• C.J. Overbeck Northwestern University • R.R. Palmer Beloit College • Marsh W. White The Pennsylvania State University

EFFICIENCY OF AN INCANDESCENT LAMP

OBJECT: To determine by means of a photometer the relationship between the efficiency of an incandescent lamp and the potential drop across it.

METHOD: A standard lamp and a test lamp are placed at opposite ends of a photometer bench. By adjusting the position of a photometer box so that its screen is equally illuminated on the two sides, the candle power of the test lamp is determined. This is repeated for various voltages on the test lamp and the relationship between the voltage and efficiency (candles per watt) determined.

THEORY: An incandescent electric lamp consists primarily of a metal or carbon filament which may be heated to

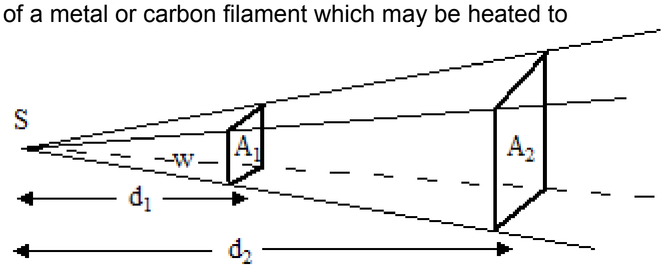

Fig. 1. The flux depends upon the solid angle subtended by the surface.

incandescence by means of an electric current. As far as the nature of the emitted light is concerned, the fact that electricity is used in heating the filament is not significant. The character of the radiation depends upon the temperature* of the filament, and if the filament were brought to the same temperature by any other means the resulting radiation would be exactly the same. Since the character of the radiation from the filament depends only on the temperature, the radiation is called *thermal radiation*. It is advisable, therefore, to begin the study of electric lamps with a discussion of thermal radiation.

*The only other factors that affect the character of the radiation are the condition of the filament's surface and the nature of the glass envelope. These factors are relatively unimportant.

If a body emits energy by means of electromagnetic waves, the body is called a radiating body and the energy carried by these waves is known as radiant energy. Suppose the point S in Fig. 1 represents a small radiating body and that this body is radiating equally in all directions. Since the radiation travels in straight lines it is obvious that the same quantity of radiant energy falls upon the surface A_1 in a given time as upon the larger but more distant surface A_2 It should be clear from Fig. 1 that the rate at which a surface receives energy from this source depends only on the solid angle ω subtended by this surface. The rate of flow of radiant energy through a surface is called the *radiant flux* and usually is expressed in watts.

The radiation from a hot body is made up of many wavelengths. The manner in which the radiant energy is distributed among these wavelengths is shown in Fig. 2. Curve A represents the distribution of the energy for a body at the temperature of melting iron, curve B for a body at the temperature of the filament in a carbon lamp and curve C for a body at the temperature of the filament of a modern tungsten lamp. Since it may be shown that the area under each of these curves is proportional to the total radiation, it is evident from these curves that: (a) as the temperature of the body rises the total energy radiated by the body increases; (b) as the temperature rises the fraction of the energy in the visible region increases; (c) even in the case of the tungsten filament a very small fraction of the energy radiated is in the visible part of the spectrum.

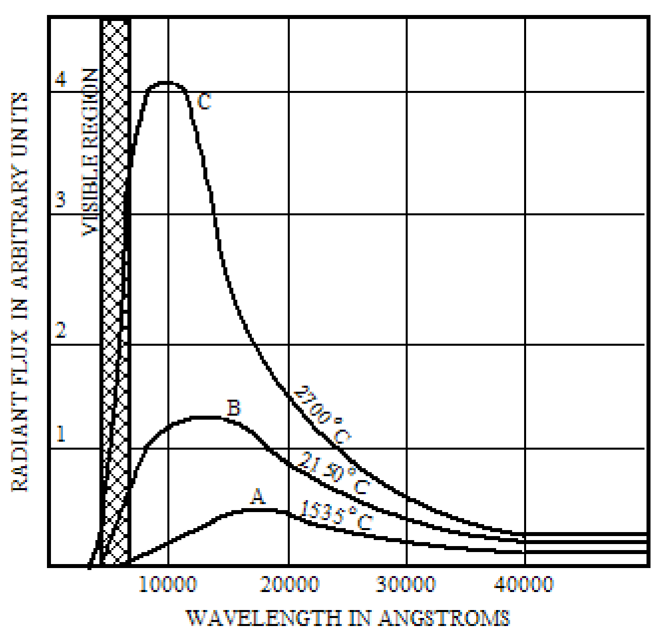

Fig. 2. The character and quantity of the radiant flux vary with the temperature. For easy identification the visible part of the spectrum is shown shaded.

