PRELIMINARY NOTE ON THE EFFICIENCY OF THE ACETYLENE FLAME.¹

BY EDWARD L. NICHOLS.

IN the study of flames or of glowing bodies of any kind, considered as devices for the production of light, and it is upon such devices that artificial lighting depends, the question of efficiency is of great importance. The complete solution of the problem involves the determination of the ratio of the light-giving radiation to the total energy expended in producing it; and the measurement of this quantity, *the total efficiency*, usually involves as an intermediate step, the determination of *the radiant efficiency*, which is the ratio of the luminous or light-giving radiation to the total radiation.

In the measurement of radiant efficiencies at least four distinct methods have been employed.

Julius Thomsen,² who was a pioneer in this field of research, read a paper at Stockholm in 1863, entitled *The Mechanical Equivalent of Light*, in which he applied the method of Melloni to the separation of the light-giving from the non-luminous radiation. Thomsen used a water cell containing a layer of liquid 20 cm. in thickness, by the interposition of which between the source of light and the thermopile used in measuring its radiation, he sought to cut off the dark heat. He studied the flames of spermaceti candles, of ordinary illuminating gas, and of the moderator lamp; determined the energy, expressed in calories per minute, emanating by radiation from these sources, and compared it with the calories of luminous energy. Blattner³ in 1886 applied the second method under consideration, that of immersing the source of light in a calorimeter of glass to incandescent lamps under varying supplies of current. Merritt and Ryder⁴ in the same year applied both methods to incan-

¹ A paper read before the American Physical Society, June 27, 1900.

² Thomsen, Poggendorff's Annalen, 125, p. 348.

³ Blattner, Das optische Nutzeffect der Glühlampen, Fraunfeld, 1886.

⁴ Merritt, American Journal of Science, vol. 37, p. 67.

descent lamps. They used a solution of alum instead of water, and made the very necessary correction for the infra-red radiation which passes through the cell by the interposition of a second cell containing a solution of an opaque solution of iodine in carbon disulphide. They checked the results obtained by this method by submerging the lamp in a calorimeter through which a constant flow of water was maintained, and measuring the temperature of the water upon entering and leaving the vessel. The non-luminous radiation was in great part retained by the water surrounding the lamp, while the light-giving rays were largely transmitted by the liquid and by the glass walls of the calorimeter. The necessary corrections were determined by a study of the transmitting power of the glass and water for dark rays, and their absorbing power for light. The total radiation was computed by measurements of the electro-motive force at the terminals of the lamp and the current traversing the filament. This quantity was likewise checked by placing the lamp in a calorimeter with opaque walls and measuring the heat energy delivered to the water directly.

Staub¹ in 1890 studied the radiant efficiency of the illumination from vacuum tubes when excited by means of the electrical discharge; for which purpose he employed a modified form of the Bunsen ice calorimeter.

Determinations of radiant efficiency have likewise been carried out by the method of the thermopile and water-cell by Nakano² and by Marks³ in the case of the arc lamp, by Rogers⁴ in his study of magnesium as a source of light, by Miss Crehore⁵ (Mrs. F. Bedell) who investigated in this manner the efficiency of the lime light, and by others.

A fourth and far more rigorous method (that of obtaining the distribution of energy throughout the visible and invisible spectrum

¹ Staub, Inaugural Dissertation, Zürich, 1890; also Beiblätter zu den Annalen der Physik, 14, p. 538.

² Nakano, Transactions of the American Institute of Electrical Engineers, vol. 6, p. 308 (1889).

³ Marks, Transactions of the American Institute of Electrical Engineers, vol. 7, p. 175 (1890).

⁴ Rogers, American Journal of Science, vol. 43, p. 301 (1892).

