THE EFFICIENCY OF THE ARC LAMP.

BY HATSUNÉ NAKANO.

Note.

The interesting results recently obtained by Mr. Merritt in the application of the method of Melloni to the investigation of the efficiency of the incandescent lamp have made it seem desirable to extend that method to the study of the arc lamp also.

Existing data concerning the efficiency of this source of light are exceedingly imperfect, being based chiefly upon measurements with the Bunsen photometer. Ordinary photometric determinations of the light giving value of sources of illumination differing widely in temperature from the standard candle are necessarily at fault; and I have endeavored in a recent paper¹ to call attention anew to the character of the errors involved in comparison of the light of the electric arc with that of other sources of artificial illumination.

The efficiency of the arc lamp has been expressed hitherto in terms of the candle-power of light produced per unit of energy expended. The estimate has been based in a few instances upon the mean spherical candle-power, as actually determined; more frequently upon the candle-power emanating from the lamp in a single, especially selected, direction, and in too many instances upon the "nominal candle-power." Such estimates of the efficiency of the arc are of small value. They afford us widely varying results which cannot be definitely compared, and even when they are based upon the most complete and careful determinations of candle-power and energy, they do not indicate the ratio of light-giving radiation to the total energy expended

¹ The Efficiency of Methods of Artificial Illumination. Transactions of the American Institute of Electrical Engineers, Vol. 6, 1889.

within the lamp. It seemed, therefore, to be of some importance to obtain the measurements of the ratio of luminous to total radiation in the case of the arc lamp by a method the results of which would be directly comparable with those already obtained for the incandescent lamp.

The investigation was undertaken, at my suggestion, by Mr. Hatsuné Nakano, M. E., of the Imperial University of Japan, the results of whose measurements are given in the following pages.

E. L. N.

ON THE EFFICIENCY OF THE ARC LAMP.

The following experiments were made in the Physical Laboratory of Cornell University during the winter of 1888-89, the object in view being to determine the efficiency of the arc lamp.

It is a well-known fact that the comparison of the candle-power of differently colored lights, such as the candle and the electric arc, is only a rough approximation. By means of one of the methods recently described by Mr. Merritt,² however, we can determine the efficiency of the arc independently of its candle-power. The method in question enables us to find the ratio of the light-giving radiation to that of the total radiation of the lamp.

In his first experiments Mr. Merritt measured the heat given out by a lamp, which was immersed in the water contained in a calorimeter. It is evident that this method, though very ingenious, cannot be employed conveniently in the case of the arc lamp. His second method is, however, applicable to arc lamps as well as to incandescent lamps. This method and the arrangement of the apparatus were fully described by Mr. Merritt in his paper, read before the American Association for the Advancement of Science at their meeting in Cleveland. It was also described by Professor Nichols in his paper read before the American Institute of Electrical Engineers, March 12, 1889.

The application of the method to the arc lamp was as follows: The rays of the light were allowed to fall upon the face of a delicate thermopile which was in circuit with a sensitive galvanometer. The deflection of the galvanometer was taken as a

² Ernest Merritt: Some Determinations of the Energy of the Light from Incandescent Lamps. *American Journal of Science*, Vol. 37, p. 167.

measure of the energy of the total radiation which fell upon the face of the pile.³ After the deflection due to the total radiation had been measured, a glass vessel of rectangular shape one decimeter thick, containing a strong solution of alum, was placed between the lamp and the thermopile, and the reduced deflection of the galvanometer observed. The use of the alum cell was to cut off the "dark heat," and allow only the rays of the visible spectrum to reach the face of the thermopile. But a certain small percentage of the longer wave-lengths passed through, and a considerably larger percentage of luminous rays were cut off by the cell. To determine the correction for the former source of error, a cell containing an opaque solution of metallic iodine in bi-sulphide of carbon was placed between the lamp and the alum cell. Any deflection now obtained was due to the dark rays passing through the alum cell, for the iodine cut off the luminous rays entirely, but allowed the dark rays to pass through. It was found that the dark rays which passed through the alum cell were exceedingly weak—almost imperceptible in most cases.

