Energy Efficiency Comparison between Compact Fluorescent Lamp and Common Light Bulb

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Abstract
For acquainting the students of applied physics and students of teaching physics with the concept of energy efficiency, electrical and spectral characteristics of two widely used lamps – integrated fluorescence lamp and common light bulb have been investigated. Characterization of the lamps has been done by measuring the spectral irradiance and constructing the voltage-current characteristics. Breaking voltage, electric resistance, energy efficiency, energy consumption and intensity spectral distribution, were determined. Also, the quantity of mercury present in the fluorescence lamp was determined by analysis of the spectral characteristics. The energy efficiency advantage of the fluorescence lamp over the common light bulb was shown through comparison of the examined parameters of the two lamps.

Keywords: Energy efficiency, common light bulb, integrated fluorescence lamp

INTRODUCTION

In 1850 Joseph Wilson Swan obtained device which consisted of carbonized paper filaments in an evacuated glass bulb, which worked in pour vacuum and inadequate supply of electricity resulted in a short lifetime for the bulb. Thomas Edison began serious research into developing a practical incandescent lamp in 1878. Namely, Edison continued to improve design with an electric lamp using a carbon filament or strip coiled and connected to platina contact wires (MacIsaac, Kanner and Anderson, 1999). The incandescent light bulb or incandescent lamp is a source of heat-driven light emissions. The principle of operation is simple. Electric current passes through a thin filament, thus heating which produces light radiation. The enclosing glass bulb prevents the oxygen in air from reaching the hot filament, which otherwise would be destroyed rapidly by oxidation. Incandescent bulbs are sometimes called electric lamps, a term originally applied to the original arc lamps. Incandescent bulbs are made in a wide range of sizes and voltages, from 1.5 volts to about 300 volts and higher. They do not need external regulating equipment and have a low manufacturing cost, and work well on either alternating current or direct current. Thus, the incandescent lamp is widely used in households and commercial lighting, for portable lighting, such as table lamps, some car headlamps and electric flashlights, and for decorative and advertising lighting. Today the incandescent light bulbs consist of a glass enclosure (the envelope, or bulb) which is filled with an inert gas to extend the lifelong by preventing evaporation of the filament. Inside the bulb is a filament of tungsten wire, through which an electrical current is passed (figure 1).

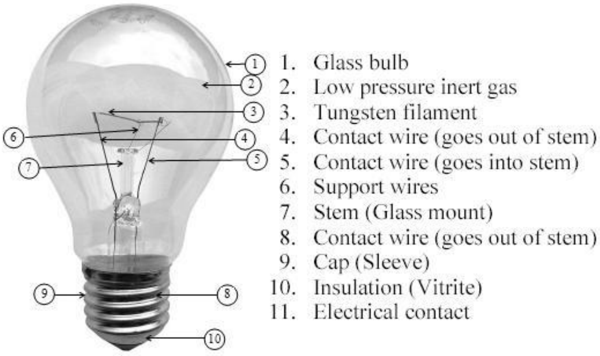

Figure 1. *A light bulb with a standard E27 Edison screw base*

Figure 2. *A spiral-type CFL*

The current heats the filament to an extremely high temperature (typically 2000 K to 3300 K depending on the filament type, shape, size, and amount of current through it according to the Joule-Lenz law or the Ohmic heating law). The heated filament emits light that approximates a black body irradiator in a continuous spectrum. The useful part of the emitted energy is visible light, but most energy is given. off in the near-infrared wavelengths.

The history of the fluorescent lamp begins with early research into electricity. By the beginning of the 18th century, experimenters had observed a radiant glow emanating from partially evacuated glass vessels through which an electrical current passed. Little more could be done with this phenomenon until 1856 when a German glassblower Heinrich Geissler (1815-1879) created a mercury vacuum pump that evacuated a glass tube to an extent not previously possible. When an electrical current passed through a Geissler tube, a strong green glow on the walls of the tube at the cathode end could be observed. Because it produced some beautiful light effects, the Geissler tube was a popular source of amusement. Thomas Edison (1847 – 1931) invented a fluorescent lamp in 1896, which used a coating of calcium tungstate as the fluorescing substance. As with a few other attempts to use Geissler tubes for illumination, it had a short operating life. Peter Cooper Hewitt (1861-1921) created the modern fluorescent lamp using mercury vapor lamp. Cooper-Hewitt’s lamp luminesced when an electric current was passed through mercury vapor at a low pressure.

