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Electrical Discharge Light Sources : A challenge for the future

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Summary:

The first electric powered lamp operated more that 150 years ago, since then the evolution of light sources is astonishing. Today, more than 10% of the global electric power produced worldwide serve for light production from several billions lamps. Since last three decades incandescent lamps are gradually replaced by more energy efficient discharge lamps. In parallel, new generations of Light Emitting Diodes, producing bright colours (including white) with luminous efficacy challenging even discharge lamps, appeared in past years. The objective of this paper is to focus on the state of art in the domain of light sources and discuss the challenges for the near future.

Keywords:

Light Sources, Luminous efficacy, Materials

1. Introduction:

Unable to tame natural light sources the Man discovered two methods to excite matter and force it to produce artificial light: the incandescence and the luminescence:

- In a first approximation we could define the “incandescence” as the production of light from any hot body (temperature higher than 500°C). The red light emitted from a heated iron piece is a characteristic example of this process. To the similar way when any organic matter is burning produces heat, gases and some carbon “particles”. These carbon particles are then agglomerated to clusters of a few micron of diameter (10^{-6} m). Because of the surrounding heat these clusters become incandescent and produce the orange-red light characterising a flame.

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- However, phenomena like phosphorescence and fluorescence demonstrated the possibility to produce light from the matter with out heating. The German scientist Wiedemann proposed, at 1888, to call this "cold" emission "Luminescence", with the possibility to add a prefix indicating the method used for triggering this phenomenon ; to this way electricity causes "electro-luminescence", friction causes "tribo-luminescence" and so on...

Nowadays, using electric lamps Man can produce artificial light when he likes and as he like. "Light is the Man's most important product" said J. Waymouth.

2. Historic evolution of the electrical light sources:

Who invented the first electric lamp ? T. Edisson ? Certainly not ! The first electric powered light source, a free burning carbon arc, has been proposed by the English scientist Faraday in 1814 in the Royal Academy of Science (historically, this can be considered as the very first application of plasmas) .

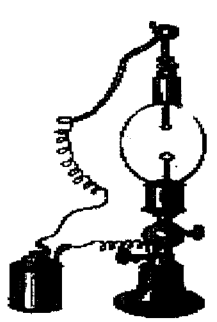
Figure 1: H. Davy's egg

In 18th century Dr Wall suspected the electric nature of sparks emerging from the amber made knob of his walking stick when rubbed up, he compared these sparks to lightning during storms. Some years latter, in 1750, Francis Hawksbee produced the first man-made glow by electrostatically charging the outside of a glass globe from which he had evacuated the air. H. Davy, in 1814, demonstrated the possibility to create an electrical discharge in a rarefied gas between two electrodes when connected to a Volta's battery (Figure 1). In 1814, Frarady in the Royal Academy of Science the first electric powered lamp for public lighting, it was a free burning carbon electrode arc able to produce stable white light during 10-20 h by keeping constant the inter-electrode distance with a complicated mechanic system. His invention, improved by other scientists has been extensively used for public and indoor lighting in Paris (the Paris' Opera were the most famous example). In the 1850s, H. Geissler discovered that a discharge through a low-pressure gas gave off light of a spectrum characteristic of the gas, thereby founding at one time the neon sign industry and the science of spectroscopy. By proper choices of gases, Geissler was able to produce light of nearly all colours. The first commercial application of this principle was a display of multicoloured lights put on at

