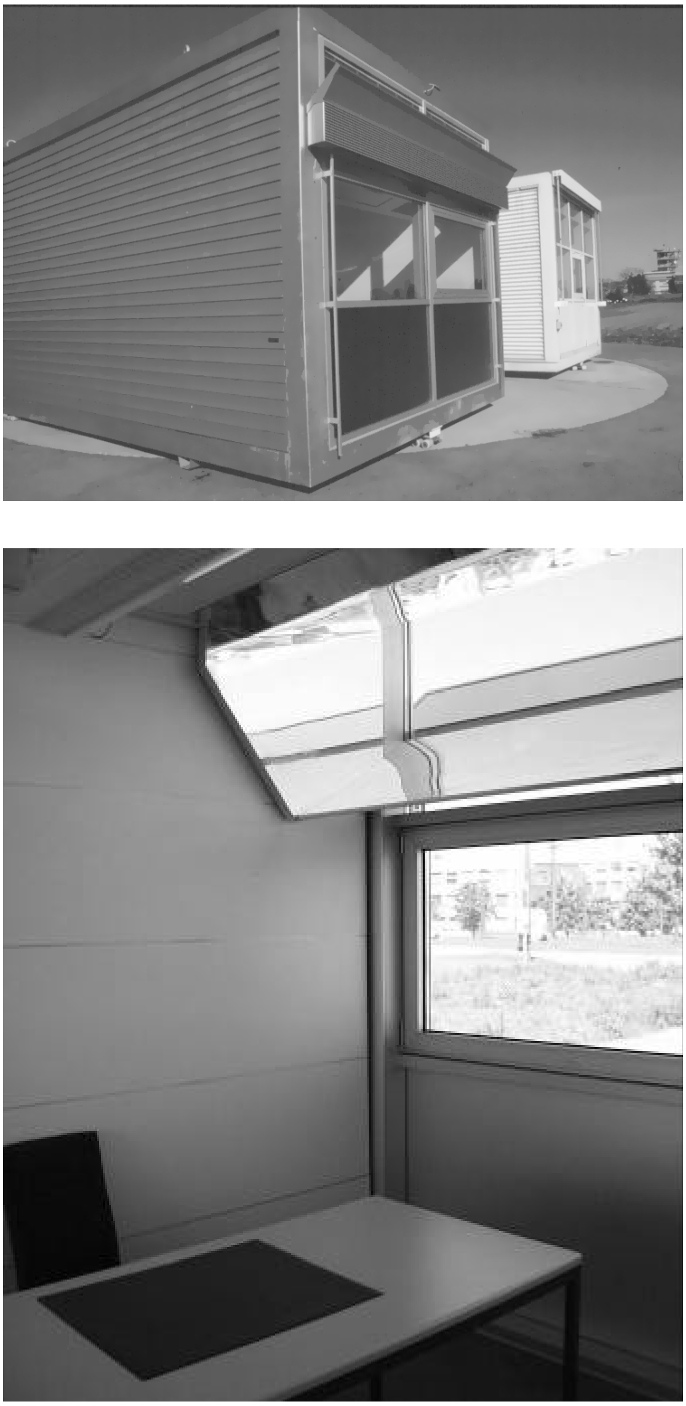


Figure 8. External and internal views of the integrated anidolic system set up on a test module (reference module visible in the same figure).

The experimental assessment of the luminous performance of the device confirmed the results achieved by the other anidolic systems regarding penetration of daylight into the room. Monitoring of the visual comfort conditions offered by these systems gave contrasted results depending on the design of the internal component of the anidolic device. Table 2 gives an overview of the overall encouraging performance of these novel devices in comparison to a conventional double-glazing façade.

<table>
<tr><th colspan="4"></th><th>Anidolic Zenithal Collector</th><th>Anidolic Ceiling</th><th>Integrated Anidolic System</th></tr>
<tr><td colspan="4">Facade protrusion / Height under ceiling</td><td>0,40</td><td>0,21</td><td>0,11</td></tr>
<tr><td rowspan="6">diffuse daylight</td><td rowspan="4">Luminous performance overcast sky</td><td rowspan="2">Open environment</td><td>a</td><td>x 1,7</td><td>x 1,7</td><td>x 1,4</td></tr>
<tr><td>b</td><td>+ 36 %</td><td>+ 32 %</td><td>+ 19 %</td></tr>
<tr><td rowspan="2">Urban environment</td><td>a</td><td>x 2,7</td><td>x 2,7</td><td>x 1,7</td></tr>
<tr><td>b</td><td>+ 50 %</td><td>+ 45 %</td><td>+ 15 %</td></tr>
<tr><td rowspan="2">Visual comfort in the rear under overcast sky</td><td colspan="2">Open environment</td><td>↘</td><td>↗</td><td>↘</td></tr>
<tr><td colspan="2">Urban environment</td><td>→</td><td>→</td><td>↘</td></tr>
<tr><td rowspan="3">direct daylight</td><td colspan="3">Protection against overheating</td><td colspan="3">NO (1)</td></tr>
<tr><td colspan="3">Protection against sunrays</td><td colspan="3">NO (2)</td></tr>
<tr><td colspan="3">Light flux directed to the rear part of the room without glare risk</td><td>NO</td><td>YES</td><td>NO</td></tr>
<tr><td colspan="7">Symbols: a: multiplication coeff. of daylight factor in deep part of room; b: percent points variation of daylight sufficiency in deep part of room; 1) external shading necessary 2) interior screen necessary</td></tr>
</table>

