THE EFFECT OF CORONA CURRENT ON THE COOLING OF A HOT WIRE*

By Samuel R. Parsons

Abstract

This article describes an experimental study of the cooling of a hot wire in air, when the air is disturbed by a corona discharge to the wire. With a copper wire, No. 30 B. & S. gauge, *in still air*, no effect was found with corona current less than 3 microamperes per cm of wire; but beginning with about that value, the cooling power of the wire increases, at first rapidly, and then more slowly, possibly passing through a poorly defined maximum. A corona current as great as 12 microamperes per cm is sufficient to give nearly the maximum effect. With small currents of air past the wire, a gradual increase of corona current, starting with zero, often shows first a heating effect, followed by a cooling effect. The slow currents of air seem to be appreciably retarded by the cross-flow of the ions carrying the corona current. The number of ions required for appreciable cooling is estimated to be considerably less than one ion per million molecules of the gas.

A SMALL wire gently heated in still air dissipates heat rather slowly, because of the fact that the air close to it forms an effective heat-insulating blanket; and any agency that disturbs this insulating blanket may be expected to increase the loss of heat from the wire. It has seemed probable that if the electrical potential of a wire is raised until a corona discharge is obtained, the motion of the ions in the corona current should cause an appreciable cooling effect. This has been found to be true, and the cooling power of a wire has been doubled, with rather small corona current. The following paragraphs describe an experimental study of this cooling effect.

Perhaps it should be stated that since the experiments are subject to the irregularities of cooling with very feeble convection currents, and also to the irregularities of the corona discharge, too much significance must not be attached to the absolute magnitudes of quantities shown. The results of the experiments should be regarded as representative of similar, but not identical, values that might be obtained under very slightly different conditions.

Apparatus

A piece of No. 30 bare copper wire, 17.2 cm long, was stretched along the axis of a brass tube of the same length, and 4.3 cm inside diameter. This wire, which will be called the "corona wire", was supported at both ends by current and potential leads of No. 22 enameled copper wire. The ends of the brass tube, supported by insulating rings of Bakelite panel-

* Research Paper No. 105, Journal Series, University of Arkansas.

board of 10.5 cm outside diameter, opened directly into wooden boxes about 15 cm square and 6 cm deep. In the side of each box opposite the opening of the brass tube was a hole 4.5 cm in diameter, covered with glass. The glass windows allowed direct observation of the corona wire, and by means of small holes drilled at their centers, additional wires were used to help center the corona wire, and to provide means for applying a suitable tension. The boxes were made fairly tight except for a 0.5 inch hole drilled in one side of each. Aside from acting as supports, they provide air chambers allowing some ventilation of the tube while shielding the corona discharge from air currents in the room. In a corona tube with closed ends, it has been found that with a steadily applied voltage, the corona current changes in value after a few seconds, perhaps largely because of the rise in temperature and the formation of ozone; but by the use of these boxes, very steady values of corona current were obtained, so long as the axis of the tube was horizontal. Its use in a vertical position was not satisfactory.

Alternating current was used for the corona discharge, the high potentials being obtained from a 25,000 volt, 1 k.v.a. transformer. The corona current passing between the wire and the tube was measured by means of a Western Electric vacuum thermocouple and sensitive galvanometer.

The corona wire was heated by direct current from a storage battery, and a standard current carrying resistance was placed in series with Potential drops across the corona wire and the standard resistance were measured by a potentiometer method,[1] furnishing data from which to compute the current in the wire, its resistance, and the rate of development of heat in it, or its rate of dissipation of heat. The temperature coefficient of resistance of the wire was found from direct measurements on a piece cut from the same spool, and the wire was used to measure its own temperature. It was not feasible to measure the temperature of the air in the corona tube by this method, because when the current was small enough to avoid heating the wire, the readings on the potentiometer were too small to be reliable. The resistance of the wire without heating current was accordingly measured by the use of a Mueller thermometer bridge with special commutator—the method used with four-lead resistance thermometers, whereby the resistance of the leads is entirely eliminated. The temperature of the wire obtained from this measurement was assumed to be equal to the temperature of the air surrounding it.

The high potential circuit was grounded close to the corona wire, and so arranged that the corona tube was the only part at high potential, so that measurements could be made in the heating circuit without interference from the 60-cycle corona current.

No attempt was made to dry the air, and at times the relative humidity was as high as 85 percent.

[1] The instrument used was the "millivolter" of the Pyrolectric Instrument Co., with an auxiliary galvanometer.

RESULTS

The cooling due to corona current is shown most directly in Fig. 1, which shows the lowering of temperature of the wire, under a certain constant heating current, as the corona current is increased. (Wherever temperature is represented in the figures, it will be shown by the difference in temperature between the wire and the air in the corona tube.) But since the resistance of the wire changes as its temperature changes, a constant heating current does not insure a steady rate of production of heat, and the cooling power of the wire is better shown in Fig. 3, where the rate of dissipation of heat is shown as a function of the corona current, for constant differences of temperature between the wire and the air. The direct results of experiment are represented by curves of which those of Fig. 2 are typical, and Fig. 3 is made from values read from these curves. Fig. 4 shows similar values obtained for the same corona wire and tube, but about a year later.