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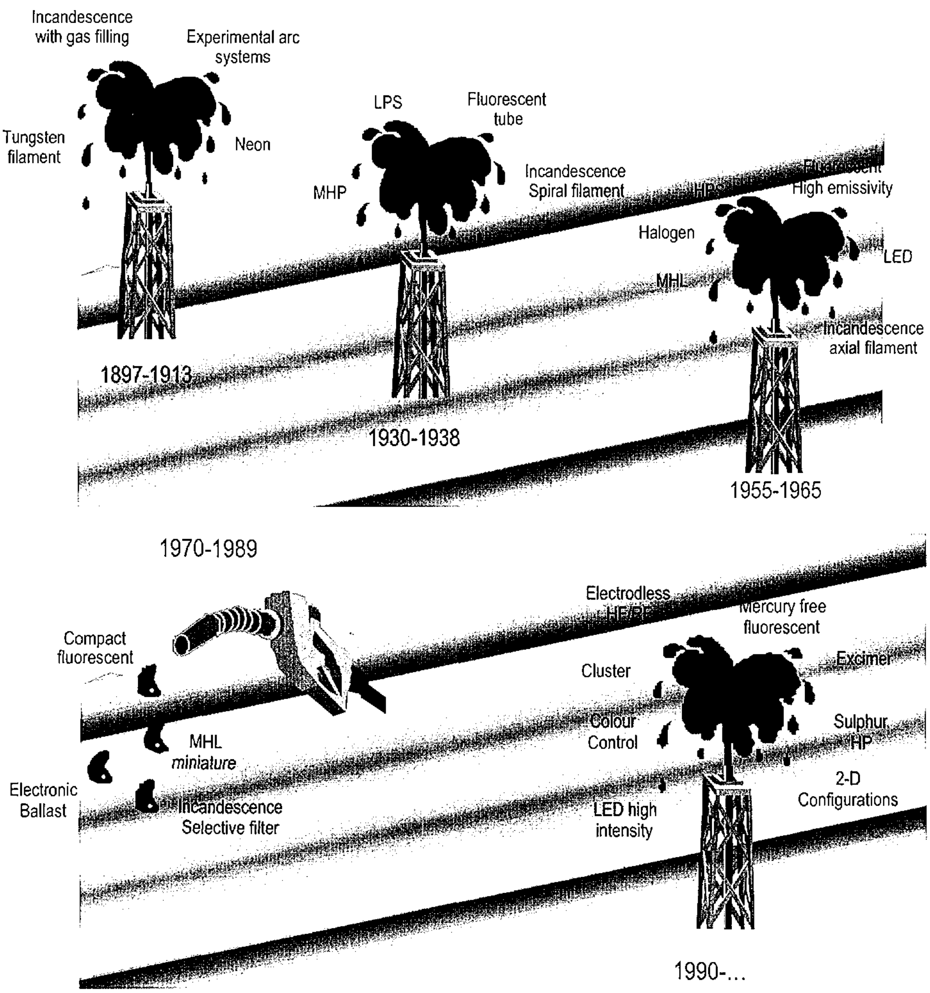
Queen Victoria's diamond jubilee. Then, in 1878, incandescence arrived with the first carbonised bamboo-filament lamp presented by Edison. Less efficient than any electric discharge but less expensive and considerably easier to manufacture this lamp rapidly dominated the market, the first commercial discharge lamp manufactured in series appeared 50 years letter. Nowadays, world-wide lighting industry produce more discharge lamps than incandescence bulbs.

The following illustration (Fig 2) resumes the historic evolution of light sources from the turn of the XIXth century up to now.



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3. Economic and environmental dimension of lighting industry:

Last year the world-wide turnover of the lighting industry is estimated to be more than 15 billion Euros. Figure 3, resumes the Japanese production during 10 years ; we notice that the Japanese lighting industry represents nowadays 15-25 % of the world-wide lamp production. However, light sources find application in several important industrial domains, for example, reprography, surface treatment, water and air purification, curing, and process monitoring and control. If these additional applications are taken into account the total word-wide turnover of light source related technology is 2-3 times higher than the above figure.

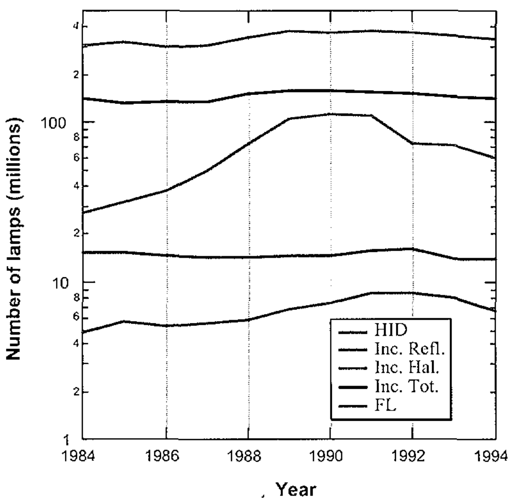

Figure 3: Annual production of Japanese lighting industry. (HID : High Intensity Discharge Lamps, Inc. Refl : Incandescence with reflector, Inc. Hal : Halogen Incandescence, Inc. Tot. : Incandescence Total, FL : Fluorescent)

Currently, more than 7.5 billion lamps operate world-wide consuming more than 2,000 billion kWh per year (10-15% of the global energy production world-wide). If, for an industrialised country, this amount is substantial (e.g. about 11% for France, 20% for US) it becomes very important for under-development nations for which lighting is one of the major applications of electricity (i.e. 37 % for Tunisia and up to 86% for Tanzania). Furthermore, the annual greenhouse gas (CO_2) due to this energy production is estimated to be in the order of 550 million tons. In future, it can be estimated that the need for light sources will increases by a factor of 3. More efficient light sources would

- limit the rate-of-increase of electric power consumption ;
- reduce the economic and social costs of constructing new generating capacity ;
- reduce the emissions of greenhouse gases and other pollutants.