Table 2. Balance of anidolic systems performance (all comparisons made versus the corresponding reference case)

3 ARTIFICIAL LIGHT SOURCES AND FIXTURES

The first reliable artificial light sources in the history of mankind were probably the oil lamps, later followed by candle sticks. Even if appropriate from a social and technical point of view, as confirmed by their large scale use in prestigious buildings, they showed important limitations from an indoor environment quality (generation of soot) and an energy conservation perspective (1 – 2 Lm/Watt of luminous efficacy).

After a period dominated by gas lights (mainly in the XIX century), two types of light sources experienced considerable development: a) incandescent lamps and b) discharge lamps. These two types represent nowadays by far the major part of the lighting market.

The incandescent lamp, continuously improved from a technical point of view since the first practical attempt of Thomas Edison in 1879, is till present in our day-to-day life. From an energy efficiency perspective, it is characterized by considerable heat dissipation and major infrared emissions, which leads to poor luminous efficacies (cf. Table 1). Tungsten-halogen lamps utilize a halogen regenerative cycle to provide a better lumen maintenance than a classical filament lamp, together with lamp compactness (20 W – 50 W power range). As a consequence, they reach a slightly higher luminous efficacy (cf. Table 1) and can be used with precise optical dichromic reflectors, achieving more delicate accent lighting configurations with higher luminances (particularly appreciated in commercial buildings). Even if continuously improved, their life time remains generally lower than 5000 hours, which impinges significantly on their maintenance costs.

Fluorescent lamps belong to the second type of light sources (discharge lamps): they are low-pressure gas discharge sources, in which light is produced predominantly by fluorescent powders activated by ultraviolet radiation generated by an electric arc. The lamps, usually in the form of a long tubular bulb with an electrode sealed into each end, contain mercury vapor with a small amount of inert gas for starting (Krypton); the inner walls are coated with phosphors emitting several wavelengths to achieve a white perception. An auxiliary device, commonly named a ballast, limits the discharge current in the lamp to a design value.

Constant improvement and fine-tuning of the essential components of the fluorescent tube (phosphor coating, mercury vapor, electrodes and starter gas) has lead to a substantial increase in their luminous efficacy (ranging today form 70 to 100 Lm/W); at the same time, the color rendering index (Ra > 80) and life time (6000 – 8000 hours) were brought to very appreciable standards.

Other significant progress was made in last decades regarding fluorescent tubes, which brought considerable benefits from an energy savings perspective: a) electronic ballasts with a lower specific consumption appear on the market (2-3 Watts instead of 10 W for a magnetic ballast), b) tube diameters were reduced, leading to better integration possibilities and higher optical efficiency of corresponding luminaries (16 mm diameter tube replaces progressively 26 mm tube) and c) tubes of different power ratings were produced (ranging form 14 to 55 Watts).

Figure 9 illustrates an office lighting case, characterized by a low specific wattage (9.5 Watt/m^2) for standard work plane illuminance (400-600 Lux). The general lighting is based on compact fluorescent tubes (PL 24W); the task lighting, via floor lamps placed close to the desk, is based on linear fluorescent 55 Watt tubes. Energy savings in comparison to halogen lamps can be estimated at 60%, only on the basis of the installed lighting power wattage. This is further improved by the dimming capability of the fluorescent tubes, equipped with high frequency electronic ballasts (10% to 100% dimming range).

Fluorescent lighting benefited since the eighties from another significant progress: the development of compact fluorescent lamps. As a result of technical innovations, compact fluorescent lamps showed major advantages with regard to the linear tubes (ease of installation, full retrofit capability of incandescent lamps). Thanks to their high luminous efficacy (50 – 80 Lm/Watt) and their large diversity in shape (six different lamp types) and power range (5 – 55 Watts), they can successfully replace incandescent lighting and simultaneously achieve 80% energy savings. They nowadays offer other significant advantages compared to classical light sources: a) a longer lifetime (10,000 hours), b) a full dimming capacity thanks to electronic ballasts (HF ballasts), c) different color temperatures ranging from warm incandescent (2700 K) to neutral white (4000 K) and d) an excellent color rendering index (Ra > 80). As a consequence, their utilization in office and commercial lighting extended in a considerable way over the last 20 years (cf. Figure 11).

Figure 9. Office lighting based on the use of compact fluorescent tubes for general lighting (PL 24 W) and direct/indirect task lighting floor lamps fitted with fluorescent tubes (TL 55W).

