

THE TOTAL LUMINOUS EFFICIENCIES OF PRESENT-DAY ILLUMINANTS.

BY HERBERT E. IVES.

LIGHTING science has lagged behind other branches of engineering in the definiteness of its quantitative aspects and in exactness of terminology largely through the chaotic condition of the question of luminous efficiency.

While the efficiency of a motor or a transformer may be derived in the form of a definite fraction or percentage from the direct comparison of output to input, both measured in the same units, the efficiency of an illuminant has not been so expressible. The engineer, who measures input in watts, and luminous output in lumens, expresses efficiency in lumens per watt, a ratio of value in comparing one illuminant with another, but one whose unit is very far from being the ideal efficiency which is understood by 100 per cent. efficiency in any other connection. The so-called "luminous efficiencies" to be found in physical literature might with greater propriety be called the "visible fractions" of the radiated power. They are expressed in percentage values, but the unit is not the most efficient illuminant—it is the most efficient illuminant possessing the same visible spectrum as the one measured. It affords no exact measure of comparison of one illuminant against another.

The unravelling of this tangle is attained by so defining luminous flux that its dimensions are the same as power, and by determining the constant of proportionality between the present arbitrary luminous flux unit and the power unit. These two steps have been taken in the definition of luminous flux as "radiant power evaluated according to its capacity to produce the sensation of light," and in the determination of the ratio of the lumen to the watt, recently published in this journal.¹ With these steps taken it is a simple matter to arrive at the luminous efficiency of any illuminant, given its power input, its power output, and its luminous output. It is only necessary to transform the last quantity from lumens to the equivalent watts, to have all the quantities in the same units. Then we have,

$$\frac{\text{Luminous output}}{\text{power input}} = \text{total luminous efficiency};$$

¹ PHYS. REV., The Mechanical Equivalent of Light.

$$\frac{\text{Luminous output}}{\text{radiant power output}} = \text{radiant luminous efficiency.}$$

Radiant luminous efficiency may be determined, as indicated, by knowledge of the radiated power and the watt value of the lumen. It can however be found much more simply by the measurement of the ratio of light-evaluated to unevaluated power. Measurements of this quantity have been made in this way by Karrer and reported in this journal.¹

For the determination of total efficiency, on the other hand, it is necessary to measure each quantity in question, since different instruments and methods are required for each. It is here that the recently determined value of the lumen in terms of the watt is indispensable, and it is with this quantity alone that the present paper deals.

The lumen has been found to be .00162 watt. The "efficiency" of any illuminant in lumens per watt can, by the use of this constant, be translated into *watts of luminous flux per watt of power input*.

This is a simple fraction, on a scale of efficiency in which the value of the most efficient possible light source is unity.

An illustration will make clear the derivation of the values for total luminous efficiency given in the table. The standard carbon incandescent lamp has an efficiency in the present practical units of 2.59 lumens per watt. Now $2.59 \times .00162 = .0042$, the ratio of luminous output to power input expressed in the same units, or the total luminous efficiency. The construction of a table of total luminous efficiencies thus involves no more arduous labor than the multiplication of the lumens per watt of the illuminants of interest by a constant, that constant being the watt value of the lumen. If the watt is adopted as the unit of luminous flux, as the writer has suggested, the ratio of output to input as measured is at once the efficiency. The superiority of the watt over a unit based merely on a certain combination of wick and wax should not require much discussion.

In the case where the power consumption is expressed in a unit other than the watt, a preliminary transformation to watts should be made, or the corresponding constant may be worked out. Thus gas illuminant efficiencies are commonly expressed in "lumens per British thermal unit per hour." This may be reduced to lumens per watt by dividing by .293, or it may be reduced at once to total efficiency by multiplication by .00162/.293 or .00553.

The appended table of total luminous efficiencies has been prepared from data collected from a number of sources. A few figures are calculated from the very full table in Liebethal's *Praktische Photometrie* where

¹ PHYS. REV., March 1915, p. 189.