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In fact, an improvement of 25% in the lamp efficacy corresponds to 250 billion kWh per year energy savings as well as 150 million tons less greenhouse gas in the atmosphere.

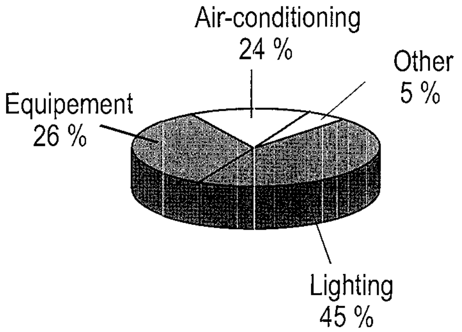

Figure 4: Repartition of electrical consumption of a typical commercial building in UK.

A large number of studies have been completed and published on the potential of energy savings through energy conservation measures. For example, as shown in Fig. 4, the commercial building sector, with more than 40 billion square meters of space in place, and representing, approximately, 30 to 35% of total electrical demand, is estimated to utilise more than 40% of its energy for lighting, and another 5 to 10% for air-conditioning necessary, in major part, for cooling air and building fabric heated directly or indirectly by current light generation technologies. Various estimates have indicated a potential for energy savings of 25 to 50% in the commercial sector by utilising newly available lighting technology. From the viewpoint of lighting design, the main focus of attention has been to increase the average efficiency from the range of 40 to 50 lumens per watt achievable using older fluorescent technology towards the figure of 100 lumens per watt made available using the latest fluorescent lighting systems.

Fluorescent lamps dominate the area lighting market and 1.2 billion are fabricated each year world-wide with Japan being responsible for 20% of this total. These light sources, as do several other commercially important types, contain a small amount of mercury. As a consequence, at the end of the lamp life-time a considerable amount of “undesirable” waste is generated, for example, 80 tons of wastes containing mercury are collected each year in France. It is well known that mercury is a highly toxic material, however, if mercury were eventually to be prohibited as a lamp dosant material on environmental grounds then this would represent an even greater challenge for the development of new generations of light sources with greater efficacy than is available at the present time.

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4. Some definitions:

The quality of a light source can only been defined in terms of the application for which it is designed. As the major application of light sources is lighting, the understanding of the "visual environment" is required before any attempt to optimise the light source. This visual environment consists on the light source, the object and the photoreceptor. In fact, "to see", means, using the photoreceptor to detect, to locate and to identify an object illuminated by a light source (Fig. 5).

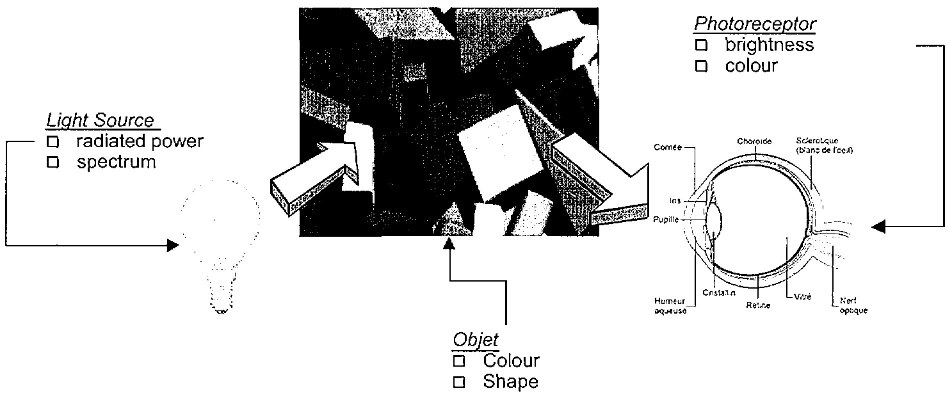

Figure 5: The visual environment

In the triad "source-object-photoreceptor" it is preferable to first examine the second item, the object, because this is a "passive" element with fixed properties. An object is characterised by its shape and its colour. The "colour" is a rather tricky idea because, as we will discuss latter, we "see" colours in our brain only. In fact, objects appear coloured by selectively reflecting or absorbing various wavelengths of light incident upon them. As an example, a red rose appears red to us (this not the case of a bee or a dog...) because it reflects light around 700 nm and absorbs all other wavelengths.

Let now focus our attention to the photoreceptor because its properties largely govern the needed visual properties of sources. In most common cases the human eye is this photoreceptor.