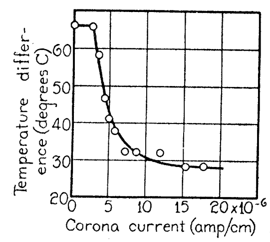

Fig. 1. Cooling of wire by corona current. "Temperature difference" is difference in temperature between the wire and the air surrounding it.

The curves show that a minimum corona current of about 3 microamperes per cm of corona wire is necessary to cause sufficient disturbance of the air for appreciable cooling; and that as the corona current increases, the cooling power of the wire increases rapidly at first and then more slowly, apparently reaching a maximum value. Very little further cooling is obtained by raising the corona current above 12 microamperes per cm. If the rate of dissipation of heat really passes through a maximum, as some of the curves seem to indicate, it is probably due to local heating of the air close to the wire, by the corona current itself; for a corona current of 25 microamperes per cm required a potential difference of 8 kilovolts, representing 0.2 watt per cm.

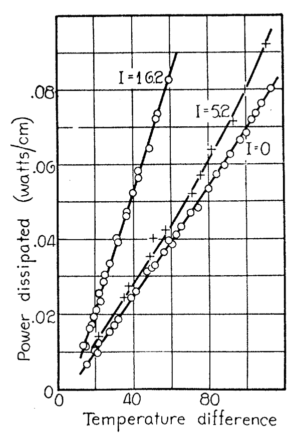

Fig. 2. Rates of dissipation of heat with corona current. I is the corona current in microamp. per cm of wire.

The corona current required for appreciable cooling was also found by another method: with a certain heating current flowing, the potentiometer was balanced on the potential drop across the corona wire, and the corona current was gradually increased until the potentiometer was thrown out of balance. This was also done with low rates of flow air through thy corona tube. The results are shown in Fig. 5. An interesting secondars effect was observed when air was flowing through the tube: in many casee, when the corona current reached about the value necessary for appreciable cooling in still air, the potentiometer was thrown out of balance in the

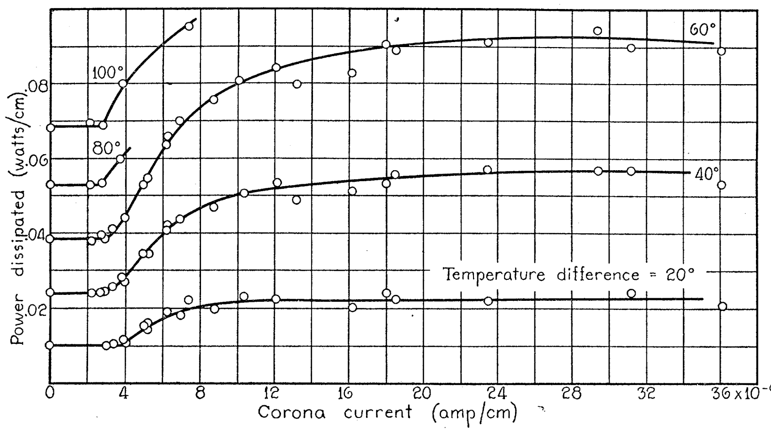

Fig. 3. Effect of corona current on cooling power of wire.

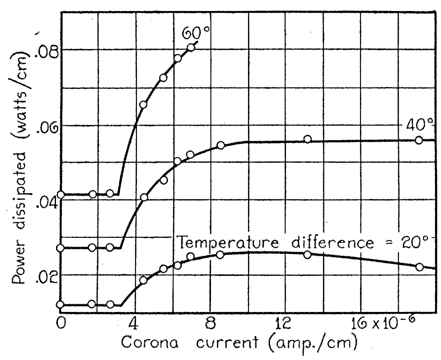

Fig. 4. Effect of corona current on cooling power of wire.

direction indicating *heating* of the wire, and some further increase of corona current was required to show a cooling effect. It is as if with low rates of flow, a small corona current interferes with the air stream close to the wire enough to reduce its cooling effect, while a larger corona current causes enough disturbance of the air to add to the cooling effect of the stream. With a higher rate of flow and a small heating current, the corona current gave a heating effect for the largest value used, which was 11 microamperes per cm. Fig. 6 is included to show the order of magnitude of the effects of air flow on cooling power of the wire, without corona current.

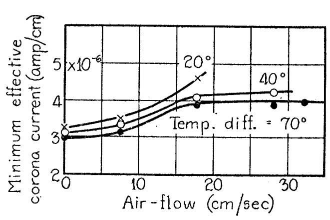

Fig. 5. Effect of flow of air on minimum corona current required for appreciable cooling.

With a given potential difference across the corona tube, the application of the heating current was found to cause some increase in the corona current. This is probably due to the rise in temperature of the air, which is known to result in greater corona current.[2]

[2] Fazel and Parsons, Phys. Rev., **23**, 598 (1924).

An attempt was made to obtain similar data with a second corona wire, No. 36 gauge, but so much trouble was caused by vibration of this fine wire that no satisfactory data could be obtained. No vibration was detected with the corona current alone, but with fairly large corona current, and a heating current of about 2 amperes, the vibration of the wire was so violent that it set up a hum much louder than the hum of the transformer.

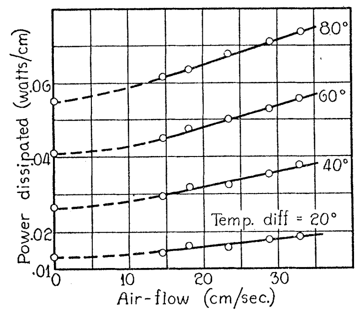

Fig. 6. Effect of flow of air on cooling power of the corona wire, without corona current.

Estimated Space Charge

It is interesting to estimate the number of ions per cubic centimeter that are required to show a cooling effect. In the corona tube, most of the ionization is confined to a region close to the wire, while the remainder of the tube contains (during a half-cycle) ions of only one sign. The density of this space charge is readily computed, on the basis of two or three assumptions. Let i be the current per cm length of wire and tube; ρ, the density of space charge; and u, the velocity of the ions at any distance r from the axis of the wire. Then the current per cm passing a cylindrical surface of radius r is

$$i = 2\pi r \rho u \tag{1}$$

If we assume that the velocity of the ions is proportional to the field, we may write $u = kX$, where k is the mobility of the ions; and X, the intensity of electric field. If the current is small, the electric field is nearly that of the electrostatic case, namely,

$$X = V/r \log_e (R/r_0) \tag{2}$$

where V is the potential difference between wire and tube; R, the radius of the tube; and r_0, the radius of the wire. From these equations,

$$i = 2\pi\rho k V/\log_e (R/r_0) \qquad \text{or} \qquad \rho = i \log_e (R/r_0)/2\pi k V \tag{3}$$

The disappearance of the factor r shows that the space charge is uniform throughout the space considered—outside of the region of intense ionization.

Unfortunately, this equation involves the mobility of the ions, about which rather little is known. If we should assume that the initial ions are like those formed by x-rays or radioactive substances, it would be safe, for the purpose of this estimate, to call the mobility 1.8 cm/sec per volt/cm; for the life of the ions is so short that very few of the positive ions have the time for the "ageing" observed by Erikson and by Wahlin.[3] But by measurements on ions taken from a corona tube, Young[4] has found mobilities very

[3] H. A. Erikson, Phys. Rev., **20**, 117 (1922); H. B. Wahlin, Phys. Rev., **20**, 267 (1922).
[4] W. M. Young, Phys. Rev., **28**, 129 (1926).

much lower than this, and distributed over a wide range of values. His values for oxygen range from 0.92 to 1.8×10^{-4} cm/sec per volt/cm; and his values for nitrogen lie within this range. His measurements were made on ions more than 2.5 seconds old.

The table shows the space charges computed by means of Eq. (3), using the three values of mobility indicated. The number of molecules

TABLE I. *Space charge accompanying lowest corona current that shows a cooling effect.*

Assumed mobility, cm/sec per volt/cm	1.8	0.92	0.00018
Space charge, e.s.u. per cm^3	2.0	4.0	2.0 (10^4)
Number ions per cm^3	4.2 (10^9)	8.3 (10^9)	4.3 (10^{13})
Ions per molecule	1.8 (10^{-10})	3.5 (10^{-10})	1.8 (10^{-6})

present in one cubic centimeter of gas at the pressure and temperature existing in the corona tube (about 25°C, 72 cm) is about 2.4×10^{19}, and the last line of the table is obtained by dividing the number of ions per cubic centimeter by this number. If each ion consisted of one molecule, this would be the fraction of the number of molecules of the gas that must be ionized before appreciable cooling results; but if the ions have mobilities as low as were found by Young, they must be much greater than one molecule, and the figures in the last line of the table represent merely the number of ions per molecule of the gas. The average numbers of ions per cubic centimeter so close to the wire as to be within the region of intense ionization, would be somewhat less than twice the values shown in the table, since the space charge outside of that region represents all the ions of one sign formed. (The conditions are such that recombination of ions is negligible.)

Since, according to Young, the mobilities are distributed in unknown proportions over a wide range of values, no close estimate can be made of the conditions in the corona tube, but is seems safe to state that less—probably very much less—than one ion per million molecules is sufficient to disturb the air close to the wire enough to cause an appreciable change in its cooling power.

THE UNIVERSITY OF ARKANSAS,
September 11, 1928.