Illuminant, Commercial Description.	Commercial Rating.	Efficiency in Present Units (Lumens per Watt).	Ratio
			Watts of Luminous Flux Watts Input or Total Efficiency on Correct Scale.
<i>Carbon incandescent lamp</i>	4-watts per mean hor. C.P.....	2.6	.0042
Oval anchored (treated) filament.			
<i>Tungsten incandescent lamp</i>	1.25 watts per hor. C.P.....	8	.013
Vacuum type.			
<i>Mazda, Type C</i>	600 C.P.-20 amp. .5 w.p.c.....	19.6	.032
	Series type C.		
	500 watt, multiple, .7 w.p.c.....	15	.024
	Type C.		
<i>Carbon Arc</i>	9.6 ampere; clear globe.....	11.8	.019
Open arc.			
<i>Enclosed arc</i>	6.6 ampere, D.C.....	5.9	.0096
Light opal inner; clear outer and street reflector.			
<i>Series enclosed carbon arc</i> ; light opal inner; clear			
outer; street reflector.....	7.5 ampere, A.C.....	5.6	.0091
<i>Magnetite arc</i>	6.6 ampere, D.C.....	21.6	.035
Series luminous arc lamp; ornamental type; clear			
globe; standard electrodes.			
<i>Enclosed white flame carbon arc</i>	10 ampere, A.C.....	26.7	.043
	6.5 ampere, D.C.....	35.5	.058
<i>Enclosed yellow flame carbon arc</i>	10 ampere, A.C.....	31.4	.051
	6.5 ampere, D.C.....	34.2	.055
<i>Open arc, white flame, inclined trim</i>	10 ampere, A.C.....	29	.047
	10 ampere, D.C.....	27.7	.045
<i>Open arc, yellow flame, inclined trim</i>	10 ampere, A.C.....	41.5	.067
	10 ampere, D.C.....	44.7	.072
<i>Moore Nitrogen Vacuum Tube</i>	220-volt, 60-cycle, tube length 113.17 feet...	5.21	.0085

Illuminant, Commercial Description.	Commercial Rating.	Efficiency in Present Units (Lumens per Watt).	Ratio
			Watts of Luminous Flux Watts Input or Total Efficiency on Correct Scale.
<i>Quartz Mercury arc</i> ¹	174-197 volt; 4.2 ampere.....	42	.068
<i>Glass Mercury arc</i> ¹	40-70 volt; 3.5 ampere.....	23	.037
<i>Nernst lamp</i> ¹		4.8	.0077
<i>Acetylene</i> ¹	1.0 liters per hour consumption.....	.67	.0011
<i>Petroleum lamp</i> ¹26	.0004
<i>Incandescent gas lamp</i> (low pressure).....	.350 lumens per B.t.u. per hr.....	1.2	.0019
<i>Incandescent gas lamp</i> (high pressure).....	.578 lumens per B.t.u. per hr.....	2.0	.0032
<i>Open flame gas burner</i>	Bray 6' high pressure.....	.22	.00036

¹ = figures from Liebhenthal's Praktische Photometrie.

they are given in Hefner lumens per watt. The figures for the more recent illuminants have been collected from authoritative sources to whom acknowledgment is made below.

A difficulty in the collection of such data lies in the common practice of publishing efficiencies in terms of horizontal or hemispherical watts per candle, instead of mean spherical. The latter is of course the only value of use in calculating total efficiencies.

It is at once obvious from these figures that light is at present only a by-product. The highest efficiencies tabulated are those of the mercury arc in quartz and the yellow flame arcs. In both cases, however, the figures are misleading, because the overall efficiency is much reduced by the steadying resistances which are indispensable for the practical operation of these light sources.

The highest present efficiencies of light production do not exceed probably 5 per cent. of what should be possible.

Perfect efficiency on this scale of course means monochromatic green light. But even if the most efficient continuous spectrum *white light* is taken as the goal, this present 5 per cent. is increased only to 5/.40 or 12.5 per cent., the most efficient white light being about 40 per cent. efficient.¹

It is of interest to compare these total efficiencies with the corresponding radiant efficiencies as determined by Karrer. The ratio:

$$\frac{\text{total efficiency}}{\text{radiant efficiency}} = \frac{L/P}{L/R} = \frac{R}{P}$$

(L = luminous flux, P = power input, R = radiant power) gives the *radiation efficiency* or fraction of the applied power which is transformed into radiation.

Now in the case of the carbon vacuum incandescent lamp the radiation efficiency = .0042/.0045 or over 90 per cent., while in the case of the incandescent gas burner this ratio is .0019/.012 = .16; in other words five-sixths of the applied power is lost as convection and conduction.

The writer takes pleasure in acknowledging his indebtedness to Mr. S. L. E. Rose, Mr. T. H. Amrine and Mr. R. B. Chillas for data on the electric illuminants.

PHYSICAL LABORATORY,
THE UNITED GAS IMPROVEMENT COMPANY,
PHILADELPHIA, PA.

¹ Ives, *Electrical World*, June 15, 1911.