The eye pick up light from the source or the object and transmit the information to the human brain as two different independently perceivable signals: "brightness" and "colour", where colour is further broken down into "hue" and "saturation". The eye perceives different wavelengths and the brain

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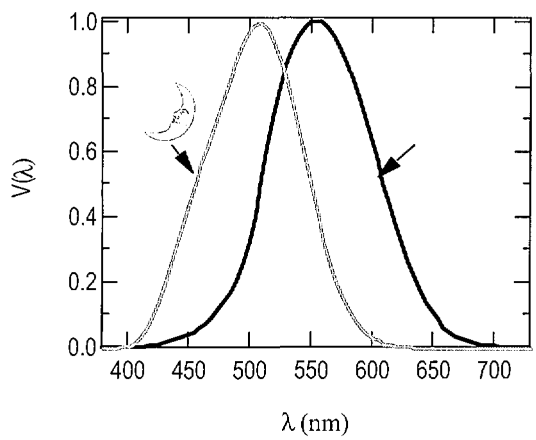

Figure 6: Brightness relative sensitivity of the "standard" human eye under photopic (sun sing) and scotopic (moon sign) vision conditions

"see" colours. The eye, as photoreceptor, is sensitive to only a narrow band of the electromagnetic spectrum, this band, corresponding to "visible light", stretch from 400 nm (violet) to 700 nm (red). Moreover, it is not uniformly sensitive within this pass band. The sensitivity varies with the illumination level, this is due to the fact two different type of detectors exist in the eye: the cones which perceive colour and necessitate a minimum illumination level of a few candelas per square meter (cd/m^2) and the rods which perceive grey levels corresponding to brightness, they are much more sensitive and faster than cones. Figure 6, shows the relative response of the "standard" human eye as function of the incident wavelength adopted since 1924 by the CIE (Commission Internationale d'Eclairage). The first curve (moon sign) corresponds to the eye response under low illumination level, called scotopic vision. The second one (sun sign) represents the receptor's sensitivity under high illumination level, this is the photopic vision. This latter is the only one concerning lighting design because the eye is "light-adapted" than "dark-adapted" under the most illumination levels produced by the man-made light. The brightness sensitivity is related to energy by the fact that at 555 nm (this wavelength corresponds to the maximum sensitivity of the human eye) a radiant watt emitted by the source is equal to 683 lumens (lm). Thus, the lumen should be considered as a "weighted" power unit taking in to account the human eye sensibility.

The light source is characterised by the radiant power and the emitted spectrum. The efficacy of a lamp is more delicate to define, in fact we will distinguish here the "electrical efficacy" to the "luminous efficiency".

We call electrical efficacy, ε, the ratio of the emitted power, P_r, expressed in watts, to all spectrum (visible, UV and IR) over the input electrical energy, P_{in} expressed also in watts:

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$$\varepsilon = \frac{\int_0^\infty P_r(\lambda)d\lambda}{P_{in}}$$

This is a unit-less quantity some times expressed as a percentage.

The luminous efficiency, η, expressed in lumens per watt, is a measure of how efficiently a lamp converts electrical power, P_{in}, expressed in watts, to visible light expressed in lumens:

$$\eta = k\frac{\int_{400}^{700} P_r(\lambda)V_{ph}(\lambda)d\lambda}{P_{in}}$$

We notice that the product, k $P_r(\lambda)V_{ph}(\lambda)$, between the radiant power (expressed in watts) and the photopic eye response, $V_{ph}(\lambda)$, gives the luminous flux expressed in lumens when k=683 lm/W.

The spectrum of an electrical lamp could be either continuum, this is the case of incandescence lamps, or line (band) spectrum characterising any discharge lamp. Recently a new lamp called “cluster lamp” produced a continuum spectrum mixed with spectral lines like a candle !

For most seeing tasks, colour perception of illuminated objects is important. If a light source has very little energy radiated in the part of the spectrum that the object can reflects then it look rather black (or grey). The Colour Rendering Index (CRI) is a measure of how well the light source reproduce the colours of any object in comparison to a black body radiating at the same “colour temperature”. The CRI of a lamp is obtained by measuring the fraction of light reflected from each of a number of surfaces of specific colours covering the visible spectrum. We arbitrary attributed a maximum CRI of 100 to this light source whose most closely reproduce colours.