⁵ Nichols and Crehore, PHYSICAL REVIEW, vol. 2, p. 161 (1894).

and comparing the areas) of determining the radiant efficiency is due to Langley¹ and has been applied by him to sunlight, to various artificial illuminants, and to the light from the Cuban fire fly. The difficulties in the way of carrying out this method properly are, however, extremely great and it is frequently a question whether under the ordinary degree of command over the conditions of the experiment, the method yields a better result than the more convenient procedure invented by Melloni and developed by Tyndall and by the various subsequent workers just cited.

Upon the problem of the total efficiency of sources of light, much less has been done than upon the radiant efficiency. Thomsen in the article already cited, estimated that in the case of the candle and of the moderator lamp the total development of heat was about three hundred and fifty times as great as the luminous energy of the flame, and that in the case of gas flames it was approximately one thousand times as great. Rogers determined the heat of combustion of magnesium, and, by means of a modification of Thomsen's method, ascertained the relation of the luminous radiation from a mass of the burning metal to the total heat produced by the reaction. Various other writers,² in the course of discussions upon the relative merits of electric lighting and of artificial illumination by means of flames, have attempted to express in one way or another the efficiency of the various methods, but actual measurements by direct experiment have been very few.

Experiments are in progress under the direction of the writer, by means of which the efficiency of the acetylene flame is to be directly determined with as high a degree of accuracy as the nature of the case may permit. For this purpose, the radiant efficiency is to be computed in two ways. First, by the method of Melloni, and second by the exploration of the spectrum and the comparison of the areas enclosed by the curve within and without the limits of visibility. The heat of combustion of acetylene gas, carefully prepared and thoroughly purified, is to be determined, and the total radiation

¹Langley (see the well-known report of the Mt. Whitney expedition, and subsequent memoirs).

²See in particular, Preece; *Nature*, vol. 38, p. 496, (also B. A. Report (1888), or the table computed from data by Preece and published by the present writer in the *Transactions of the American Institute of Electrical Engineers*, vol. 6, p. 175 (1889).

from a flame of this gas found by a modification of Thomsen's method. Measurements of the amount of gas supplied to the flame will then make it possible to ascertain with considerable accuracy the total efficiency of this source of light.

Preliminary measurements from which it is possible to compute the value of the efficiency of acetylene flames obtained from the ordinary gas, such as is produced from the usual form of generators in which calcium carbide is thrown into water, are already completed and since the interest in this source of illumination is at present widespread, it seemed worth while to report these preliminary results without waiting for the completion of the more refined experiments which are to follow.

RADIANT EFFICIENCY.

These preliminary experiments naturally divide themselves into three parts, of which those upon the radiant efficiency were carried out by Messrs. Stewart and Hoxie. Their apparatus differed in several respects from that used by most of the earlier observers. Instead of a thermopile, they employed a bolometer of iron wire. The acetylene flame was of the flat type produced by the well known *Naphey* burner. Between the flame and the bolometer, a water cell was moved in and out. This cell was much smaller than those commonly employed, the dimensions being such that the rays traverse 1 cm. of water and 0.4 cm. of glass. The use of water instead of solutions of alum frequently employed in such work is justified by the investigations of Ernest Nichols¹ upon the perviousness of these and other substances to the infra-red rays of the spectrum. It will be seen by reference to Fig. 10 in that article, that water, potassium alum, and ammonium alum, all possess approximately the same transmitting power between the red end of the spectrum and wave lengths 1.5μ where they all become opaque.

From thirty-nine sets of readings Stewart and Hoxie obtained the value 0.207 for the ratio of the light transmitted through this cell to the total energy reaching the thermopile when it was interposed. That this ratio does not express the true relation between the light-giving and the total energy from the flame is obvious.

¹ Nichols, PHYSICAL REVIEW, vol. I, p. I, 1893.

Water and glass, on the one hand, absorb a certain proportion of the light and there are four reflecting surfaces at which losses occur. On the other hand, water transmits a considerable amount of non-luminous energy. The degree of this perviousness to rays lying beyond the limits of the visible spectrum is known to be considerable¹ and it is clear that, contrary to the view expressed by Thomsen in his article on the *Mechanical Equivalent of Light*, a large correction must be applied. This correction was determined in the usual way. Iodine was dissolved in carbon disulphide, the solution being of such strength as to be opaque to visible rays. The water cell and the cell containing the iodine were set up in such positions that the rays from the acetylene flame passed through both in the order named, on their way to the bolometer. The iodine cell was of the same size as that which contained the water. It was moved in and out, and twenty-two sets of readings were taken from which it appeared that the iodine cell absorbed fifty-one per cent. of the energy which passed through the water cell. Upon the assumption that the iodine cell is entirely transparent to the rays of the infra-red spectrum and entirely opaque to visible rays, we obtain for the radiant efficiency of the acetylene flame

$$0.51 \times 0.207 = 0.105.$$

This value can only be considered as approximate since no corrections were made for reflection from the surfaces of the glass, nor for the absorption of light by water, nor of infra-red energy by the iodine. From the following statement of the theory of these corrections, worked out by the observers, it will be seen that the losses in the water and iodine cells tend to annul each other and that consequently they may be ignored altogether without serious error.

Fig. 1.

Let the curve *cd* in Fig. 1 represent the distribution of energy in the spectrum of the flame, let the line *mn* mark the limit of the spectrum transmitted by water, and let the total energy of the spectrum from the flame be *A*; then

¹ See Ernest Nichols, l. c.

$$a + b = A \quad (1)$$

By moving the water cell in and out of the path of the rays, we are able to determine the ratio

$$a = \frac{a'}{A}$$

where a' is the value of a , less losses due to reflection and to absorption by water. Let the area d (Fig. 2) be that portion of the

Fig. 2.

energy transmitted by the iodine solution and let e be that which will traverse both solutions. If the water cell be kept in the path of the rays and the iodine

cell be moved in and out, we are able to obtain from observation the ratio

$$\varepsilon = \frac{e'}{a'}$$

in which e' is e , minus the losses by reflection and by absorption in the water and in the iodine. If c be the visible energy of the spectrum and c' the part of the same transmitted by water; then, since for a given surface and solution, the loss by reflection and by absorption is proportional to the intensity, we have

$$e' = (a' - c') (1 - k_i) \quad (2)$$

where k_i is the coefficient for the reflection and absorption by the iodine cell in the infra-red. We may write in like manner

$$c' = c(1 - k_w) \quad (3)$$

where k_w is the coefficient for the water cell in the visible part of the spectrum. From these, by substitution, we have

$$e' = a' - c - (a' - c')k_i + ck_w \quad (4)$$

and substituting this value of e' , we have an expression for the energy absorbed by the use of water and iodine cells

$$\varepsilon = \frac{a' - c - (a' - c')k_i + ck_w}{a'} \quad (5)$$

Now the approximate radiant efficiency 0.105, given as the result of these preliminary experiments is

$$E = \left(1 - \frac{e'}{a'}\right) \frac{a'}{A} = \frac{c + (a' - c')k_i - ck_w}{A}, \quad (6)$$

while the true radiant efficiency is

$$E = \frac{c}{A}.$$

In equation 6, $(a' - c')k_i$ is the loss due to reflection and to absorption of the infra-red rays in the iodine cell, while ck_w is the loss due to reflection and to absorption of the light rays by water. If these

TABLE I.

Radiant efficiency of various sources of light.

Source.	Observer.	Luminous radiation. Total radiation.
Sperm candle.	Thomsen.	0.0210
Paraffine candle.	Rogers.	0.0153
Moderator lamp.	Thomsen.	0.026
Illuminating gas.	Thomsen.	0.0197
“ “	Langley.	0.0240
“ (bat's wing).	Rogers.	0.0128
“ (argand).	Rogers.	0.0161
Incandescent lamp.	Blattner.	0.05 to 0.06
“ “	Merritt.	Various values up to 0.06
“ “	(From integration of Abney and Festings' curves).	0.055
Welsbach mantle.	Stebbins.	0.02 to 0.07
Lime light (new).	Crehore.	0.14
“ (old).	“	0.084
ACETYLENE.	Stewart and Hoxie.	0.105
Arc light (Foucault).	Tyndall.	0.104
“	Nakano.	0.104
“	Marks.	0.08 to 0.13
Magnesium light.	Rogers.	0.125
Geissler tubes.	Staub.	0.32

two losses are equivalent, the method gives us the true radiant efficiency c/A without attempting any further corrections. In precisely similar cells, the losses by reflection will be nearly equivalent. Data for the absorption losses in water are available but the curves

for solutions of iodine have, so far as I know, never been obtained. Since the two quantities tend to annul each other, there is probably less error involved in neglecting corrections altogether than in correcting for the water cell and in attempting without requisite data to correct for the losses in the iodine. While the nature of these losses is not accurately known, it is probable that the uncorrected result is at least approximately true.

These preliminary measurements give to the acetylene flame a position in the scale of radiant efficiencies very nearly equal to that of the arc light. The relation which different sources of light bear to each other in this respect may be seen from the table on page 221, which contains a list of previous determinations of radiant efficiencies.

HEAT OF COMBUSTION.

The preliminary experiments upon the heat of combustion of acetylene, necessary to the computation of the efficiency of the flame, were undertaken at the writer's suggestion by Mr. H. A. Rands. The gas used was the ordinary unpurified acetylene obtained from a generator in which the carbide of calcium was dropped into a large mass of water. The gas produced by this so-called wet process contains a larger percentage of acetylene and is less subject to polymerism than where water is applied in small quantities to the carbide. Unless special processes of purification are employed, however, the product is by no means pure acetylene. Analyses of several samples of the gas generated from the same lot of carbide as that used in these experiments showed from 20% to 25% of other gases, chiefly inert. The Favre and Silbermann calorimeter was used, the combustion jet being slightly modified so as to secure complete and smokeless burning of the acetylene. Various samples of the gas taken on different days, gave a mean result of approximately 10,000 calories for the heat of combustion. This is considerably below the theoretical value of 12,200 as given by Pellissier, but the difference is essentially what one would expect from the analysis of the gas itself. In the completion of the investigation, it is proposed to make an extended series of determinations of the heat of combustion of acetylene after the gas has been

subject to thorough purification, and to give the analyses of the gas employed.

RATIO OF TOTAL HEAT GENERATED TO TOTAL RADIATION.

Upon the relation between the total heat generated in the flame and the heat dissipated in the form of radiation, our experiments are still in progress. This portion of the subject is being studied by Mr. Albert Ball. His method, the results of the preliminary application of which only are given in the present note, is as follows :

A thermopile is connected in closed circuit with a galvanometer of suitable sensitiveness. At a convenient distance from the face of the thermopile, the acetylene flame is mounted, and between the two is a shutter by means of which the aperture in an intervening screen can be opened and closed by an observer situated at the telescope of the instrument. Readings are made by removing the shutter from the aperture for an interval of time corresponding to that of the first swing of the galvanometer. As soon as the needle makes its first turning point, the aperture is closed so that further heating of the face of the thermopile may be avoided. It is well established that the deflection, counting from the original position of the needle to its first turning point, is, under these conditions, always proportional to the total deflection which the galvanometer would take.¹ The method is one which enables a great saving of time and also reduces the risk of error from the shifting of the zero point. To calibrate a thermopile and galvanometer thus used, the following modification of Thomsen's procedure was employed. A spherical flask with its outer surface blackened was filled with water and its center was placed exactly in the position occupied by the flame in the operation just described. In the bottom of the flask, a coil of German silver wire was mounted, the terminals of which were brought out through the neck by means of copper lead wires of low resistance. By means of this coil, the water in the flask was heated to a temperature sufficient to produce upon the galvanometer an effect comparable to the radiation from the flame, and to maintain it at that temperature permanently. The shape and position of this coil was found to be a matter of considerable importance, and it was

¹ See Merritt, *American Journal of Science*, vol. 41, p. 417.

only after several trials that a form of coil was obtained which gave a satisfactorily even distribution of temperature throughout the flask. By giving this coil the form of a spiral wound upon a cylinder with axis horizontal and placing the same as near the bottom of the flask as possible, and centering it carefully, it was found that the convection currents were of such a character as to maintain the water in

the flask at a constant temperature throughout. Exploration of the temperature in different portions showed variations amounting only to a small fraction of a degree.