Not only is it true that the eye does not respond to all light frequencies, but even in the visual region the eye is not equally sensitive to all colors. The relative visibility of the eye for radiation of various wavelengths is shown in Fig. 3. From this curve it is evident that the eye is most sensitive to radiation having a wavelength of approximately 5550 Angstroms (5550 x 10^{-8}cm). In other words, a certain amount of radiant energy received by the eye will produce a much greater visual sensation if the radiation is in the green-yellow part of the spectrum than if it is in the blue or red parts of the spectrum. Relative visibility may be thought of as visual efficiency and the curve of Fig. 3 as showing graphically the relative efficiency of the eye for various colors.

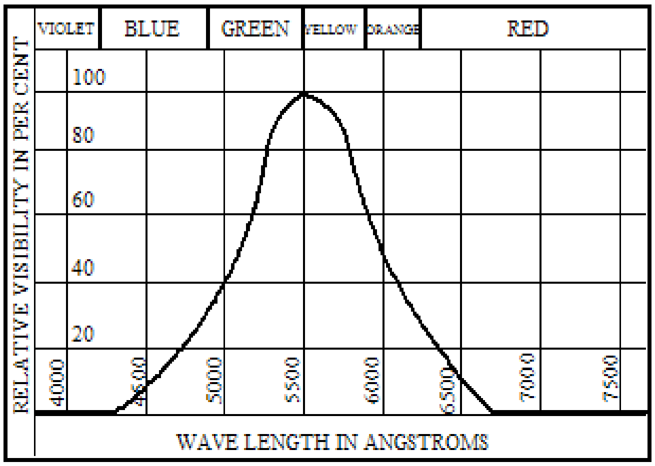

Fig. 3. The eye is most sensitive to light in the middle part of the spectrum.

Photometry is concerned with the measurement of light, and light has been defined† as "radiant energy evaluated according to its capacity to produce visual sensation." In practical photometry it is customary to base all definitions on the *unit light source*. Since in the early days of photometry candles were widely used, it was natural to take the candle as the unit light source. The statement that a certain light source has a luminous intensity *I* of 5 candles means merely that it radiates as much light as five candles. Originally, candles made according to rigid specifications and burning at a specified rate were used as standards. Until recently the unit candle in the United States was defined in terms of 45 carbon-filament lamps carefully maintained at the National Bureau of Standards and operated under accurately specified conditions.

At the present time the international standard candle is defined as 1/60 of the luminous intensity of a source, 1 square centimeter in area, at the freezing point of platinum (1773°C).

Luminous flux is radiant flux "evaluated according to its capacity to produce visual sensation." Whereas radiant flux may be expressed in watts and measured objectively with physical apparatus, luminous flux, since it depends upon visual response, must be measured subjectively. Although visual flux may be measured with physical apparatus, this apparatus must (either directly or indirectly) be calibrated visually. The unit of *luminous flux* is the *lumen*, and the lumen is defined as the quantity of light flux radiated through a unit solid angle (steradian) from a point source of one candle. It follows that the flux *F* through a solid angle of ω steradians from a source of *I* candles is $I\omega$. If this radiation falls normally on a surface of area *A* at a distance *d* from this source, the angle ω (subtended by this area) is by definition ‡ equal to A/d^2. These conclusions are summarized in the following equation:

$$F = I\omega = IA/d^2 \qquad (1)$$

---

† I.E.S. Nomenclature and Standards Report, 1932. Trans. I.E.S., 28,263 (1933).

‡ If a plane angle at the center of a circle of radius *R* is subtended by an arc *S* on the circumference of the circle, the angle is *S/R* radians. In a similar manner, if a solid angle at the center of a sphere of radius *R* is subtended by an area *A* on the surface of the sphere, the solid angle is A/R^2 steradians.

