CENCO Physics
Selective Experiments In Physics

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ILLUMINATION AND PHOTOMETRY

OBJECT: To measure the luminous intensity of an incandescent electric lamp and its luminous efficiency for several applied voltages.

METHOD: A standardized electric lamp and a test lamp illuminate opposite sides of the screen of a Bunsen photometer. Equal illumination from the two sources is achieved by adjusting the position of the screen. Thus the luminous intensity of the test lamp and its luminous efficiency may be determined for a series of applied voltages.

THEORY: The word *luminous* as applied to the intensity or efficiency of a source of light refers to that portion of the emitted radiation which affects the retina of the eye as *visible* light. The human eye is sensitive to electromagnetic radiation only in the range of wavelengths from about 4000 to 7000 Angstroms or 4 x 10^{-7} meter (violet) to 7 x 10^{-7} meter (dark red). However, the eye is not equally sensitive to all colors of the visible spectrum. For a given amount of radiation in each of the wavelengths, the eye has its greatest visual response to radiation in the green-yellow (GY) part of the spectrum as noted in Fig. 1.

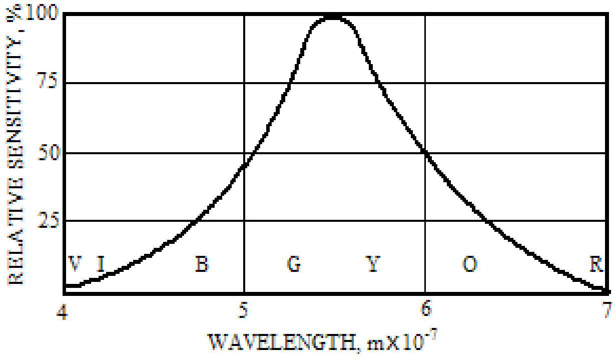

Fig. 1. Relative sensitivity of the eye to radiation in the visible spectrum.

The type of *radiant flux* emitted by a source of light depends on the nature of the source and the manner in which it is excited. If the source is an incandescent lamp, the prime factor determining its radiation characteristics is the temperature of the heated filament. When the temperature is below about 700°C, the emitted energy is almost entirely heat radiation and, hence, invisible to the eye. Increasing the filament temperature not only increases the amount of radiation emitted, but also adds increasingly shorter wavelengths which fall in the visible part of the spectrum. The color of the filament becomes progressively dark red, bright red, yellow red and eventually white-hot. The white-hot color occurs when all the visible wavelengths are added in the correct amount. This requires a temperature of approximately 3000°C. To equal the white of sunlight would require a temperature of about 6000°C, which is above the melting temperature of the filament. Figure 2 shows this change in radiant flux as a function of wavelength. The visible or luminous flux, shown within the shaded area, is that part of the total radiant energy per unit time that is effective in producing the sensation of light. It will be noted that only a small portion of the radiant energy is visible light or luminous flux. Incandescent lamps seldom emit more than ten percent of their input energy as visible light.

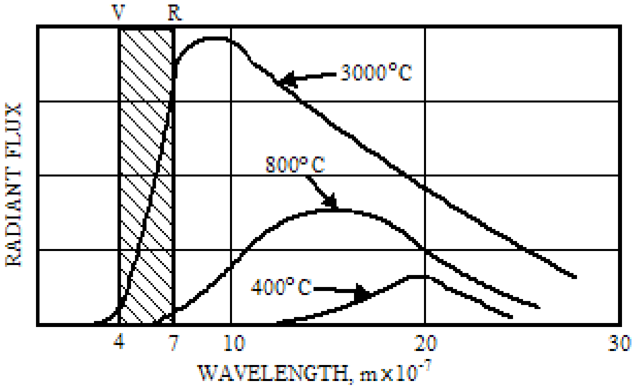

Fig. 2. Change of radiant flux with temperature of an incandescent body. Shaded area is the visible spectrum.

The *luminous intensity I* of a source is normally expressed in candles. This word, selected many years ago, comes from the original and arbitrarily accepted standard source, which was a given spermaceti candle. By international agreement, this very unsatisfactory standard was later replaced by another, but the name candle was retained. For practical purposes, an electric lamp whose luminous intensity has been calibrated in candles is used as a standard lamp.

The *luminous flux F* emitted by a standard one-candle source is accepted as being 4π *lumens*. Therefore,

$$F = 4\pi I \tag{1}$$

A source that has an intensity *I* of 20 candles thus emits a luminous flux *F* of 4π lumens/candle × 20 candles = 80π lumens. Note that the luminous intensity of a source may be expressed also by stating the rate of emission of light in lumens.

When the source of the light is a point source in space, the luminous flux F emitted flows outward and equally in all directions. At any distance R from the source this flux is incident on spherical area equal to $4\pi R^2$. The luminous flux incident on a surface per unit area is called the *illuminance E* of the surface. The defining equation is

$$E=\frac{F}{A} \tag{2}$$

A commonly used unit of illuminance in the metric system is the lumen per square meter. In the English system, illuminance is expressed in lumens per square foot (foot-candles). Relating the area A to the spherical surface gives

$$E=\frac{F}{4\pi R^2}$$

Combining Eq. (1) and (2) gives

$$E=\frac{4\pi I}{4\pi R^2}=\frac{I}{R^2} \tag{3}$$

This equation states that the illuminance of the surface at a distance R from a point source of luminous intensity I is directly proportional to the luminous intensity of the source and inversely proportional to the square of the distance between the point source and the surface.

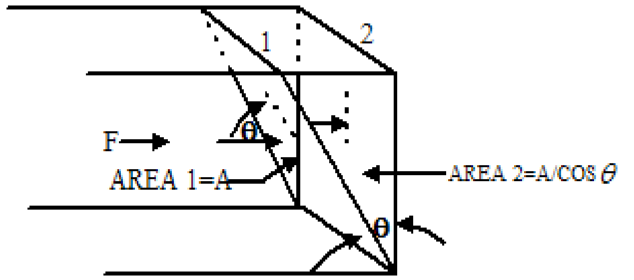

Fig. 3. Effect of angle of flux incidence on the illumination of a surface.

If the surface on which the luminous flux falls is not perpendicular to the flow direction, less flux falls upon each unit area. When a surface of area A (see Fig. 3), has an angle θ to the direction of flow, the surface receives the same flux F as the smaller "normal area" beyond it. This area is $A/\cos\theta$. Consequently the illuminance of the first surface is less than that of the second surface by a factor $\cos\theta$.

The eye is not capable of an accurate comparison of the light intensity of two lamps by viewing them directly. However, one can match quite accurately two surfaces which are illuminated by white-light sources. This is the principle of a device called a *photometer.* The photometer is so constructed that two light sources, shown as 1 and 2 of Fig. 4, each illuminate a separate white surface which can be viewed simultaneously by the eye. The two mirrors M make this possible in the photometer shown. Next, the distances, R_1 and R_2, of the lamps from the surfaces are varied until both surfaces appear equally illuminated.

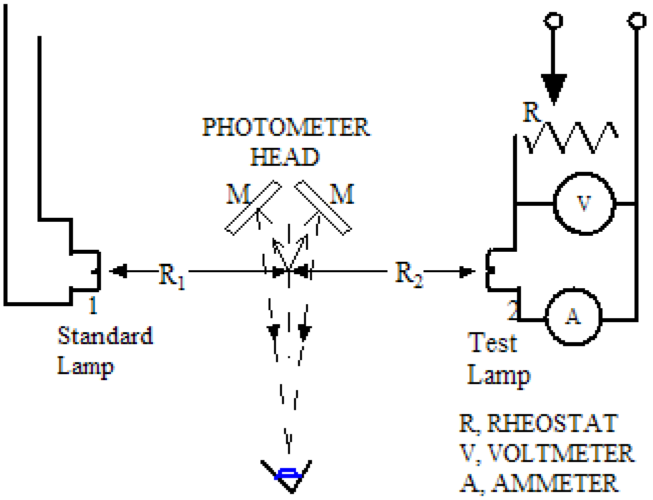

Fig. 4. Bunsen photometer.

Then $E_1 = E_2$. Applying Eq. (3) gives

$$\frac{I_1}{R_1^2}=\frac{I_2}{R_2^2} \tag{4}$$

Thus, if the luminous intensity I_1 is standardized or known, the value of I_2 may be computed.

The *luminous efficiency* of an incandescent lamp is sometimes defined as the number of lumens of luminous flux emitted by the lamp per watt of electric power P supplied to the lamp. Expressed in equation form,

$$\text{Luminous efficiency}=\frac{4\pi I}{P} \tag{5}$$

To measure the power P supplied, it is necessary to use a voltmeter and an ammeter in the test lamp circuit. A watt-meter may be substituted for the ammeter and voltmeter to read directly in watts the power supplied. The product of the voltmeter and ammeter readings, V times i, gives the power P in watts.

Notice that the unit of luminous efficiency, so defined, is in lumens per watt. A 40-watt incandescent lamp operating at its prescribed voltage has a luminous efficiency of about 12 lumens per watt. Its luminous intensity then is

$$I=\frac{F}{4\pi}=\frac{12 lumens/watt\times 40 watts}{4\pi lumens/candle}=38 candles$$

When a greater potential difference is applied to the lamp, the temperature of the lamp rises, and thus the luminous intensity of the lamp increases.

The luminous efficiency of a fluorescent lamp (40-watt) is some five times greater than the incandescent type of lamp. This ratio is less when higher wattage sources are compared.

Fig.5 Bunsen photometer (complete)

APPARATUS: Bunsen photometer (Fig. 5), standard lamp and test lamps (preferably 40watts each), 0 to 0.5amp ammeter, 0-150volt voltmeter, 150ohm rheostat. (The standard lamp must be operated at its prescribed terminal voltage. If the source voltage deviates from the value prescribed, an additional rheostat and voltmeter are required for the standard lamp circuit.) Experiments I and II may be performed without the meters and rheostat.

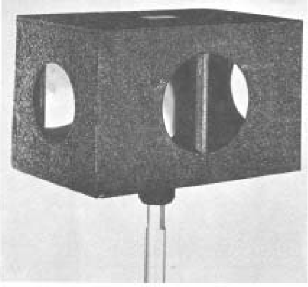

Fig. 6. Head of Bunsen photometer.

The head of the Bunsen photometer is shown in Fig. 6. The center portion, on which the incident light falls, is made of two sheets of heavy white paper with a star-shaped center opening. A thin sheet of paper, inserted between the two, has a grease spot which fills the opening. When the screen is illuminated from one side, and viewed from the same side, the grease spot appears darker than the surrounding area. This is because the grease spot transmits light, and thus the surrounding area reflects more light than does the grease spot. When viewed from the other side, the grease spot is made brighter than the surrounding area by the transmitted light.

When the surfaces are equally illuminated from both sides, the contrast between the spot and the surrounding paper will be the same on both sides. This is the condition needed to satisfy the photometer expression, Eq. (4). The distances R_1 and R_2 for the two light sources are adjusted to provide the same illuminance on both sides.

PROCEDURE: Arrange the apparatus as shown in Fig. 4.

Check to see that the standard lamp has the prescribed potential difference on its terminals and that it maintains this potential in order that its luminous output will be of the rated candle value. The laboratory room should be as dark as possible, and any reflecting surfaces in the line of sight of the photometer head should be shielded.

The theory calls for a point source and normal incidence of flux on the surface illuminated. This condition is approximated to the extent that the distances R_1 and R_2 are made large compared to the size of the sources. It is suggested that the following plan be used for all measurements: Place the standard lamp near one end of the meter stick and the photometer head near the other end of the stick. Locate the test lamp on the opposite side of the photometer head at such distance that the screen illumination or illuminance is approximately balanced on the two sides. Measure the distance R_2. Move the standard lamp to the best position for equal illuminance. Record the reading. Displace the standard lamp and again find the best balance position. Repeat several times. Use the mean of these readings to determine R_1.

One may find it difficult to locate accurately the position of equal illuminance. As a substitute locate the position of just perceptible imbalance on each side of it and use the midpoint between these two as the accepted position.

Experiment I. To measure the luminous intensity of the test lamp.

Adjust the potential applied to the test lamp (preferably a 40-watt lamp) to the voltage marked on the bulb. Using the procedure stated above determine R_1 and R_2 and compute the luminous intensity of the test lamp in candles. Repeat for a second similar lamp placed at the same distance R_2 from the screen.

Experiment II. To test the inverse square law.

Place side by side at a distance R_2 from the screen the two lamps whose luminous intensities were measured in Experiment I. The illuminance of the screen is now approximately doubled. Experimentally determine the distance R_1 of the standard lamp for equal illumination. Compare the experimental value of R_1 and the computed value, using Eq. (4).

Experiment III. To determine how the applied voltage affects the luminous intensity and luminous efficiency of the source.

Following the procedure stated previously, obtain data to compute the power input and the luminous intensity of a test lamp operated in succession at several terminal voltages. Use 100, 110, 120volts and the maximum voltage available.

The data and computed results can be recorded conveniently in Table 1.

Plot the graphs:

(a) Applied potential as a function of luminous intensity.

(b) Applied potential as a function of luminous efficiency.

Draw conclusions from each of these graphs

QUESTIONS: 1. A small lamp placed 1m from a surface provides the surface with an illuminance of 12 lumens per meter. What is the illuminance when the source distances are increased to 2, 3, and 4m?

2. An incandescent lamp is marked "120volts." What gains and what losses would the user experience if he used

the lamp on a 110volt circuit? On a 130volt circuit?

3. Photocells are used in illuminance measurements. What characteristics must the cell have in order to be a suitable substitute for the apparatus of this experiment?

4. The illuminance on a study table is 100lumens per square meter when the light source is 8ft directly above the table. What is the approximate illuminance on the table when the lamp is moved 6ft horizontally?

5. Two-inch squares of black, red and white cloths are placed side by side on the wall of alighted room. Is the illuminance and the brightness of each the same? Discuss.

6. A 20watt, 120volt lamp has a luminous efficiency of 10 lumens per watt. What is the luminous intensity, in candles, of this lamp?

7. What assumptions were made in the performance of this experiment?

8. Explain what bearing the theory of this experiment has on the seasons summer and winter.

TABLE I

Potential (volts)	Current (amp.)	R_1 (cm)	R_2 (cm)	Power, P (watts)	Lum. Int., I (candles)	Lum. Eff.= $\frac{4\pi I}{P}$ (candles/watt)
100						
110						
120						
(max.)						