The correction for the second source of error, viz., the absorption of the luminous rays by the alum cell, was determined photometrically. The average of some thirty measurements gave 26 per cent. for the value of the correction.

In my first measurements, the lamp (the centre of the arc) and the thermopile were placed in the same horizontal plane. The lamp used was a "rack-feed" arc lamp requiring 45 volts and 9 ampères for its normal operation. Experiments were made with a dozen or more of different sizes of carbons, ranging from 2-16 up to about 13-16 inch in diameter.

The efficiency, or the ratio of the energy of the luminous radiation to that of the total radiation, luminous and non-luminous, in this plane was found to be exceedingly small, varying from about

³ John Ericsson in his "Contributions to the Centennial Exhibition," 1876, says that the calorific energy imparted to a thermopile is not proportional to the arcs through which the needle of the galvanometer sweeps, as stated by Melloni, but that for deflections not exceeding 15 degrees, the calorific energy imparted to the pile by radiant heat is very nearly as the square root of the versed sine of the angle of deflection; the deflection of the needle at the termination of the first degree exceeding the energy transmitted, in the ratio of 100 to 89, and beyond 90 minutes the energy becoming greater than the deflection in a constantly increasing ratio. Ericsson does not state, however, what kind of galvanometer he used in his investigations. The one used by me was a low resistance reflecting galvanometer of Sir William Thomson's pattern. It had been tested by Mr. Merritt, who found that the deflections were proportional to the energy imparted to the pile. In my experiments this proportionality was assumed to be true.

5 per cent. to a little less than 15 per cent., the ratio increasing as the diameter of the carbons used decreased. This relation between the efficiency and the diameter of the carbons, which is shown graphically by means of the curve in Fig. 1, ceased to exist, however, when the point was reached at which the whole length of the carbons was rendered hot by the current passing through them. After this point was reached the efficiency fell off again.

Table 1 gives the results of these measurements. In the first column the diameters of the carbons (in thousandths of an inch) are given. The second column shows the "mean horizontal

Fig. 1.

efficiency ;" that is to say, the ratio of the deflection produced by the total radiation of the lamp to that due to the light-giving radiation alone, after the proper corrections for absorption and diathermancy have been applied. Each value is the mean of a series of observations. The third column gives the potential difference between the terminals of the lamp.

TABLE I.

Diameter of Carbons. (In inches.)	Horizontal Efficiency.	P. D. (Volts.)
.832	.01484	42
.730	.02162	35
.605	.02527	43
.563	.03125	38
.500	.03393	38
.432	.05014	38
.370	.05861	28
.305	.07338	31
.250	.0813	56
.185	.0458	25
.124	.0514	30

The curve c d, given in Fig. 1, shows the relation between the efficiency, measured in the horizontal plane, and the diameters of the carbons. The ordinates represent efficiencies, and abscissæ the diameters. It will be noticed that the points A and B corre-

sponding to 2-16 and 3-16 inch carbons, are far below the curve, showing that the relation is modified as soon as the carbons become too small to carry the current without heating.

In the electric arc, as Professor Nichols has shown in the paper already referred to, "the entire light giving area is included between the line surrounding the positive carbon, which is at red heat, and the corresponding line upon the negative carbon. Now the surface of total radiation is much larger than that from which the light-giving rays emanate. It includes in addition to the incandescent surfaces near the arc, all those portions of the carbons which are heated, either by conduction or by the current. Were the distribution of total radiation in the vertical plane identical with that of the light-giving rays, the measurement of their ratio with

the axis of the thermopile in any plane which passes through the arc would give us the efficiency of the lamp, but the curve of distribution of total intensity is not the same as that of candle-power, and the ratio in question is a function of the angle which the axis of the pile makes with the horizon. It becomes necessary, therefore, to make an exploration of the entire zone through which the lamp sends out rays, determining the ratio of luminous to total radiation for each angle and then to integrate the results."