High pressure discharge lamps (high pressure iodide, high pressure sodium, metal halide) found excellent application opportunities in all situations where both a large luminous flux (50,000 – 500,000 Lumen) and a high luminous efficacy (up to 100 Lm/W) were required (industrial and road lighting). Over the years, their field of application extended even to commercial lighting thanks to the improvement of their color rendering index (Ra > 90) and the availability of lower power range sources (250 – 400 W).

Two major breakthroughs were however achieved by the lighting industry since the beginning of the nineties: a) the development of the induction lamp and b) the emergence of solid state lamps (light emitting diodes).

Induction lamps use the same physical principles as fluorescent sources to produce light: the generation of ultraviolet radiation toward a mantle of phosphors by means of a current discharge in a low pressure gas. The movement of electronic charges is in this case created by an antenna emitting a high frequency electromagnetic field within the glass vessel (cf. Figure 10). The absence of filament or electrodes is responsible for the long lifetime of the induction lamp (60,000 hours) which reaches, moreover, a reasonable luminous efficacy (70 Lm/W). Thanks to these important features, the induction lamp, which is available for different power ratings (55 – 165 Watts), suits application cases where maintenance costs play an important role.

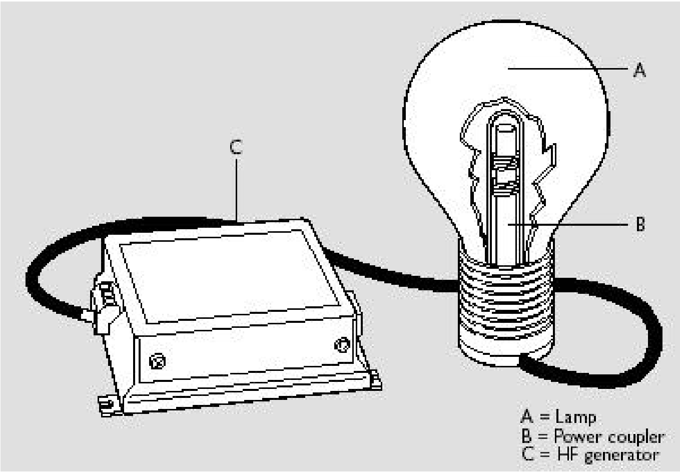


Figure 10. Sketch of an induction light source (Philips 2003)

Light emitting diodes (LED) produce light by electro luminescence when a low-voltage current is applied to the junction of the semiconductors of this solid state device. Up to now, this type of light source found an excellent application field in the domain of display lighting (signaling usage, display screens): all colors are available from red to blue in efficacies which outperform colored incandescent lamps.

Recently, progress was made in the design of white LED by either combining red, green and blue LEDs or by using LEDs emitting blue light converted to white by means of internal phosphor. Their efficacy reaches today about 20 Lm/W for white light; the power range of an individual LED is close to 5 Watt. For both types of white LED sources, a steep rise to 35-40 Lm/W in efficiency is expected within the next 5 years, making this light source applicable beyond its traditional signaling usage.

The LED light sources have other very important advantages compared to the present sources: a) a lifetime up to 100,000 hours, b) almost infinite switching cycles with instantaneous full power output, c) full dimming capability and d) very small dimensions allowing their use in built-in precision optics. As a consequence, solid state lighting is expected to compete with conventional sources in the near future.

4 INTEGRATION OF DAY AND ARTIFICIAL LIGHTING

A successful integration of daylighting and artificial lighting systems, which meets the needs of building users regarding visual comfort and amenity, can lead to substantial energy savings. New lighting technologies available in the market today have contributed to ease this integration process during the past decade (novel daylighting components, more efficient light sources and luminaires, etc.). Figure 11 shows an example of lighting systems integration in a commercial building (Copenhagen Airport, Denmark), based on daylight responsive compact fluorescent tubes (see switching off of first luminaires row).

Figure 11. Daylight responsive electric lighting system in a commercial building (Copenhagen Airport, Denmark)

Besides the new features of lighting sources (dimming capacity, luminance and presence sensors, etc.), research is still aiming toward more integrated and user responsive daylighting and electric lighting systems. This is currently the case for several EPFL projects in the field addressing: a) the control of the daylight flux into anidolic systems by means of electrochromic glazing (Page et al. 2003), b) the use of neuro-fuzzy management strategies to integrate the control of blinds and electric lighting systems (Guillemin & Morel 2001) and c) the use of genetic algorithms to take into account user wishes in such building control (Guillemin 2003). Several lighting products will rely on these approaches in a near future.

5 CONCLUSION

Recent progress in daylighting and artificial lighting technologies has lead to the improvement of building energy efficiency, which will contribute to the curbing of greenhouse gas emissions. A more intensive use of daylight as well as a more general use of efficient light sources and luminaries is expected in the near future in non-residential buildings. By combining both day and artificial lighting in an appropriate way, significant improvement of users' visual comfort and amenity can be reached as well: it is a key issue toward a broader audience for sustainable building design.

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