The electrical connections, by means of which the current from the coil was adjusted and measured, and the fall of potential between its terminals was determined are shown in Fig. 3.

The source of the current was a storage battery in circuit with which in series were an adjustable resistance (R), the heating coil (H), and a standard coil (R_b) of manganin wire, having a value of .1 ohm. The current was measured by placing a sensitive d'Arsonval galvanometer (g) in multiple with this standard coil and measuring the fall of potential through the same. The

Fig. 3.

galvanometer was calibrated by means of a Clark cell. Wires connected with the terminals of the heating coil were carried to the same galvanometer, a six point switch (S) being so arranged that the instrument could be used alternately for measuring the fall of potential in the heating coil and in the standard coil (R_b) already described. Suitable resistances, (R_c) and (R_d), were placed in the galvanometer circuit and the instrument itself was shunted around a resistance

R_s by means of which its deflection could be reduced to the proper size. The delicacy of this galvanometer was such that in order to secure the desired reading, R_d was given a value of 1,000,000 ohms, and R_c 9,930 ohms, which latter, together with the resistance of the galvanometer itself, made the total resistance of that circuit 10,000 ohms.

The energy imparted to the flask was computed from the electrical measurements and to determine what proportion of this energy was lost by radiation and what by convection, the flask was placed in a bell-jar from which the air was subsequently removed. The loss by conduction was, for the purpose of these preliminary determinations, assumed to be negligible.

Assuming the loss of heat by radiation to be the same for a given temperature at the surface of the flask in air and in vacuo, and that all the heat developed in the flask by the action of the electric current is, in vacuo, dissipated by radiation, we may plot a curve having as abscissæ the units of heat radiated at different temperatures as computed by means of these electrical measurements when the flask is in vacuo, and the deflection produced when the thermopile is exposed to the flask *in the air* at the same temperatures. This curve serves to enable us to find *directly* the total amount of radiation from *any source* radiating equally in all directions, which may be placed in the position of the center of the flask, by means of the deflection of the galvanometer exposed to it under conditions similar to those made with the flask in situ. It is true that there is a small error due to the fact that the flask is not a perfect sphere and that the radiation from it is not strictly the same in all directions. It is likewise true that the distribution of radiation from the acetylene flame is not perfectly uniform, but these errors are so small that it was not necessary to consider them, in this preliminary determination of the efficiency.¹ It is obvious that the ratio of total radiation to total energy of combustion must be a function of the gas pressure and that it will reach a maximum for some particular size of the flame. With increasing pressures, the tendency is for the gases to be hurried away from the hot center of the flame so that there will be

¹ For a curve of horizontal distribution of intensities, see a paper on the acetylene flame read by the present writer before The Franklin Institute in March, 1900.

increasing losses of heat by convection with increasing pressure. Up to a certain point, this loss is overbalanced by the improved conditions under which combustion takes place, and there will be a value for the pressure at which, for any given burner, the efficiency will be greatest. Mr. Ball's work in these preliminary experiments divided itself, as will appear from the foregoing, into two parts. First, a calibration of the flask for convection losses, and secondly, the reading of the galvanometer when the thermopile was exposed to the action of the flame. The range of temperatures of the flask lay, as will be seen by inspection of the following table, between 81.8° and 96.1°C .

TABLE II.

Relation between temperatures of flask, galvanometer throws, and the total radiation of heat.