The illuminating engineer designing lighting equipment, the student interested in properly lighting his study table and the photographer estimating exposure time are all interested primarily in *illuminance*. The illuminance *E* is defined as the luminous flux per unit area, or stated algebraically

$$E = F/A \qquad (2)$$

Combining Eqs. (1) and (2) yields

$$E = I/d^2 \qquad (3)$$

Equation (3) is an algebraic statement of the well-known inverse square law; in other words, the illuminance produced by a point source of light is inversely proportional to the square of the distance from the source. It is evident from Eq. (2) that illuminance may be expressed in lumens per square foot, but in practice a lumen per square foot is called a *foot-candle*. The name is unfortunate because it seems to indicate that the illuminance is obtained by multiplying the number of feet by the number of candles. It is clear, however, from Eq. (3) that in this particular case (a point source of light) the illuminance is obtained by dividing the number of candles by the number of feet squared. A lumen per square meter is called a meter-candle or a *lux*. A lumen per square centimeter is called a *phot.*

Illuminance on a surface should not be confused with the brightness of the surface. If a body is not self-luminous, the *brightness* of the surface depends upon the illuminance and upon the *reflectivity*-the fraction of the incident light that is diffusely reflected. In fact the brightness B is given by the equation

$$B = kER \qquad (4)$$

where *R* is the reflectivity and *k* is a constant which depends only on the units in which the various factors are measured. The reflectivity of white paper is approximately 80 percent. This indicates that 80 percent of the light that falls on apiece of white paper is reflected and 20 percent is absorbed. The reflectivity of black velvet is approximately 3 percent. If, therefore, white paper and black velvet are equally illuminated, the paper will appear to be about 27 times as bright as the velvet.

The luminous intensity of two sources may be compared by adjusting the position of a screen so that it is equally illuminated by these sources. Therefore, if the intensity of one is known, the intensity of the other may be determined. The illuminance E_1 on the left side of screen P (Fig. 4) is I_1/d_1^2, where I_1 is the luminous intensity of the lamp L_1. Similarly the illuminance E_2 on the right side of P is I_2/d_2^2. If the screen is so placed that $E_1 = E_2$, it follows that

$$I_1 \big/ d_1^2 = I_2 \big/ d_2^2 \qquad (5)$$

or, rearranging terms

$$\frac{I_1}{I_2} = \frac{d_1^2}{d_2^2} \qquad (6)$$

Equation (6) applies in the special case of equal illuminance from each of two sources. The direct square relation of Eq. (6) is not inconsistent with, but is a result of, the inverse square relationship of Eq. (3).

APPARATUS: An optical bench, a standard lamp, test lamp, photometer box, two lamp sockets, two support rods with bases, two 150volt voltmeters, ammeter, 20ohm rheostat, and 180ohm rheostat are required.

If a source of constant potential is available, one of the voltmeters and the 20ohm rheostat are not required. To perform the optional part of the experiment, a universal lamp holder, Fig. 10, is required.

If a piece of white paper containing a grease spot is illuminated on one side and then viewed from the illuminated side, the grease spot will appear darker than the spot will appear darker than the surrounding area. This is due to the fact that the grease spot transmits a considerable fraction of the incident light but the untreated paper diffusely reflects most of the light falling on it.

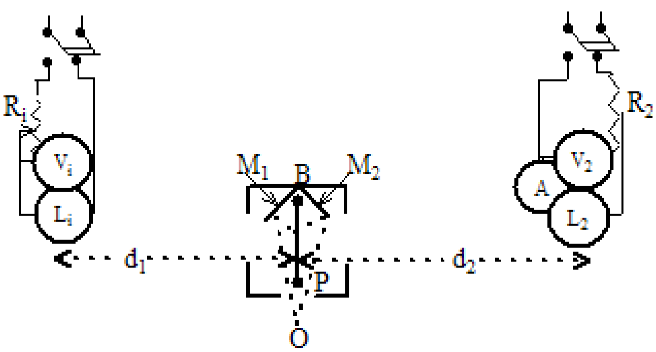

Fig. 4. Arrangement of apparatus for comparing the luminous intensity of two lamps.

