Determining luminous efficacy of selected light sources

Exercise goals:
- determining illuminance as a function of distance from a source of light
- determining luminous efficacy of examined light sources (LED lamp, halogen bulb and traditional bulb)
- determining dependence of luminous efficacy from power consumption

Introduction

Patented by Thomas Edison in 1879 bulb is still very popular in home lighting. It's caused by low production cost, lack of stroboscope effect and electromagnetic spectrum similar to sunlight spectrum. Big disadvantage of light bulb is low luminous efficacy, only 2 – 4 % of energy consumed is converted to light. Because of that people were working on finding more economic substitutes for years. Currently a lot of different electrical light sources are available but their relatively higher luminous efficacy comes witch disadvantages. For over a decade fluorescent lamps can be found in our homes and efficient LED lamps in last few years. Big advantage of latter is long lifetime and high luminous efficacy (often more than ten times efficacy of traditional bulb). In this exercise we will focus on measuring latter parameter.

Determining luminous efficacy of light source

Luminous efficacy η is defined as ratio of *total luminous flux* Φ_C emitted by a source to *power* consumed by source P

$$\eta=\frac{\Phi_C}{P} \qquad (1)$$

Consumed power can be calculated by multiplying *voltage* U by *electric current* I flowing through light source

$$P=UI \qquad (2)$$

Luminous flux Φ is the amount of energy going through surface in the unit of time. By measuring the energy of light waves going through surface surrounding light source we get total luminous flux of light source Φ_C..

Measuring Φ_C is not easy because light sources have different shapes and energy of radiation they emit depends on direction (radiation is anisotropic). Special experimental methods are used to determine total luminous flux, such as photometric sphere or photometers mounted on special arm that allows measurement in different spacial configurations. Latter method allows the creation of spacial map of light distribution. In this exercise we will use simplified method of measuring total luminous flux based on the assumption that examined light source is isotropic point source. This means that the size is negligibly small and energy of emitted radiation is equal in all directions. This assumption is not true but later we will show that this simplification is justified.

Determining total luminous flux of isotropic point source based on measurement of illuminance.

Luminous intensity I_S is a basic photometric parameter. It's a ratio of luminous flux $d\Phi$ contained in infinitely small solid angle to value of this angle $d\omega$ (Figure 1)

$$I_S=\frac{d\Phi}{d\omega} \qquad (3)$$

The unit of luminous intensity is the *candela (cd)*. This unit is strictly defined, it belongs to the SI system. Name comes from latin (candela – candle) and originally luminous intensity of 1 *cd* corresponded to luminous intensity of specially created candle. Today, obviously, this definition is not precise enough.

When we are dealing with isotropic source of light we can write luminous intensity as a ratio of total luminous flux to value of entire sphere $I_S = \Phi_C / 4\pi$. After transformation we get the formula for total luminous flux

$$\Phi_C = 4\pi I_S \tag{4}$$

The unit of luminous flux is the *lumen (lm)* defined as luminous flux of a light produced by isotropic point source that emits one candela of luminous intensity over a solid angle of one steradian (1 *lm* = 1 *cd* · 1 *sr*).

In our exercise we will determine Φ_C using different physical quantity – *illuminance E* – using lux meter. Illuminance is the ratio of luminous flux $d\Phi$ to *area* dS on which light falls.

$$E = \frac{d\Phi}{dS} \tag{5}$$

The unit of illuminance is lux ($1 lx = 1 lm/m^2$) Figure 1 shows point light source and a part of surface *dS* being illuminated by flux $d\Phi$. If as *dS* we use total surface of a sphere with radius r ($S = 4\pi r^2$), then $d\Phi$ will be equal to total luminous flux emitted by source Φ_C. Formula for illuminance will be

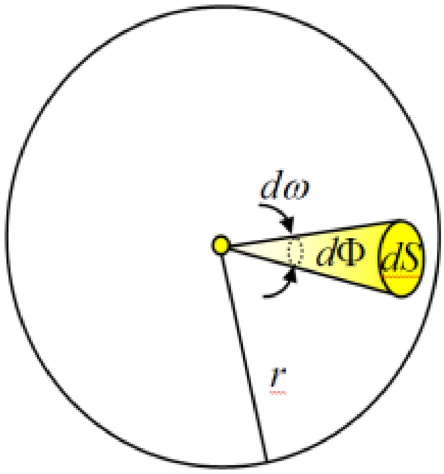

Figure 1: Radiation of point light source

$$E = \frac{\Phi_C}{4\pi r^2} \tag{6}$$

This equation shows that if we have isotropic point source measuring illuminance E from the distance of r from light source will allow us to calculate total luminous flux.

Can we treat bulb as point isotropic light source

Of course bulb is not a point source. It's proven, however that with a small approximation we can treat light sources as point sources if distance of measurement is at least 5 times bigger than size of light source. If our measurement will be made from far enough we can treat our light source as point source.

Isotropy is a more complicated problem. real sources more or less don't meet this criteria. for example so-called matt bulbs sends light evenly in all directions but in the direction of handle it's not emitted at all. Figure 2a shows so called candlepower-distribution solid showing intensity of radiation depending on direction from light bulb. Figure 2b shows illuminance depending on the angle (direction) from light bulb. It's easy to notice that we can observe highest values of illuminance for angles of 150^o and 210^o, for the 0^o angle value of illuminance is equal to zero. Dotted line of figure 2b shows average value of illuminance. Average value is close to the value for 90^o. We can approximate that the measurement of illuminance in the direction perpendicular to the axis of symmetry (90^o angle) is equal to the average value of illuminance. This approximation can be used only for selected light sources and can't be used for professional measurements.

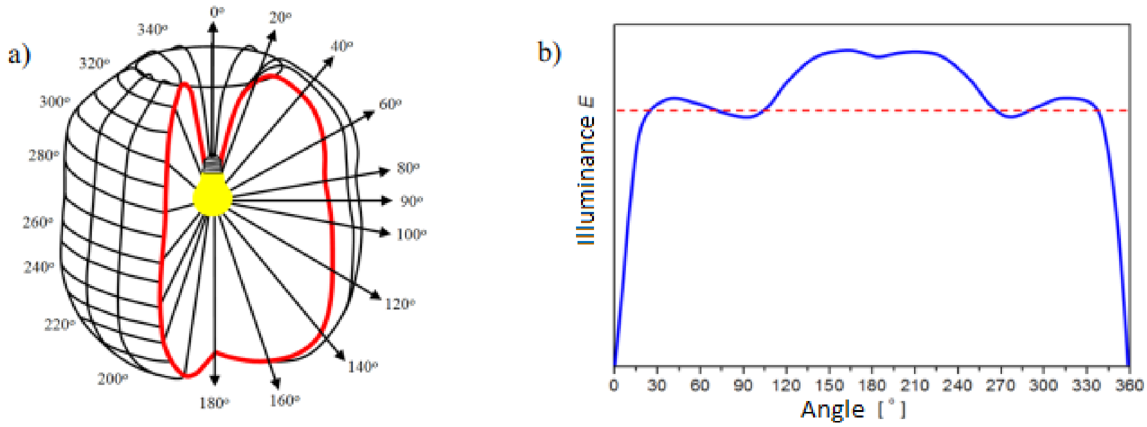

Figure 2: Example of light distribution by light bulb a) candlepower-distribution solid, b) illuminance as function of angle (direction) of emission. Dotted line shows average value.

Why is luminous efficacy of light bulb low?

Construction and working principle of light bulb hadn't change much in the last 100 years. It's a glass bulb usually filled with nitrogen, with tungsten wire inside (filament). As a result of flow of electric current filament is heated to about 2600 K. Every body at a temperature higher than 0 K emits electromagnetic waves. Most objects that surround us emit infrared light, invisible to human eye. Only after exceeding about 1000 K objects start so emit dark red light. Increasing the temperature causes emission of more colours: yellow, green, blue. We can observe combination of those colours as yellow-white colour. Still more than 95% of radiation is infrared. Luminous efficacy could be increased by increasing the temperature of the filament. For example if the temperature would be comparable to the temperature on the surface of the Sun (6000K) more than 40 % of radiation would be visible. Unfortunately this temperature is too high. Commonly used tungsten starts to rapidly evaporate in temperatures above 2600 K. In order to increase the temperature light bulbs started to be filled with halides (for example iodine, fluorine, bromine). Halides bond with atoms of evaporated tungsten, then, when they are close to heated up filament those compounds fall apart and tungsten is again settled on filament. This cycle is called halogen cycle and the bulb is called halogen bulb. Thanks to this cycle temperature of the filament in halogen bulb can be increased to 3000 K which gives us increase of luminous efficacy of about 30 % compared to traditional light bulb.