Temperatures of flask.	Total heat radiated (in calories per second).	Throw of the galvanometer.	Temperatures of flask.	Total heat radiated in calories per second).	Throw of galvanometer.
81.8°C .	6.976	10.05 s. d.	90.1°C .	7.619	12.35 s. d.
84.8	7.143	11.15	92.6	7.917	12.70
86.1	7.238	11.35	94.2	8.143	13.10
88.0	7.393	11.78	96.1	8.452	13.70

The total heat radiated from the flask at these temperatures is computed from the electrical measurements already described. The throw of the galvanometer when exposed to the flask at the same temperature in air is given in column 3. From these, a curve of the sort already alluded to for the radiation between heat radiation per second and galvanometer throws was drawn (Fig. 4).

To use the method just described, for the determination of the ratio of radiated to total heat, the acetylene flame was substituted for the heated flask, the deflection produced when the thermopile was exposed to its action being interpreted by means of the curve given in Fig. 4. Gas for the supply of this flame, passed first into an automatic regulator, the construction of which has been given in a previous paper.¹ From this regulator, it passed through an experimental gas meter reading in liters per minute, thence to a

¹ Nichols, l. c.

tube provided with a side arm leading to an open tube manometer, and thence to the flame. The flame was set up, as the flask had been in the calibration experiments, in an inner room quite free from drafts, through the wall of which an aperture was cut, with a

Fig. 4.

double shutter capable of being raised and lowered. Opposite this opening the thermopile was mounted in such a position that one of its faces would receive the radiation from the flame. This thermopile, as has already been indicated, was held in closed circuit with the galvanometer and the reading was made by alternately raising and lowering the shutter. In computing the results of these measurements, the heat of combustion found by Mr. Rands in the experiments already described (namely, about 10,000) was assumed to be correct. Two determinations were made, the data for which together with the results obtained are given below.

Experiment A.

Molecular weight of acetylene (C_2H_2), 26.

Molecular volume of acetylene (760 mm. and 273° abs.), 22.4.

Pressure at which the gas was supplied to the burner, 766 mm.

Temperature of the gas, 293° (abs.).

Volume of 26 grams of the gas at above pressure and temperature, 23.85 liters.

Rate of delivery of gas, 0.174 liters per minute, or 0.00316 grams per second.

Total heat produced by the reaction per second, $0.00316 \times 10,000 = 31.6$.

Deflection of galvanometer, 11.0 s. d.

Calories indicated by flame per second, as indicated by above deflection, 7.13.

$$\text{Ratio: } \frac{\text{total radiation}}{\text{total heat}} = \frac{7.13}{31.6} = 0.225.$$

TOTAL EFFICIENCY; assuming the radiant efficiency to be 10.5%; $0.225 \times 0.105 = 0.0236$.

In experiment *A* the flame was below normal size.

Experiment B.

Rate of delivery of gas, 0.297 liters per minute, or 0.00539 grams per second.

Total heat produced by the reaction, per second, $0.00539 \times 10,000 = 53.9$.

Deflection of the galvanometer, 16.12 s. d.

Calories radiated by flame per second, as indicated by above deflection, 10.25.¹

$$\text{Ratio: } \frac{\text{total radiation}}{\text{total heat}} = \frac{10.25}{53.9} = 0.190.$$

TOTAL EFFICIENCY, assuming the radiant efficiency to be 10.5%, $0.190 \times 0.105 = 0.0199$.

¹ This value is much less reliable than that used in experiment *A* because it is taken from a portion of the curve not covered by the calibration observations. It is unlikely, however, that the extrapolation is sufficiently at fault to vitiate the conclusion that the efficiency of this flame, which was of fully normal size, was lower than that of the foregoing.

These values are many times greater than the corresponding values for ordinary gas and oil flames. They are at least double the corresponding value for the arc light under the most favorable conditions for the latter source.

The magnesium flame alone, which, according to Rogers, has a total efficiency of 0.1025, is, on account of the very small loss by convection and the very high radiant efficiency, superior to acetylene in this respect.

PHYSICAL LABORATORY OF CORNELL UNIVERSITY,
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