A fluorescent lamp or fluorescent tube is a gas-discharge lamp that uses electricity to excite mercury vapor in argon or neon gas, resulting in a plasma that produces short wave ultraviolet light (figure 2). This light then causes a phosphor to fluoresce, producing visible light. Unlike incandescent lamps, fluorescent lamps always require a ballast to regulate the flow of current through the lamp. In common tube fixtures (typically 122 cm or 244 cm in length), the ballast is enclosed in the fixture. Compact fluorescent light bulbs may have conventional ballast located in the fixture or they may have ballasts integrated in the bulbs, allowing them to be used in lamp holders normally used for incandescent lamps. Until recently, the design of fluorescent lighting relied on electromagnetic ballast circuits. The main principle of fluorescent tube operation is based around inelastic scattering of electrons. An incident electron (emitted from the coating on the coils of wire forming the cathode electrode) collides with an atom in the gas (such as mercury, argon or krypton) used as the ultraviolet emitter. This causes an electron in the atom to temporarily jump up to a higher energy level to absorb some of the kinetic energy delivered by the colliding electron. Therefore, the collision is called 'inelastic' as some of the energy is absorbed. This higher energy state is unstable, and the atom will emit an ultraviolet photon as the atom's electron reverts to a lower, more stable energy level. The photons that are released from the chosen gas mixtures tend to have a wavelength in the ultraviolet part of the spectrum. This is not visible to the human eye, so must be converted into visible light. This is done by making use of fluorescence. This fluorescent conversion occurs in the phosphor coating on the inner surface of the fluorescent tube, where the ultraviolet photons are absorbed by electrons in the phosphor's atoms, causing a similar energy jump, then drop, with emission of a further photon. The photon that is emitted from this second interaction has a lower energy than the one that caused it. The chemicals that make up the phosphor are specially chosen so that these emitted photons are at wavelengths visible to the human eye. The difference in energy between the absorbed ultra-violet photon and the emitted visible light photon goes to heat up the phosphor coating.

Fluorescent light bulbs come in many shapes and sizes. The compact fluorescent light bulb (CF) is becoming more popular. Many compact fluorescent lamps integrate the auxiliary electronics into the base of the lamp, allowing them to fit into a regular light bulb socket (figure 2). Fluorescent lamps are more efficient than incandescent light bulbs of an equivalent brightness. This is because a greater proportion of the power used is converted to usable light and a smaller proportion is converted to heat, allowing fluorescent lamps to run cooler. Typically, a fluorescent lamp will last between 10 to 20 times if an equivalent incandescent lamp (Spezia and Buchanan, 2011).

Beginning in the 1990s a new type of ballast came into the mainstream, with a more expensive but significantly more efficient design: high frequency operation. The electronic ballasts convert the 50 or 60 hertz coming into the ballast to an output frequency more than 100 kHz. This allows for a more efficient system that generates less waste heat and requires significantly less power to light the lamp, while operating in a rapid starting manner. These are used in several applications, including new generation tanning lamp systems, whereby a 100-watt lamp can be lighted using 65 to 70 watts of actual power while obtaining the same lumens as traditional ballasts at full power. These operate with voltages that can be almost 600 volts, requiring some consideration in housing design, and can cause a minor limitation in the length of the wire leads from the ballast to the lamp ends (Kolawole and Akinsanmi, 2007; Parson, 2006). This technique is also applied in a steadily increasing number of so-called switch-mode power supplies, there to facilitate the use of a very much smaller transformer. This advantage comes as a by-product also to the electronic ballast because the principle of transforming at higher frequencies is the same. These ballasts run just a few degrees above ambient temperature, which is partly why they are more efficient and allows them to be used in applications that would be inappropriate for hotter running electronics (figure 3).

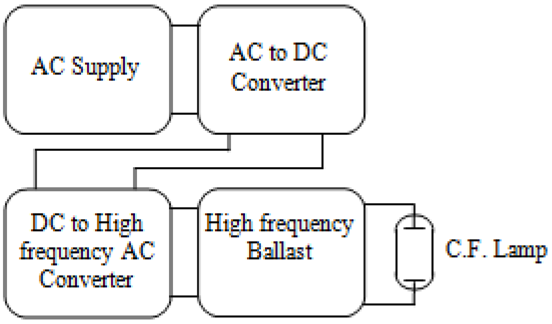

Figure 3. *Block Diagram of Electronic Ballast of a Compact Electronic Fluorescent Lamp*

Physical Fundamentals of Electrical Fluorescent Lamp and Common Light Bulb

There are two types of CFLs: integrated and non-integrated lamps. Integrated lamps combine a tube, electronic ballast and either an Edison screw or bayonet fitting in a single CFL unit. These lamps allow consumers to easily replace incandescent lamps with CFLs. Integrated CFLs work well in standard incandescent light fixtures. This lowers the cost of CFL use, since they can reuse the existing infrastructure. In addition, incandescent light fixtures are relatively inexpensive.

Some people find the color rendition produced by some fluorescent lamps to be harsh and displeasing. A healthy person can sometimes appear to have an unhealthy skin tone under fluorescent lighting. The extent to which this phenomenon occurs is related to the light's spectral composition, and may be gauged by its Color Rendering Index (CRI). CRI is a measure of how well balanced the different color components of the white light are, relative to daylight or an ideal blackbody irradiator. By definition, an incandescent lamp has a CRI of 100. Real-life fluorescent tubes achieve CRIs of anywhere from 50% to 99%. Fluorescent lamps with low CRI have phosphors, which emit too little red light. Colored objects appear muted. For example, a low CRI 6800K halophosphate tube will make reds appear dull red or even brown. Correlated color temperature (CCT) is a measure of the "shade" of whiteness of a light source, again by comparison with a blackbody irradiator. Typical incandescent lighting is 2700 K, which is yellowish-white. Fluorescent lamps are manufactured to a chosen CCT by altering the mixture of phosphors inside the tube. Warm-white fluorescents have CCT of 2700 K and are popular for residential lighting. Neutral-white fluorescents have a CCT of 3000 K or 3500 K. Cool-white fluorescents have a CCT of 4100 K and are popular for office lighting. Daylight fluorescents have a CCT of 5000 K to 6500 K, which is bluish-white. Daylight-type fluorescents look natural only if they are very bright. Some of the least pleasant light comes from tubes containing the older halophosphate type phosphors (chemical formula $Ca_5(PO_4)^3(F, Cl)$: Sb^{3+}, Mn^{2+}). The bad color reproduction is due to the fact that this phosphor mainly emits yellow and blue light, and relatively little green and red. In the absence of a reference, this mixture appears white to the eye, but the light has an incomplete spectrum (Nassara and Mednik, 2003). The CRI of such lamps is around 60. Since the 1990s, higher quality fluorescent lamps use either a higher CRI halophosphate coating, or a triphosphor mixture, based on europium and terbium ions, that have emission bands more evenly distributed over the spectrum of visible light. High CRI halophosphate and triphosphor tubes give a more natural color reproduction to the human eye. The CRI of such lamps is typically 82-100. A typical "cool white" fluorescent lamp utilizing two rare earth doped phosphors, Tb^{3+}, Ce^{3+}: $LaPO_4$ for green and blue emission and Eu: Y^2O^3 for red. The color of the light output can be adjusted by altering the ratio of the blue emitting antimony dopant and orange emitting manganese dopant. The spectrum is nearly identical to a normal fluorescent bulb except for a near total lack of light below 500 nanometers. This effect can be achieved through either specialized phosphor use or more commonly using a simple yellow light filter. These lamps are commonly used as lighting for photolithography work in cleanrooms.

EXPERIMENTS, RESULTS AND DISCUSSIONS

Electric resistance and energy consumption for the two types of investigated lamps, and the breaking voltage of the CF lamp, were determined from the experimentally constructed voltage-current characteristics. The experiments were conducted simply by working with universal power supply with integrated current and voltage meters. implies necessary recycling are given on figure 4.

The students could easily determine the voltage-current characteristics, with gradual increase of the voltage and reading the values of the current. Some of them asked about the jump of the current of one hundred volts of the CF lamp. The answer of the assistant was that is the minimum voltage for leakage current and emission of the light from the CF lamp. On the other hand, other students were intrigued about the non-ideal slope of the voltage-current characteristic of the compact fluorescent lamp. The explanation of the assistant should be that is because the temperature of the tungsten filament changes their resistance.

Electric resistance (in Ohms) and electrical energy consumption (in Watts) were determined at 220 V of operation. For the common light bulb, the obtained values are 1300 W and 37.5 W, respectively. For the CFL the obtained values are 6500 W and 7.5 W, respectively. The spectral characteristics of the two lamps were determined by doing measurements on spectral irradiance (in W/m^2/nm) in the visible range of 380 nm – 760 nm with incremental steps of 5 nm by using a Spectroradiometer ILT950, USA. The detection system was positioned at same distance for the two lamps (40 cm). On figure 5, intensity of spectral irradiation for CFL is given, and on figure 6, for the common light bulb, also. The two peaks in the spectrum at 435 nm and 550 nm on figure 5 are very close to the spectral lines of mercury in the CFL: 436 nm and 546 nm, respectively. The third peak at 580 nm comes from calcium halophosphate phosphor in powder state at the inside of the CFL glass.

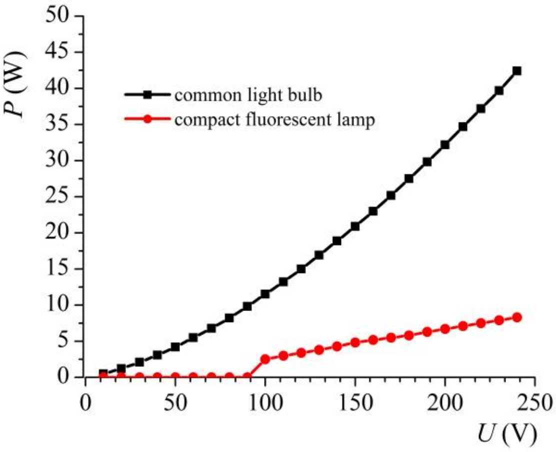

Figure 4. *Voltage-current characteristics of incandescent filament lamp and CFL*

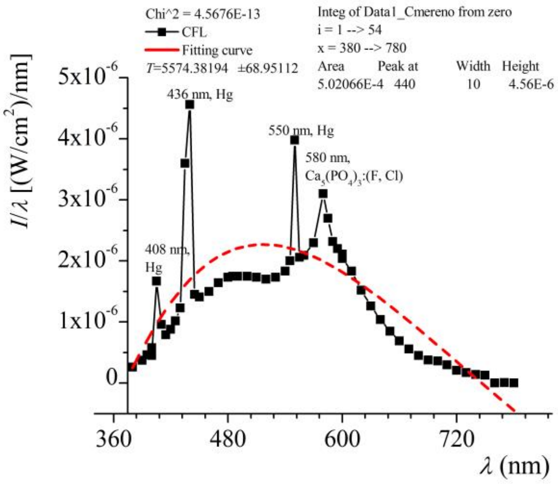

Figure 5. *CFL spectral irradiation. Fitting curve to the Planck’s formula with dashed line*

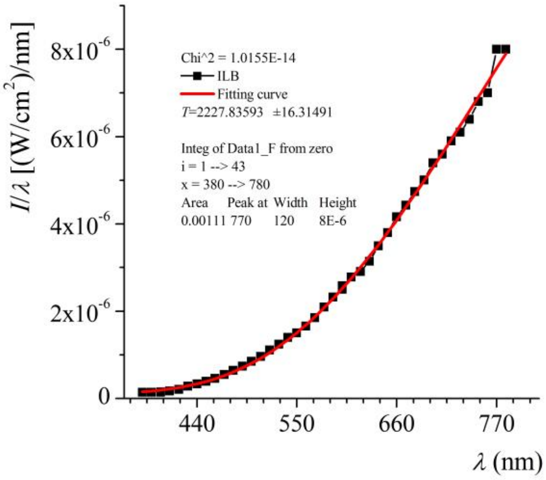

Figure 6. *Spectral irradiation of common light bulb. Fitting curve to the Planck’s formula with full line*

The equivalent temperatures of the lamps as black body irradiators were determined from the spectra of irradiation (fig.5 and fig.6) by appropriate fitting of measured values to the Planck’s formula for black body irradiation, given by the equation [Ralich and Ramsier, 2001]:

$$I(\lambda,T)=\frac{2hc^2}{\lambda^5}\frac{1}{e^{\frac{hc}{\lambda kT}}-1} \qquad (1)$$

Where λ is the wavelength, $h=6.62\times10^{-34}$ J·s is the Planck's constant and $k=1.38\times10^{-23}$ J·K^{-1} is Boltzmann's constant and $c=3.00\times10^{8}$ m/s speed of the light.

Origin software gives great opportunities of fitting curves (fig. 5 and fig. 6) with equations. Therefore, the students fitted the experimental results with function

$y=(P_4)*((P_1/(x^{\wedge 5}))*(1/(\exp(P_2/((P_3*x)-1)))))$, where the expression $2hc^2$ is replaced with constant P_1, hc/k is replaced with constant P_2, T-temperature is replaced with constant P_3, λ - wavelength is replaced with constant x and P_4 is constant. The students should set the function for the assistant to check. Then, they should choose the measured data and fit it with function, after couple of iterations. The software will show the value of the temperature and curves of fitting. If the difference between fitting curve of CF lamp and incandescent lamp raises questions, the assistant should explain furthermore that the mechanisms of radiant intensity is different for those two lamps.

It can be concluded that the measured 5574 K λ -68 K is in good agreement with the declared 6000 K λ -5 % for the CFL. Following the same procedure, for the common light bulb, 2227 K λ -16 K was found (figure 6). Although there is a visible disagreement with the spectral irradiation of a blackbody irradiator for the CFL (figure 5, red line), it has been found that the spectral irradiance distribution comes from the very intensive line spectral emission from mercury and calcium phosphate (Sharkov, 2003).

The radiance emitted over a wavelength range of λ_1 to λ_2 can be obtained from the integral $I = \int_{\lambda_1}^{\lambda_2} I(\lambda,T)d\lambda$. Light energy efficiency is defined as part from the input electric energy converted into electromagnetic waves in the visible region of the spectrum. It has been determined by integration of the spectral intensity distribution in the wavelength range 380 nm – 760 nm, then dividing it to the electric power of the lamps when illuminating.

Another, application of Origin software is the possibility of integrating the curves (fig. 5 and fig. 6). From the spectral characteristics of the two lamps, the integration will give the output energy of the lamps in watts, when the distance between the lamp and spectroradiometer ILT950 is considered. If the students have knowledge about photometric magnitude, they might ask for a solid angle. In fact, the solid angle is a measure of the relationship between the surface of the aperture in a spectroradiometer and the surface of an imaginary sphere around a light source, which is important in determining the lamp efficacy. The assistant should therefore explain the relation between the intensity of the light and distance from the source of light. It has been found that the energy efficiency of the common light bulb is 12 % and 27 % for the CFL, respectively. By comparing relative intensity of spectral line of mercury at 435 nm (figure 5) and handbook of spectra of various illuminators, it has been found that the CFL we used minimum of 3.5 mg of mercury. The fact that CFLs contain mercury, which is a toxic element, implies necessary recycling of CFLs after usage.

CONCLUSIONS

In the work presented, the basic knowledge how students at college, university or secondary school level can easily determine the voltage-current and spectral characteristics of incandescent lamp and compact fluorescent lamp, is presented. Several very important parameters for the quality of the lamps can be measured following this procedure: electric resistance, energy consumption, energy efficiency, intensity spectral irradiation, and breaking voltage for CFL. In addition, students can prove that there is mercury in CFL and thus careful disposal and recycling is needed for them because of its toxic effects.

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