With such an object in view the piece of apparatus which is shown in Fig. 2 was devised. The lamp was hung from a horizontal beam *a*, supported by two upright pieces *b b*, which could be kept always vertical by means of a "parallel motion"

arrangement. The alum bath *A* and the thermopile *P* were also carried upon a board, pivoted at *c c*, so that it could be turned to any desired angle. All necessary changes of angle

Fig. 3.

Fig. 4.

Fig. 5.

Fig. 6.

Fig. 7.

Fig. 8.

could be made without altering the distance between the arc and the thermopile, or the relation of the alum cell to either of them. By means of this apparatus measurements were made at angles of

0°, 10°, 20°, 30°, 40°, 50°, 60° and 63° below the horizontal planes. The following carbons were used:

(1)	Uncoated Carbons.....	diameter = .832"
(2)	" " " " " " " "	.563"
(3)	Copper-plated Carbons.....	.500"
(4)	" " " " " " " "	.450"
(5)	Uncoated Carbons.....	.370"
(6)	Copper-plated Carbons.....	.250"

The results of these measurements are given in tables 2, 3, 4, 5, 6 and 7, and curves showing the distribution of luminous and total radiation, emanating from the lamp under the above conditions, are given in Figs. 3, 4, 5, 6, 7 and 8.

The radii show the positions for which measurements were taken and distances measured along these lines from the origin to each curve give the intensity of luminous and total radiation in each position. The curves of luminous radiation are similar in form to those of candle-power. Note, for purposes of comparison, the set of curves of candle-power at various angles published by M. Schreihage,⁵ of the Polytechnic School at Braunschweig, who has made extended measurements of lamps with different sizes of carbons. In the following tables D is the deflection for total radiation, d that for light-giving radiation (corrected).

TABLE II.

Carbon (unplated), diam. = .832 inch.

Angle	d	D	$\frac{d}{D}$	P. D. (Volts).
0°	4.	230	.0182	44
10°	6.8	265	.0256	42
20°	16.4	300	.0547	42
30°	27.3	350	.0780	40
40°	35.1	390	.0900	40
50°	27.3	330	.0827	38
60°	20.3	300	.0677	39
63°	5.4	125	.0432	39

TABLE III.

Carbon (unplated) diam. = .563 inch.

Angle.	d	D	$\frac{d}{D}$	P. D. (Volts.)
0°	6.8	165	.0412	41
10°	10.8	195	.0554	42
20°	22.9	245	.0956	43
30°	32.8	264	.1242	39
40°	39.2	274	.1441	42
50°	28.4	252	.1137	41
60°	10.8	128	.0625	40

⁵ Schreihage, *Centralblatt für Elektrotechnik*, No. 22, 1888. See also *La Lumière Electrique*, T. 29, p. 585.

TABLE IV.

Carbon (copper-plated), diam. = 5 inch.

Angle.	d	D	$\frac{d}{D}$	$P. D. (Volts.)$
0°	5.4	110	.0491	45
10°	12.2	140	.0872	45
20°	21.5	172	.1250	45
30°	29.7	190	.1563	45
40°	33.8	195	.1733	45
50°	20.3	155	.1310	45
60°	4.1	93	.0441	45

TABLE V.

Carbon (copper-plated), diam. = .45 inch.

Angle.	d	D	$\frac{d}{D}$	$P. D. (Volts.)$
0°	10.8	197	.0548	45
10°	20.3	225	.0901	45
20°	29.7	242	.1228	45
30°	39.2	260	.1506	45
40°	41.9	270	.1552	45
50°	27.3	255	.1059	45
60°	12.2	180	.0676	45
63°	5.4	110	.0492	45

TABLE VI.

Carbon (unplated), diam. = .37 inch.

Angle.	d	D	$\frac{d}{D}$	$P. D. (Volts.)$
0°	10.	180	.0555	40
10°	14.9	190	.0789	42
20°	24.4	200	.1220	38
30°	31.8	217	.1474	37
40°	39.2	230	.1696	40
50°	42.	240	.1750	42
60°	33.8	205	.1659	42
63°	10.8	115	.0869	38

TABLE VII.

Carbon (copper-plated), diam. = .25 inch.