We speak earlier of “colour temperature” without defining the term; this quantity, also called “Correlated Colour Temperature” (CCT) corresponds to the temperature of the black body whose spectra most closely represents the spectra of the light source. This CCT thus tell us something about the appearance of the light source. The “natural light” referring to direct sunlight has a CCT of 5100 K, whereas cloudy sky corresponds to higher CCT (6500 K). We notice here that a high CCT corresponding to a bluish light appear to create a “cold” ambience, on the opposite, a low CCT light source seems to a

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human being "worm"... Definitively, it is difficult to dissociate physical, physiological and psychological factors in the study of light sources ! Therefore, it is desirable for light sources designed for a variety of illuminating purposes to radiate light of all visible wavelengths, so that all coloured objects may be seen in something approaching their natural hues and saturation. Human beings differ widely in preferences, and it is therefore very difficult to quantify this measure of light source performance. In general, however, a universally accepted subjective criterion appears to be how people look when illuminated by the light source in question. If people look vibrant and alive, the colour balance of the light source is acceptable for most uses; if they look cadaverous or ill, it is unacceptable for applications in which people see one another illuminated by it.

Depending on the intended applications, commercial light sources will have different rating for the above characteristics (see Fig.7). The particular application, and the demands of the consumer are the principal driving force in lighting research.

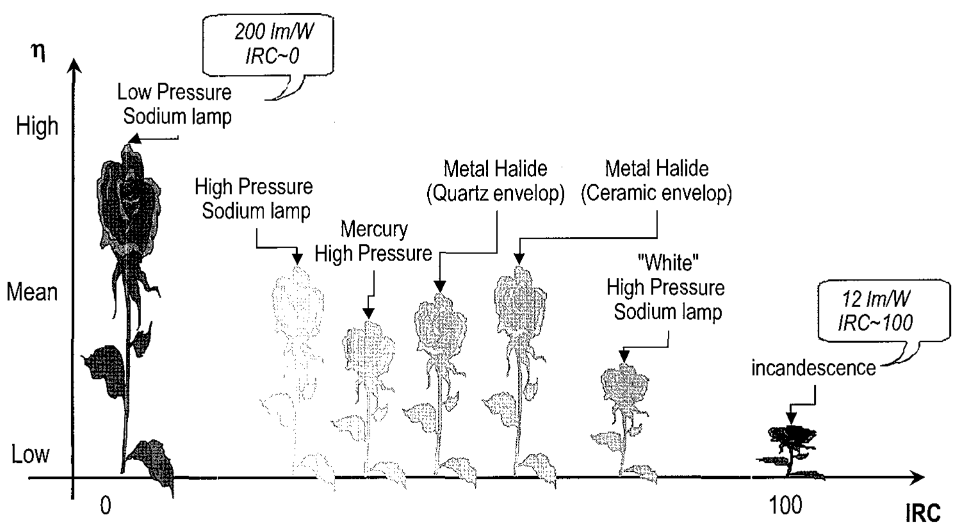

Figure 7: Rating of some electrical light sources according IRC and luminous efficiency

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5. The ideal white light source:

It is possible to define the theoretical optimum light source in terms of maximum luminous efficacy at 100% radiant power efficiency for a "white" light source having good colour rendering capabilities. If one were to specify a blackbody-like spectral power distribution in the visible, with zero radiant emission at any other wavelength, then at 100% radiant power efficiency, the luminous efficacy is about 200 lm/W.

However, it proves to be possible to do better than that; radiation in the far red or far blue is not effectively utilised by the eye for either colour response or brightness response, although these extremes are customarily considered part of the visible spectral band. Acceptably good colour-rendering properties may be achieved in a light source which is radiating in just three narrow wavelength bands: blue, green, and red. Most coloured objects have sufficiently broad reflectance spectra that they reflect light in two or more of these bands, and the eye-brain system accepts a colour definition dependent on the ratio of these two intensities of reflected light. Provided the wavelengths of the emission bands are chosen to be those corresponding to the maximum of the action spectra for the eye response to red, green, and blue, the brightness sensation perceived by the eye can be maximised simultaneously with the colour response. Light sources with such spectra can simultaneously have higher luminous efficacy than any continuous-spectrum source while maintaining nearly equivalent colour-rendering properties.