For the same reason, if the paper is viewed from the opposite side, the grease spot will be brighter than the surrounding paper. It is only in the case of equal illuminance on the two sides that the contrast between the spot and the untreated paper is the same on both sides. Since some of the transmitted light is absorbed in going through the grease spot, it will not be possible to make the spot disappear on both sides of the paper simultaneously. When equally illuminated the grease spot will appear dark on both sides but the contrast between it and the surrounding area will be the same. It is shown in Fig. 4 how, by means of a pair of mirrors M_1 and M_2, an observer at O may view the two sides of the paper screen P, simultaneously. This arrangement of grease-spot, screen and mirrors in a housing is called a Bunsen photometer box, one form of which is shown in Fig. 5. In one form of Bunsen photometer the screen P does not have an actual grease spot but the screen is made of cardboard and over a hole in the cardboard is placed a very thin piece of tissue paper.

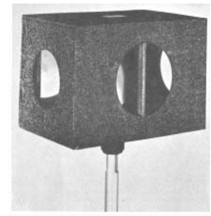

Fig. 5. The Bunsen Photometer Box.

For more accurate results the Lummer-Brodhun type of photometer box, illustrated in Fig. 6 and shown schematically in Fig. 7, is used. In this type of photometer the two sides of the white diffusing screen P are respectively illuminated by the light E_1 and E_2 from the two separate sources. By means of the totally reflecting prisms T_1 and T_2 and the glass cube C the two sides of P may be viewed simultaneously by an observer at O. The cube C consists of two 90° prisms with a figure etched on the hypotenuse face of one of the prisms. If the two sides of P are unequally illuminated the etched figure will be visible, but when equally illuminated the figure disappears. Since, however, it is easier to judge equality of contrast than equality of brightness, the glass plates G_1 and G_2 are interposed.

Fig. 6. The Lummer-Brodhun Photometer Box.

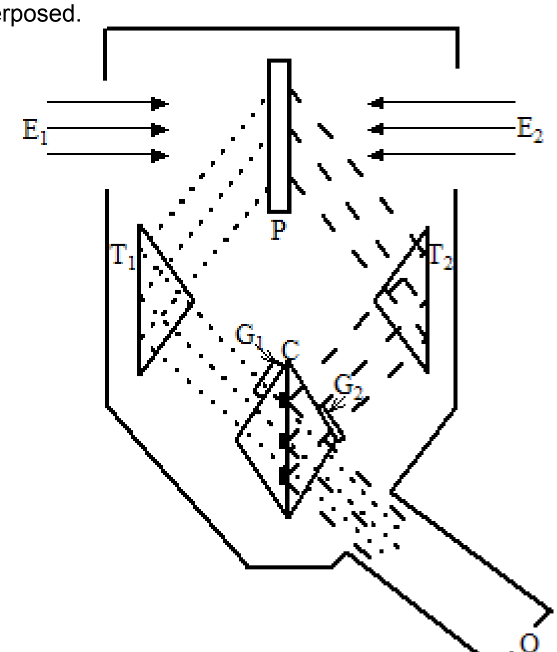

Fig. 7. Schematic diagram of the Lummer-Brodhun Photometer box.

With these plates in place about 8 percent of the light in certain regions of the cube is absorbed and the figure is always visible. Figure 8 shows the appearance of the field as seen by an observer at O (with the glass plates in position) for the three different conditions of illumination. Actually with this apparatus it is the brightness of the two sides of screen P that are compared. If the brightness of the two surfaces is the same, the illuminance E_1 provided the reflectivities

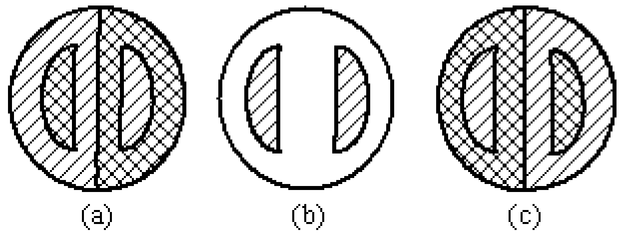

Fig. 8. Shows the appearance of the field in a Lummer-Brodhun Photometer when (a) the right side of the screen is brighter, (b) the two sides are equally bright, and (c) when the left side is brighter.

are equal. To correct for small differences in reflectivity the photometer is so mounted that it may be rotated about a horizontal axis. Half of the readings are taken in each position.