Angle.	d	D	$\frac{d}{D}$	$P. D. (Volts.)$
0°	13.5	160	.0844	37
10°	22.9	185	.1238	37
20°	39.2	225	.1742	39
30°	45.9	255	.1800	38
40°	41.9	230	.1822	38
50°	29.7	150	.1980	39
60°	4.1	75	.0547	38

The distribution of total radiation differs widely from that of luminous radiation, so that the efficiency expressed by their ratio depends upon the angle of measurement. The values of the efficiency in each case for the various angles at which measurements were made have been calculated. They are shown in the diagram of efficiencies in Fig. 9.

Fig. 9.

In order to determine the mean or "hemispherical" efficiency of the lamp the ratio of the radii of two semi-circles, the areas of which equal the areas of the curves of total and luminous radiation was found by means of a planimeter. The following are the values thus obtained:

TABLE VIII.

Diameter of carbons.	Spherical efficiency.
.832	.0687
.563	.1100
.500	.1266
.450	.1330
.370	.1554
.250	.1660

The above table forms the basis of the curve shown in Fig. 10, which represents the relation between the diameter of the carbons and the "hemispherical" efficiency of the lamp. The diagram is a straight line. Thus we see that the hemispherical efficiency varies inversely as the diameter of the carbon.

It will be interesting to compare this with the result of M. Schreihage's experiments. He measured the mean spherical

candle-power with the different sizes of carbons, and found the same relation to hold true, as will be seen from the following table:

TABLE IX.

M. SCHREIHAGE'S MEASUREMENTS OF CANDLE-POWER AND CURRENT DENSITY.

Cross-section of positive carbon. mm.	Diameter d. m.m.	Spherical c. p.	d. X c. p.	Current density.
40	7.12	417	3,353	0.134
95	11.0	383	3,128	0.066
134	13.6	254	3,462	0.047
194	16.1	189	3,045	0.032
254	18.0	161	2,905	0.25

Fig. 10.

M. Schreihage states that this relation is not completely satisfied in the case of the mean horizontal candle-power, especially when the carbons are very small or very large. We have seen that this statement applies also to the experiments upon the horizontal efficiency described in the first part of this paper.

Physical Laboratory of Cornell
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DISCUSSION.

THE PRESIDENT:—The subject of the paper just read is certainly one of considerable importance, and some of the conclusions are unexpected, you may say. As there are persons here having experience in this line, we would like to hear from them.

MR. PRESCOTT:—I would simply like to ask Prof. Nichols if this law that he discovered is independent of the current density. I understand the law to be that the efficiency of the arc lamp depends on the diameter of the carbon without reference to the current density.

PROF. NICHOLS:—I should have said that these experiments were made with constant current and as nearly as possible with constant electromotive force to the arc. The arc was maintained at about 45 volts, and the current was maintained at about 9 amperes; but quite a little range of voltage and current in the lamp showed surprisingly small changes in the efficiency. Probably toward the end of the test there was not the same care taken to hold the current and voltage constant that would have been taken if the efficiency had been found sensitive to changes in this respect, but the law holds true strictly where the current and voltage are maintained constant.

PROF. M. M. GARVER:—In some experiments I made with arc lamps for 20 amperes we would use 7-16 carbon in summer, but in the winter, in order to make them last longer, we used the larger carbon. We found in our experience that the light was not as good, and consequently we would have to increase the current. However, when we got hard carbons they lasted better. We observed, also, in that case, without measurements, that the light was not so good with the hard carbon as with the soft carbon. I would like to ask if anything of the kind was observed.

PROF. NICHOLS:—I would say simply that it was not the intention to go into the question of different carbons. In starting the investigations we simply took such carbons as happened to be available in the laboratory, of different sizes. It was taken up originally as practice work, and I did not know at that time that it would ever come to the light, because I did not expect as good a result as was obtained; but all the carbons were probably carbons of good quality. They were of different makes, American and European.