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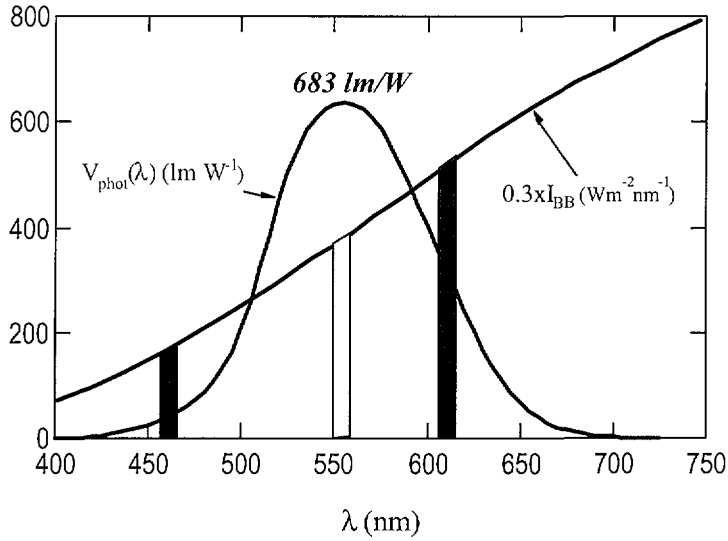

Figure 8: How calculate the maximum nominal efficiency of a white light source

For instance (see fig 8), consider an ideal source radiating as a black body at 3,000 K the following narrow spectral lines: 450, 555, and 610 nm, the eye photopic response has the values of 51.5, 683, and 343 lm/W at the three wavelengths respectively. Using the definition of the luminous efficiency, the integral in this relation is reduced to a simple sum:

$$\int_{400}^{700} P_r(\lambda) V_{ph}(\lambda) d\lambda = \sum_{i=1}^{3} I_{BB}(\lambda_i; 3000K) V_{ph}(\lambda_i)$$

where $I_{BB}(\lambda_i;$ 3000 K) is the emitted power from the black body at 3000 K and at a wavelength λ_i. The resulting luminous efficiency is approximately 300 lm/W, with the apparent "colour" of the light being the same as that of a blackbody at 3000K (this a realistic CCT value for white light), and colour rendering comparable to this blackbody emitter. This figure of 300 lm/W then represents the probable upper limit for luminous efficiency of a three-wavelength-emitting source having colour rendering acceptable for nearly all lighting applications.

As shown in Fig. 9, after increasing steadily throughout the previous seventy-five years, efficiency of conversion of electric energy into light by commercial light sources appears to have reached a plateau of about 33% of the theoretical maximum. No truly revolutionary new light sources have been

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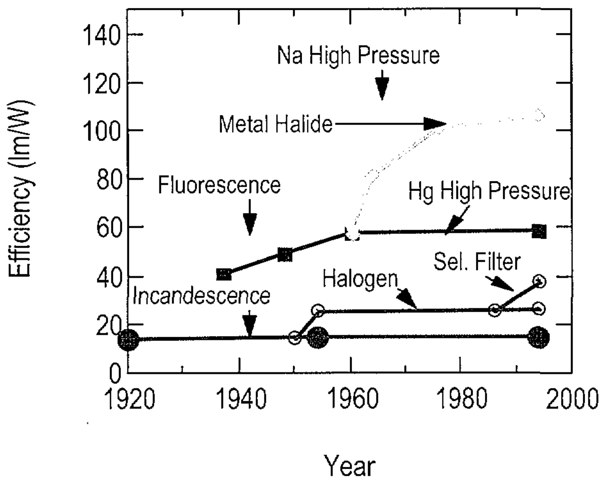
introduced since the mid-1960's, marked by the debut of metal-halide and high pressure-sodium arc discharge lamps. Light source developments since then have been primarily evolutionary, with incremental improvements in efficiency. Overall system gains in lighting efficiency have in the last decade primarily resulted from the substitution of more efficient sources for less efficient ones (viz. compact fluorescent replacing incandescent). To achieve the continued load-saving challenges that will be required in the future, much greater efficiency improvements, of about a factor of two, will be required. Furthermore, from an environmental point of view a drastic reduction or elimination of harmful substances is required (viz. complete elimination of mercury).



The inability to develop dramatically-improved light sources in recent decades has not resulted from lack of effort by the lamp manufacturers themselves. All of the major lamp manufacturers in the US and Europe have for many years maintained significant applied research and advanced development groups unburdened by day-to-day problem-solving responsibilities, but immersed in a highly-focused corporate climate. These groups have been, and continue to be, well aware of the limitations of existing lamps, materials and processes, and have been free to seek out better light-generating phenomena on which to base dramatically-improved products. If such phenomena were known at the present time then these groups would have explored them, modified them as necessary, and exploited them in commercial products. It seems, therefore that a fundamental reason for the present plateau in efficiency of light sources is that the industry has outrun the scientific base that has supported the technology since its inception: atomic physics and spectroscopy, and electron and plasma science, electronics and electrical engineering. Thus, the development of revolutionary new light sources having double the efficiency of current light sources can only be based on new scientific phenomena not previously considered for light source applications.

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All the above discussion concerns the two main characteristics of the ideal white lamp, the luminous efficiency and CRI. Furthermore a "good" lamp should fulfil several other requirements. In fact a "good" lamp should:

1. have a high efficiency
2. have a high CRI
3. have a long life
4. produce a stable light level during its lifetime
5. avoid flickering
6. produce its nominal flux instantaneously when turned on
7. be exchangeable with other types of lamps
8. be compact and light
9. avoid harmonic distortion feedback to the electric network
10. avoid environmental harmful materials
11. avoid electromagnetic interference with any other electronic equipment
12. avoid excessive heat and UV rejection
13. be recyclable
14. be inexpensive

6. Electric discharge lamps: Principle of operation:

An electric discharge lamp presents several advantages in comparison with any incandescence bulbs: It is a very efficient energy converter, transforming as 25 to 30% of the input energy into light; it last a long time, more than 2 years of continuous service (~10,000 hours); it have an excellent maintenance of the light output, typically delivering more than 80% of its nominal luminous flux during 85-90% of its life-time. This is excellent, but how a discharge lamp works ?

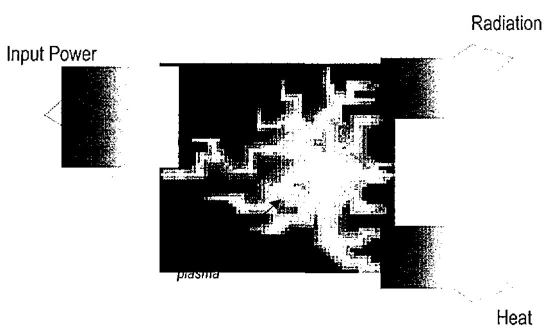

Fig. 10: An electric discharge transforms input power to radiation and heat

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Any electric discharge convert electrical input power to radiation and heat escaping from the plasma (Fig. 10). Depending on the intended application its possible to privilege radiation or heat escape (radiation should be predominant for a lamp !). In order to better understand who this transformation occurs we will artificially split the plasma into two populations: the charged and neutral particles and we will study the energy exchange mechanisms between these two populations and the environment.

The figure 11 illustrate the most important energy transfer mechanisms in the discharge plasma. The electric field generated by the external power supply represents, in most common cases, the unique energy input into the plasma. This field act on the charged particles, thus the electrical energy is transformed into the kinetic energy of moving electrons (the ion contribution is

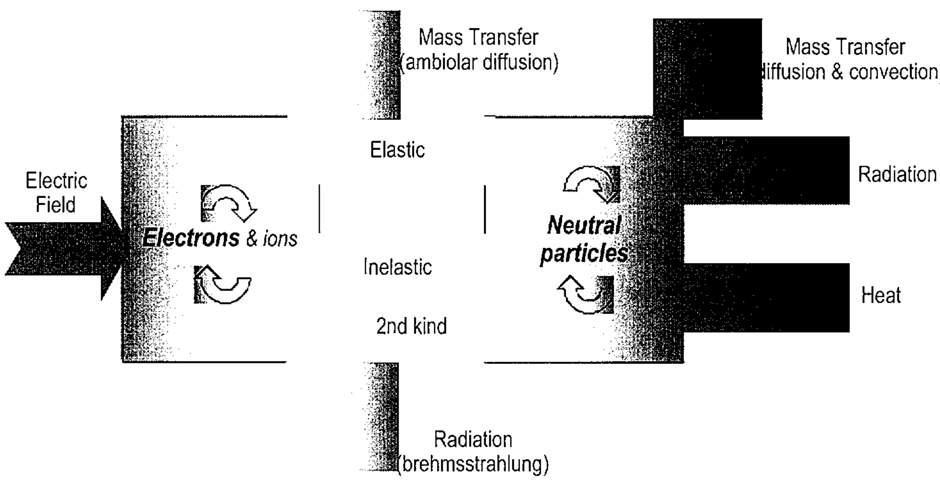

Figure 11: Energy transfer channels in a electric discharge plasma

in most cases negligible because of their high inertia). This energy is essentially redistributed via “collisional” and “radiative” channels. Elastic collisions between electrons or electrons and ions haven’t any direct incidence to energy transfer studied here. However, this type of collisions has a big influence on the Electron Energy Distribution Function (EEDF): it is generally accepted that EEDF is closer to the Thermal Equilibrium Maxwellian function when the electron-electron collision frequency is high.

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Elastic collisions between electrons and neutral particles (atoms and/or molecules), transfer energy from "hot" electrons and "cold" neutral particles. The number of such collisions is directly proportional to the product between the densities of electrons and neutral particles. In most cases the external circuit fixes the electric current in the discharge, by the way, the electronic density is almost fixed also. As the energy fraction transferred in each interaction is very low (proportional to the ratio of electron over neutral particle masses) it is clear that, for a given value of the electron density, a big number of collisions is needed for an efficient transfer of energy between those two populations. Thus, when the total neutral particle density (linked to the pressure by the perfect gas law) is relatively low, in steady state, the kinetic energy of the electronic population could be significantly higher than this of the neutral particles, the discharge is then very far from the Local Thermal Equilibrium (LTE) conditions. An example of a such system is the fluorescent lamp: the global operating pressure is in the order of a few hundred pascals, the mean kinetic energy of electrons is around 1 eV whereas the mean energy of the neutral particle gas is in the order of 1/40 eV. In the case of higher operating pressures (in the proximity of the atmospheric pressure) the energy exchange in efficient and both electrons and neutral gas have the same kinetic energy, this corresponds to a LTE discharge for which Maxwell's, Boltzmann's and Saha's laws are functions of the local temperature. The mercury high pressure (HID) lamp is a *typical* example.

The elastic collisions govern also the electron transport phenomena. The electron mobility and the discharge electrical conductivity are directly linked to the electron's mean free path in the plasma. This mean free path should stay in all cases lower than the dimensions of the vessel containing the discharge, otherwise the mean "life-time" of an electron in the plasma is not sufficient for the discharge maintenance. For several reasons, the most convenient way for controlling the mean free path is to impose the operating pressure. However, in some cases, like the fluorescent tube or other non LTE systems, increasing the pressure leads to a dramatic decrease of the radiant power and luminous efficiency. The solution to this problem consist to use gas mixtures and dissociate the role of each constituent: the "active" gas produce radiation (and new electrons) and the "buffer" gas, the role of the latter is, in principle, to control the mean free path of electrons in the plasma (this is an *idealistic* situation...). For example in the fluorescent TL lamps the active gas is mercury (partial pressure less than 1 Pa) and the buffer gas is in most cases argon (partial pressure 400 Pa). When pressure is high, the distinction

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between active and buffer gas is no more necessary, the active gas can play now himself the role of the buffer gas also. This the case of the HID mercury high pressure lamp. We would like to notice here the fact that in some cases, like sodium high pressure (SHP) or metal halide (MHL) lamps the use of the "buffer" gas is different than that described earlier.

Inelastic collision channels (excitation and ionisation) are responsible also for energy transfer between the "hot" electrons to the "cold" gas. This type of collisions is directly linked to the production of excited states (radiative and metastables) and generation of new electrons necessary for the discharge maintenance and electric current continuity. On the opposite, all 2nd kind collisions contribute to an additional heating of the electron gas and the non radiative destruction of the excited states.

Two additional channels exist for energy transfer from electron cloud to the discharge's environment:

The losses by "collective" mass transfer phenomena, the most known is the ambipolar diffusion. These transfer fluxes get electrons from the hotter parts of the discharge toward to the colder discharge's limits where energy is deposited.

Electromagnetic radiation is also emitted when electrons are decelerated because of interactions between charged particles. This radiation called brehmsstrahlung corresponds to a continuum spectrum, it is responsible for energy transfer from the discharge to its environment.

Finally, the energy communicated to the neutral particles via elastic and inelastic collisions is dissipated mainly as heat and radiation, a small part of this energy disappears by mass transfer (diffusion and convection) from the hotter part of the plasma to its colder outer zone. The radiation emitted from the discharge corresponds to a line (or band) spectra. This radiation can be generated everywhere in the plasma and photons travel to all directions. Some of these photons, during their travel will be reabsorbed and re-emitted several times before escaping from the plasma. Some others will "disappear" because of 2nd kind collisions responsible for the destruction of the excited states, this phenomenon called the "radiation trapping" play a prime role on the Thermal Equilibrium State of the discharge. For example, resonance radiation is the most concerned by this trapping because of the presence of an important number of potential absorbers, in the case of a relatively high pressure discharge an important part of this radiation will be trapped and the

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number density of the first excited states will increase. Then, by means of inelastic collisions between electrons and excited atoms it will be easier to get electrons to higher excited states and thus privilege the emission of some spectral line normally absent from a low pressure discharge.

In order to conclude this general discussion we should underline the fact that the Thermal Equilibrium State of the discharge has an important influence on what of the above channel are privileged instead of some others. A good knowledge of these energy transfer mechanisms coupled to all species population balance in the plasma offer us the possibility to predict optimal operating conditions according to the application.

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