In past few years LED lamps are becoming more popular. LED lamp is usually a collection of light-emitting diodes covered in phosphor placed in casing designed for light bulbs. Working principles of LED lamp is completely different from light bulb, it's not heated up to hight temperatures. Diodes emit blue light which excites phosphor to shine. Yellow-green light emitted by phosphor combined with blue light of diode gives white light. In case of LED lamp, unlike light bulb, all emitted light is visible. Losses are result of efficiency of the device, which means that luminous efficacy of LED lamps is much higher compared to light bulb.

Measuring system

Measuring system is designed to measure luminous efficacy of 3 light sources: LED lamp, halogen bulb and traditional light bulb (filled with nitrogen). Additionally it can measure luminous efficacy as a function of power consumption by sources. Figure 3 shows experimental system. Light sources are in box PZ which can be moved perpendicularly to optic bench. Light detector connected to lux meter in located on scaled bench which allows measurements of illuminance depending on the distance of light source. Autotransformer ATr is used to power the light sources. Light sources, voltmeter, ammeter and autotransformer are connected through connection panel. On this panel switches P_1 and P_2 are located, those switches are used to turn on selected light source. Fig 4 shows scheme of electric circuit.

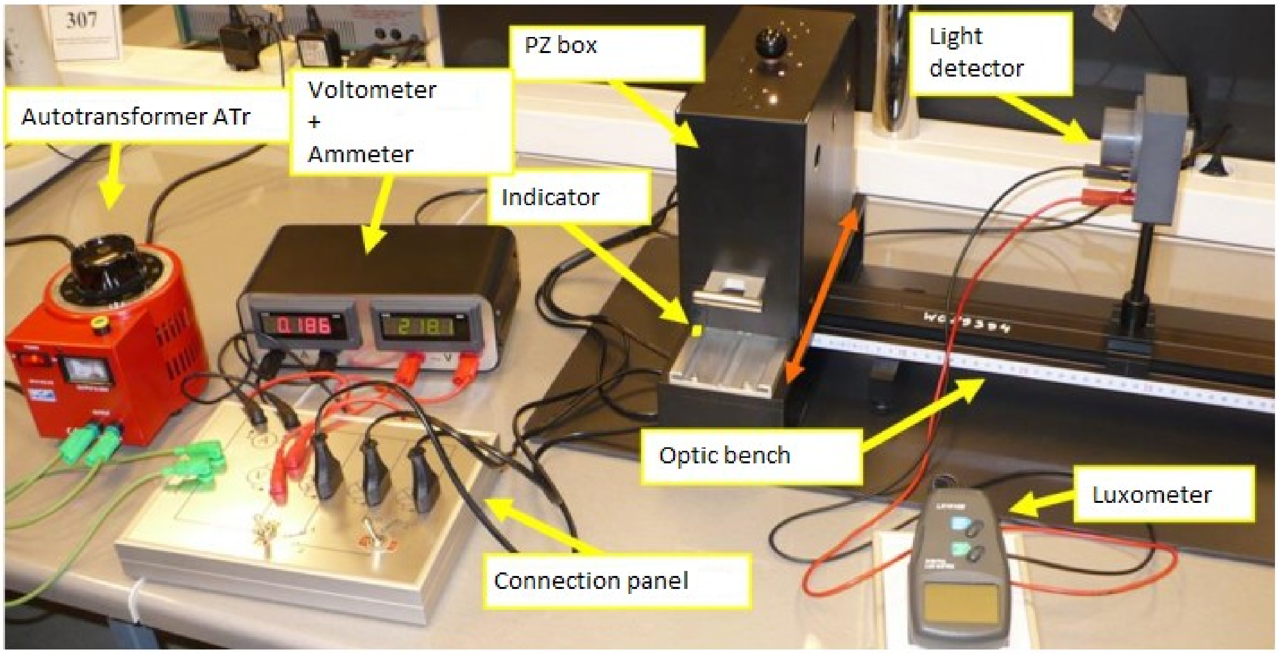

Figure 3: Experimental system used to measure luminous efficacy of selected light sources

Measuring luminous efficacy η of selected sources

In order to measure luminous efficacy of a light source box PZ should be moved in a way that light source is in front of light detector. Position "closest to yourself" means LED lamp is measured, middle position (box indicator on bench marker) means halogen bulb is measured, and position "farthest from yourself" is traditional light bulb. After turning selected source on values of voltage *U* and current *I* should be measured. After that measurements of illuminance *E* depending on distance *r* should be made. In order to calculate total luminous flux Φ_C formula (6) should be used. Using this substitutions: $y = E$, $x = 1/r^2$ and $a = \Phi_C/4\pi$, we get $y = ax+b$ type formula. This is linear function where *a* is slope. Creating chart of illuminance as a function of reversed squared distance: $E = f(1/r^2)$ should give straight line. Applying the method of linear regression to this results can give the value of slope *a*, and after that total luminous flux $\Phi_C = 4\pi a$. Using measurement of voltage U and current I we can calculate power consumption $P = UI$. Finally luminous efficacy can be calculated using formula (1).

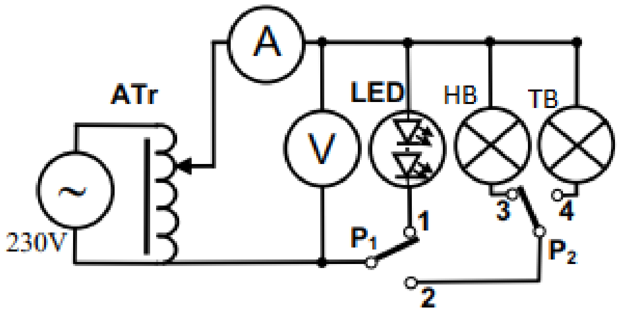

Figure 4: Electric scheme of power system and power measurement

Measuring luminous efficacy as a function of power consumption

In order to calculate how luminous efficacy depend on consumed power light detector should be placed in constant distance *r* in front of tested bulb. After that, perform measurements of illuminance *E* while changing Voltage using autotransformer. Using formulas (1), (2), and (6) we can create formula that will allow to calculate luminous efficacy of point isotropic source.

$$\eta = \frac{4\pi r^2 E}{UI} \tag{7}$$

Power should be calculated using formula (2).

Course of exercise

A. *Determining luminous efficacy η of light sources*
1. Move PZ box to position “closest to yourself” so LED lamp is in front of lux meter detector.
2. Move switch P_1 to position 1. Turn on voltmeter ammeter and autotransformer, next set voltage to 230 V. Write down values of voltage and current.
3. Make 10 to 12 measurements of illuminance depending on distance in range from 25 to 90 cm. Because dependence is not linear at first change distance by 2 cm, later by 5cm, in the end by 10 to 15 cm.
4. Repeat measurements for halogen bulb (switches P_1 and P_2 in positions 2 and 3) and traditional bulb (switches P_1 and P_2 in positions 2 and 4)
5. Using those results plot on one chart dependences of illuminances from distances from light sources $E = f(1/r^2)$ for examined sources.
6. Using method of linear regression calculate slopes of generated lines a and their errors, afterwards total luminous flux $\Phi_C = 4\pi a$ and measurement errors.
7. Using received results and formulas (1) and (2) calculate luminous efficacy of examined sources and errors.
8. Compare results and write down findings.

B. Calculating luminous efficacy as a function of power consumption $\eta = f(P)$.
1. Set up traditional bulb 35 cm in front of lux meter detector. After that turn on bulb circuit and using autotransformer set voltage to 230V.
2. Make 10 measurements of illuminance while changing voltage by 10V. Each time note down values of voltage and current.
3. Using formulas (2) and (7) calculate each value of power and luminous efficacy.
4. Repeat measurements for halogen bulb.
5. On one chart plot values of luminous efficacy depending on consumed power $\eta = f(P)$.
6. Write down findings.