PRESIDENT THOMSON:—I would add a word just on this point from my own experience. I think, undoubtedly, the density and

hardness of the carbon has an effect on the luminosity, and practical experience, without even referring to refined measurements, is that if a carbon is entirely too hard for the current, the luminosity is so much lessened that people complain at once, although the voltage and current remain the same. I can confirm what Prof. Nichols says also in regard to changes in the length of arc not changing the luminosity very much beyond a certain separation, when the light seems to go out freely, and as it mostly emanates from the carbon ends themselves, a little separation, more or less, will not make a great difference in the effects. It would be interesting in this connection to know exactly what was the combustion of carbon in the different cases. Of course, a part of the cost—the practical cost—is the rate of consumption of carbon, and sometimes we can sacrifice a little light by using a larger carbon and getting a longer life, since the carbon costs something in the running of the lamp. This gives rise to the question as to whether the combustion of the carbon itself does not have to do with the efficiency of illuminating power—whether, in other words, the carbon is not to be regarded in part as a piece of coal, which, if it burns rapidly, gives out more light in a given time than if it burns slowly; consequently with a low current density and small combustion of carbon we lose that effect and depend on the current altogether to produce the light. At the rate of burning of carbon in the arc light there must be a considerable amount of light, due entirely to the combustion of the carbon, without reference to the current, the current merely maintaining the carbon at that temperature which permits this effect to exist.

MR. WESTON :—I understand Prof. Nichols did not make any experiment with any other lamp except this arc lamp. Experience has shown, I think, that the efficiency of an arc lamp is very much increased where the power of the light is increased. If I remember rightly, some experiments I made myself in 1875 and 1876, showed that to a very marked extent, and I think experiments probably earlier than mine showed it. So that the efficiency, as it stands for an ordinary commercial lamp to-day, is not anything near what we can get if we make the lights larger. How far that would extend it is somewhat difficult to say, and as Prof. Nichols has all the appliances for making these measurements, including dynamos, I think it would be a very nice thing if we could get some facts in regard to efficiency of lamps, running up to 100 or 200 amperes instead of 9 or 10. It would

probably throw a great deal of light on the matter. The small amount of useful luminous energy compared to the total energy employed, is a sad thing, always. That, together with the low efficiency of the steam engine shows how much we have to do. There is no lack of work in this field.

PROF. NICHOLS:—I would like to say that in presenting this paper I have presented it not as an exhaustive investigation of this subject, but rather as pointing out a line of work which, I think, may be a good deal of benefit to the study of the light-giving power of various illuminants, and that undoubtedly in order to make it complete it ought to be worked out for the efficiency as a function of the length of arc, independently again, as a function of current, and then those could be combined, so as to give it as a function of the energy for a constant length of arc. In short, it ought to be worked out under all the conditions under which lamps can be used. Here we have only worked it out for a single condition of affairs, because that was convenient to us—the ordinary long arc lamp of to-day.

PROF. GEYER:—May I ask Prof. Nichols whether any attempt was made to see if in the part which he calls luminous energy any appreciable amount, was energy other than luminous—that is, what is ordinarily called actinic. I should think that in a light centre, as an arc light, an appreciable amount might be other than luminous, which would reduce all those figures slightly; but the effect would probably be greater on those which are lowest on the column, and probably less on those which are on top of the column.

PROF. NICHOLS:—Mr. President, I would say that very careful corrections were made for the dark rays—the waves of longer wave length than the red which were able to pass through the alum, but the energy of the ultra-violet rays is so very small when measured on the thermopile that we regarded it as unworthy of mention.

DR. MOSES:—While suggestions are flying thickly, I would like to recall some experiments which might have bearing on future experiments in this direction. On one occasion, in order to get an absolutely uniform light I tried the effect of various colored media on an arc, and I found that with a monochromatic light, the general effect is more uniform throughout different areas; you did not see the sudden sharp flash of light that occurred by the reflection from the crater. Now, if experiments were car-

ried on perhaps by allowing the arc to burn its way through a disc of mica, you would get a perfectly uniform monochromatic atmosphere and that would perhaps be the best medium for making these experiments. Monochromatic light may give uniformity of result.

The following paper on "The Spiral Coil Voltameter," by H. J. Ryan, was then read by Professor Nichols: