Variation of light intensity - inverse square law

Background Theory

i Light emitted from any kind of source, e. g. the sun, a light bulb, is a form of energy. Everyday problems such as lighting required for various forms of labouring or street illumination, require one to able to determine and evaluate the intensity of light emitted by any light source or even the illumination of a given surface. A special group of studies is formed around these issues and it is called *photometry* .

Luminous flux is a scalar quantity which measures the time rate of light flow from the source. As all measures of energy transferred over a period of time, luminous flux is measured in Joules/Seconds or Watts (SI units). It can therefore safely be said that luminous flux is a measure of light power.

Visible light consists of several different colours, each representing a different wavelength of the radiation spectrum. For example red colour has a wavelength 610-700 nm, similarly yellow 550-590 nm and blue 450-500 nm.

The human eye demonstrates different levels of sensitivity to the various colours of the spectra. More specifically, the maximum sensitivity is observed in the yellow-green colour (i. e. 555nm). From all the above, it is clear that there is the need to define a unit associating and standardising the visual sensitivity of the various wavelengths to the light power which are measured in Watt's; this unit is called the special luminous flux unit of the *lumen (lm)* .

One lumen is equivalent to1/680 Watt of light with a wavelength of 555 nm. This special relationship between illumination and visual response renders the lumen the preferred photometric unit of luminous flux for practical applications. On top of that one of the most widely used light sources in everyday life such as the electric light bulb emits light which consists of many different wavelengths.

A measure of the luminous strength of any light source is called the light sources intensity. At this point, it should be said that the intensity of a light source depends on the quantity of lumens emitted within a finite angular region which is formed by a solid angle. To give a visual representation of the solid angle, recall that in a bi-dimensional plane the plane angle is used for all kinds of angular measurements. A further useful reminder regards the arc length s ; namely for a circle of radius r the arc length s is calculating by the formula

$S = r * q$ -Equation. 1

(qis measured in radians)

Now, in a three dimensional plane the solid angle W is similarly used for angular measurements. Corresponding to the q plane angle, each section of surface area A of a sphere of radius r is calculating by using the following formula;

$A= r^{2} *W$ -Equation. 2

(Remember that W is measured in steradians)

By definition one steradian is the solid angle subtended by an area of the spherical surface equal to the square of the radius of the sphere.

Taking into account all the above mentioned, the luminous intensity I of a light source (small enough to be considered as a point source) pointing towards the solid angle is given by:

$I = F/ W$ -Equation. 3

Where F is the flux measured in lumens. It is clear that the luminous intensity unit is lumen /steradian. This unit used to be called a candle, as it was defined in the context of light emitted from carbon filament lamps.

Generally speaking, luminous intensity in any particular direction is called the candle power of the source. The corresponding unit in the SI system is called the *candela (cd)* which is the luminous intensity emitted by 1/60 cm^2 of platinum at a temperature of 2054K (which is the fusion point of platinum).

A uniform light source (small enough to be considered as a point source) whose luminous intensity is equal to one candela, is able to produce a luminous flux of one lumen through each solid angle. The equation shown below is the mathematical expression of the above definition:

$F =$

$W * I$

-Equation. 4

Where I is equal to one cd and W is equal to one sr.

In similar terms the total flux F_t of a uniform light source with an intensity I can be calculated with the aid of the following formula.

$F_t = W_t * I$ – Equation. 5

And taking into account that the total solid angle W_t of a sphere is 4p sr, the above formula becomes

$F_t = 4p * I$ -Equation. 6

When a surface is irradiated with visible light it is said to be illuminated. For any given surface, the illuminance E (which is also called illumination) is intuitively understood and defined to be the flux indenting on the surface divided by the total area of the surface.

$E = F / A$ – Equation. 7

In the case where the several light sources are present and illuminate the same surface, the total illuminance is calculated by adding up all of the individual source illuminations. The SI unit allocated the illuminance is the *lux (lx)* where one lx is equal to 1 lm / 1 m^2 .

Another way of expressing illumination in the context of light sources intensity and the distance from the light source can be derived by forming a combination of the last few mentioned equations:

$E = F / A = I * W / A = I / r^2$ -Equation. 8

Where r is the distance measured from the source or the radius of a sphere whose total area is A ($W = A / r^2$). An important side note at this point is that 1fc equals 1cd/ft^2 and also 1lx is equal to1cd/ m^2 .

It is evident that the illumination is inversely proportional to the square of the measured distance from the light source. In the case of constant light source intensity I, it can be said that:

$E_2 / E_1 = r_1^2 / r_2^2 = (r_1 / r_2)^2$ – Equation. 9

In the real world, the incident light is very rarely normal to a surface; nearly always light impacts on a surface at an angle of incidence q.

In this case the illuminance is calculated by:

$E = I * \cos q / r^2$ -Equation. 10

To sum up, there are several ways which can be employed in order to measure illumination. Nearly all of them are based on the photoelectric effect originally discovered by Albert Einstein (for which he was awarded a Nobel Prize in 1921). In a few words when light strike sa material electron emission is observed and electric current flows if there is a circuit present.

This current is proportional to the incident light flux and to the work function of the material; the intensity of the resulted current flow is measured by instruments calibrated in illumination units.

Apparatus Components:

Light Sensor – Light Dependent Resistance (LDR)

Light bulb

Ruler

Power supply

Voltmeter

Ammeter

Connecting wires and Inline conductors

Two Vertical Stands

Black Paper

Experimental Apparatus

The experimental apparatus consisted off various parts. The basis of the light reception circuit was a Light Dependent Resistor (LDR) which is the essential part of the apparatus since in enables the measurement of the light’s intensity.

To give a brief introduction to this type of devices, it should be said that all kinds of materials exhibit some kind of resistance to electric current flow (which by definition is orientated flow of electrons). The particularity of an LDR device lays in the fact that its resistance is not constant; instead, it varies its value according to the light’s intensity that impacts on it. Generally speaking, LDR devices can be categorized in two main divisions: negative and positive coefficient. The former decrease the irresistance as the light’s intensity grows bigger; on the other hand, the latter increase their resistance as the light’s intensity becomes greater.

At the microscopic level, such a device consists of semi-conducting material like doped-silicon (the most commonly used material for electronic applications). When light impacts on the device material, this energy is absorbed by the covalent bonded electrons. Subsequently, this excessive energy breaks the bonds between the electrons and creates free electrons inside the material. These electrons are free to move inside the material and hence increase there sistivity of the material since they are no longer bonded.

Another essential part of the apparatus is the light source, which in this particular cause was an incandescent lamp (these lamp sare the most commonly used ones found in most everyday applications). The basic component of an incandescent lamp is the wire filament which is usually made of tungsten; this filament is sealed in glass bulb. Now, the bulb itself is filled with a mixture of low pressure argon and nitrogen in gaseous form. The use of those two gases is to delay the evaporation of the metal filament as well as itoxidation.

Ones current begins to flow through the tungsten filament, it gets so hot that it looks white. Under these operating conditions the filament itself ranges in temperature from 2500-3000 degrees Celsius. All incandescent lamps have continuous spectrum which lies primarily in the infrared region of the electromagnetic spectrum. The basic drawback of these devices is they poor efficiency, since more than 95% of the lamps energy is lost to the ambient environment in the form of heat.

The detailed apparatus used for this investigation is shown schematically in figure. 1. According to this figure the light source(incandescent lamp (light bulbs electrical characteristics required here)) is placed on a fixed stand and is kept at a vertical upright position looking upwards. It is evident that ones the bulb is switch on the light will be emitted isotropically towards all directions. A power supply((power supply’s electrical characteristics required here)) was used for powering up the light bulb and providing variable voltage values. In that way, as will be explained later, the intensity of the light emitted by the bulb will not stay constant and neither will the voltage across the LDR.

Opposite the light bulb, on another stand the LDR device has kept fixed in place with the aid of cohesive material (blu tack). The LDR device was placed normally to the light bulb so that the angle of incidence of the light coming of the source remains constant and normal throughout the experimental measurements.