PROCEDURE: Arrange the apparatus as shown schematically in Fig. 4. The standard lamp L_1 is connected through the 20ohm rheostat R_1 to a 120volt line. This lamp has been standardized at a particular potential and the potential drop across the lamp, as indicated by the voltmeter V_1, is maintained at this value throughout the experiment by means of R_1. If a source of constant potential is available, the voltmeter V_1 and the rheostat R_1 may be omitted.
The potential across the test lamp L_2 is varied by means of the 180ohm rheostat R_2. The potential drop across this lamp and the current through it are given by the voltmeter V_2 and the ammeter A, respectively. Although there are some advantages in the use of direct current, either direct or alternating current may be used.
It may be convenient to use alternating current for the standard lamp and direct current for the test lamp. If the type of optical bench illustrated in Fig. 9 (125cm long) is used, each lamp should be mounted exactly 50cm from the near end of the scale as shown in Fig. 9. Once the lamps are located, care should be taken that neither the lamps nor the bench are moved. Either the Bunsen or Lummer-Brodhun type photometer box may be used.

Fig. 10. The Universal Holder.

Adjust the rheostat R_1 so that the standard lamp L_1 is operating at the specified voltage. Adjust R_2 so that the potential drop across test lamp L_2 is 80volts. Slide the photometer box B along the bench until the screen is equally illuminated on the two sides and record the position as read from the scale on the bench. Check the readings of V_1 and V_2 and redetermine the position. In all, 5 or 6 settings of B should be recorded and the voltmeter readings checked before each trial. If the Lummer-Brodhun photometer box is used, half of the observations should be taken with the sight tube pointing toward the right and half with the tube pointing left. Read the ammeter A.
Repeat the above experiment with 90, 100, 110, etc., volts across L_2, increasing the potential in steps of 10volts until R_2 is reduced to zero. Results may be recorded as indicated in Table I. It is suggested that the individual readings taken from the scale on the photometer bench be recorded in a separate table, the values of d_1 and d_2 determined from the average of each set of photometer readings and only these average values of d_1 and d_2 recorded in Table I.
Plot the graph (curve A) which shows the relation between the luminous intensity I_2 of lamp L_2 and the potential across it. Also plot (curve B) efficiency in candles per watt against potential drop. Potentials should be plotted as abscissas in both cases and the two curves may be plotted on the same sheet. Thoroughly interpret these curves.

Optional: 1. The effective candlepower of an electric lamp depends upon the direction in which it is measured. Mount lamp L_2 in a universal holder, and with the potential held constant at 120volts, measure the candlepower in various positions distributed uniformly around the horizontal axis. Plot results on polar coordinate paper.
2. With the lamp held vertically (base down) in the

Fig. 9. Optical bench equipped for photometric work.

universal holder, measure its candle power in. various directions distributed uniformly around the vertical axis. Plot results on polar coordinate paper. Determine the mean horizontal candlepower.

3. Determine the mean spherical candlepower of lamp L_2. The amount of work involved in this determination is considerable and the problem should be attempted only as a special project. For instructions on the proper distributing and weighting of observations, consult some standard work on illuminating engineering, or see Ch. XIII in *Laboratory Physics* by D. C. Miller.

QUESTIONS: 1. Show that the total luminous flux from a point source of *I* candles is $4\pi l$ lumens.

2. The test lamp used in this experiment is connected to a 115volt line and supported 3ft directly above a 12 x 18in. sheet of paper on a horizontal surface. Determine the number of foot-candles, luxes, phots and lumens on the paper.

3. If it were not for atmospheric absorption the illuminance at the earth on a surface normal to the sun's radiation would be 13,600 foot-candles. Determine the luminous intensity of the sun.

4. What are the dimensions of illuminance?

5. In deriving Eq. (3) it was assumed that the incident light is normal to the illuminated surface. How must this equation be modified if the incident light makes an angle θ with the normal to the surface?

6. In what ways is a photoflood lamp superior to an ordinary tungsten lamp for photography?

7. Using the information given by the graphs in Figs. 2 and 3, plot a curve which shows roughly the relation between the luminous flux from a tungsten filament lamp and the wavelength.

8. An object looks equally bright whether viewed from a distance or close at hand. Explain. Is the same thing true of stars?

TABLE I

Potential V (volts)	Current A (amperes)	Power P (watts)	Distance d_1 (cm)	Distance d_2 (cm)	Luminous Intensity I (candles)	Efficiency I/P (candles/watt)