Another observation that can be made from Figure. 1 is the interconnection between the LDR device, the voltmeter, the ammeter and the power supply. More specifically, in order for the LDR to function properly, a voltage was applied across the receiver circuit (4 Volts power pack in our case). The voltmeter was connected across the LDR device in order to constantly measure the value of the voltage across the LDR. These variations were due to the alternations to the intensity of the incident light (since the resistance value was changing).

The volt meter ideally would have infinite resistance, however in reality its resistance is finite and thus small deviations of the indicated voltage from the real value were expected.

Another quantity under monitoring was the current flowing into the LDR device. For this purpose an ammeter was placed in series with the LDR. Its rule was very important since the current flow into the LDR device had to remain constant throughout the experimental measurements. Again, the ideal ammeter would not have any impendence at all. In reality all ammeter demonstrate a finite albeit very small value of resistance: thus deviation of the indicated value from the actual one should be expected.

(Missing resistance for potential divider?)

A very interesting configuration (and very widely used) for light intensity measurements using the same components as the ones available for this practical can be seen in Figure. 1 with a little insight. A closer look to the receiver circuit reveals that a potential divider is formed by the way that the above mentioned components are connected. On a side note, measuring the current coming out of the LDR device would be feasible and relatively easy since the output current would be directly proportional to the value of the LDR resistance. A better way would be to measure the output voltage which happens to be the voltage across the LDR (i. e. the value monitor by the voltmeter). In this case the voltage is proportional to the current flowing through the LDR device. The second resistance required to form the potential divider comes from the finite internal resistance of the ammeter. The value of the output voltage V output can be calculated by using the standard potential divider formula shown below:

Vout = RLDR / (RLDR + RAMMETER)* Vin – Equation. 11

Where Vinis the voltage applied across the receiver circuit, RLDR and RAMMETER are the resistance of the LDR device and the internal resistance of the ammeter respectively.

Since the aim of those measurements is to investigate the relationship between the light intensity with distance, despite the fact that both the light bulb and LDR are kept fixed vertically the stand of the light bulb was able to be translated horizontally. For the purpose of the experiments the translation of the light bulb was made parallel with a ruler which was placed between the two stands. This configuration was quite optimal since it allowed the exact distance between light source and receiver to be know throughout the experiments.

In all optical experiments one of most fundamental error is the background illumination and the interference of other light sources. For this reason the apparatus was surrounded by black paper.

Experimental Procedure

The LDR sensor and the light bulb have to be at the same vertical height during all experimental measurements. One key point to notice is in that way the light bulb behaves as more like a point source of light, justifying the use of all mathematical equations. The LDR sensor has to point towards the light bulb at all times.

Having set up the experimental apparatus and chosen the range of the distance between the light bulb and the LDR sensor, a reference measurement of the LDR sensor was made having the light bulb switched off. Depending on the power of the light bulb a starting distance of 10 cm was deemed to be sufficient for the calibration purposes. Progressively, after performing the calibration this distance as explained below increased. Similarly, the rest of the experimental apparatus’s components (i. e. receiver device, voltmeter, ammeter, etc.) were also switched off during this very crucial calibration phase of the practical; generally speaking it is very good and common practice as well as much more preferable to carry out the calibration and experimental procedure in conditions of total darkness. The previous step insured that the background illumination was measured and this value would have to be deducted from all further measurements. Hence the error of the measurements is eliminated and their credibility is increased by a great degree.

The light bulb was initially switched on by applying a specific voltage across it; subsequently the exact distance between the light bulb and the LDR was measured using the ruler. The next and most important step at this stage was to measure the value of the potential difference across the LDR device for this specific position of the light bulb. For reasons of reference, the value of the ammeter was also recorded.

The position of the light bulb stand was then altered along the ruler in constant and knows intervals of distance. For each known distance the above measurements had to be repeated over and over. At this stage it would be useful to emphasize that the acquisition of the above data can be made for more than one time per known distance r, since averaging of data decreases the error percentage in the experimental measurements obtained. In that way, a comprehensive chart or table can be formed associating distance values (between the two stands) to output voltage values.