JANUARY 15, 1939 PHYSICAL REVIEW VOLUME 55

Convection Currents in Arcs in Air

C. G. Suits
Research Laboratory, General Electric Company, Schenectady, New York

(Received December 5, 1938)

Convection currents in and around arcs in air have been studied by Kenty's method of photographing solid particles in the gas stream. By the use of BN powder the air velocities around an arc column with vertical axis are measured throughout the entire region of convection currents. These velocities vary from 130 cm sec.$^{-1}$ at the arc axis to zero at a distance of 2.5 cm. By integrating over the velocity curve, the total heat flow is found to be 75 percent of the electrical input. That portion of the heat flow included in the luminous arc core is 7 percent of the total. By equating the buoyancy force and the viscous force at the arc boundary, the gas viscosity η is measured. The gas temperature corresponding to η is 7000°K, in agreement with known arc temperature measurements.

Introduction

THE general character of conduction-convection heat loss from solid bodies has been studied by numerous investigators.[1] It is found that the convection currents, which are zero at the surface of the hot body and at a distance of several centimeters, rise to a maximum at a distance of several millimeters from the surface. The full drop in temperature takes place in this region of a few centimeters, with the steepest temperature gradients being directly at the surface of the hot body.

In order to ascertain the similarities between heat loss from solid bodies and from high pressure arcs we have studied experimentally the convection currents within and around arcs in air by a method similar to that used by Kenty with the Hg arc.[2] Kenty introduced CaO and MgO powder into the arc column mechanically and observed the rate of rise of this material as incandescent particles and ionized vapor. In this way he measured the maximum velocity in the axis of the arc, finding values around 50 cm sec.$^{-1}$, increasing for increasing vapor density.

Experimental Methods

In applying Kenty's method to arcs in air, three methods have been found which yield particles satisfactory for photographing: (1) With cored carbons it was found that a sharp tapping of the electrodes knocks out luminous particles which travel upward on the convection currents; (2) carbon dust blown into the arc can be photographed not only in the arc core but also at distances up to five mm from the arc boundary; (3) boron nitride in the form of a very light white powder can be photographed by reflected light at distances as great as one cm from the boundary of the luminous core.

An error will be made in the measurement of these convection currents if the particles which are introduced are so large that they have an appreciable rate of fall in air at the temperature of the convection currents. This error can be estimated from Stokes' law by observing the rate of fall in quiet air at room temperatures. In this way we find that at room temperatures the carbon dust falls freely at a velocity v of 50 cm sec.$^{-1}$ while the boron nitride falls at a rate estimated to be one cm sec.$^{-1}$ The boron nitride is so fine that it will follow the slight convection currents in a still room to an extent which makes the free fall measurement difficult. By Stokes' law,

$$v = 2ga^2\Delta d/9\eta,$$

where g is the customary quantity, a is the radius of the particles, Δd is the difference in density between the gas and the body, and η is the vis-

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[1] (a) L. Lorenz, Wied. Ann. **13**, 582 (1881); (b) W. Nusselt, Gesundh.-Ing. **38**, 477 (1915); (c) I. Langmuir, Phys. Rev. **34**, 401 (1912); (d) C. W. Rice, J. Inst. Elec. Eng. **42**, 1288 (1923); (e) E. Griffiths and A. H. Davis, Report 9, Food Invest. Bd., H. M. Stationery Off., London (1922); (f) E. Schmidt, Zeits. f. Gesamte Kalt-Ind. **35**, 213 (1928); (g) W. Nusselt and W. Jurges, Zeits. V.D.I. **72**, 597 (1928); (h) E. Schmidt and W. Beckmann, Tech. Mech. & Thermo. **1**, 341, 391 (1930); (i) R. H. Heilman, Trans. Am. Soc. Mech. Eng. **51**, 287 (1929).

[2] C. Kenty, J. App. Phys. **9**, 53 (1938).

cosity. For BN the rate of fall correction will evidently be negligible for 100 cm sec.$^{-1}$ convection currents; on the basis of the measured fall rates, the particle radii a are calculated to be

$$a_{\mathrm{BN}}=0.6\times 10^{-3}\ \mathrm{cm},\quad a_{\mathrm{C}}=4.3\times 10^{-3}\ \mathrm{cm}.$$

The particle diameter in the case of the BN is such that for 1 : 1 magnification it is near the resolving power of the photographic film. The observed traces on the film are larger than indicated by the calculated radii, probably because of halation.

It evidently will be safe to interpret the photographically observed particle velocity as the convection current velocity in the case of the C particles only in the high temperature regions of the arc core, where by virtue of the temperature increase of viscosity the fall rate decreases. Thus for η, calculated from Hassé and Cook,[3] the fall rate for the carbon dust is 17 cm sec.$^{-1}$ at 1000°K and 5 cm sec.$^{-1}$ at 6000°K. Kenty did not observe the fall rate of the particles used in his experiments, but from the evidence that they vaporized and from the fact that his measurements were made on the axis of the arc column an error from this cause does not seem probable.

The photographic method used was similar to that employed in the sound velocity experiments,[4] except that a rotating drum film holder replaced the rotating mirror and stationary film.

The principal observations on the convection velocities in arcs in air are given by Table I and Fig. 1.

Throughout this set of measurements of arc convection currents the following constants apply: Arc current $i\cong$ four amp.; arc length $l\cong$ three cm; electrodes, National (Projector) cored carbons; for $I=10$ amp. cm^{-2} the arc diameter $D=0.7$ cm. A slit in the optical system restricts the observation to a segment, one mm in width, parallel to the arc axis. An examination of Table I shows that the velocities measured by particles from the electrodes[5] are smaller than by the other two methods and show a large polarity effect. From the measurements with C and BN powder it is believed that the velocity measurements based on these core particles are unreliable. The particles are obviously large and probably have an appreciable free-fall correction. If the size of the particles depends upon the electrode temperature, the large polarity effect would be explained, since the anode crater is much hotter than the cathode. When a particle is released from the upper electrode, it falls for a few millimeters and then reverses its direction and rises rapidly. Although the method of electrode particles is of doubtful merit for quantitative work, it lends itself very well indeed to the demonstration of the existence of the velocity currents in the arc gas.

TABLE I. *Particle velocity in and near arc.*

Case 1—Carbon particles from anode* and cathode**						
Position of anode	Top	B'm	B'm			
Distance from arc axis (cm)	0	0	0			
Velocity (cm sec.$^{-1}$)	75**	35*	80**			
Case 2—Carbon dust blown into arc						
Anode	Top	Top	B'm	B'm		
Dist. (cm)	0	0.5	0	0.7		
Velocity (cm sec.$^{-1}$)	120	112	130	110		
Case 3—Boron nitride blown into arc						
Anode	B'm	B'm	B'm	B'm	B'm	B'm
Dist. (cm)	0	0.5	0.7	1.2	1.4	2.5
Velocity (cm sec.$^{-1}$)	130	70	50	41	34	0.0

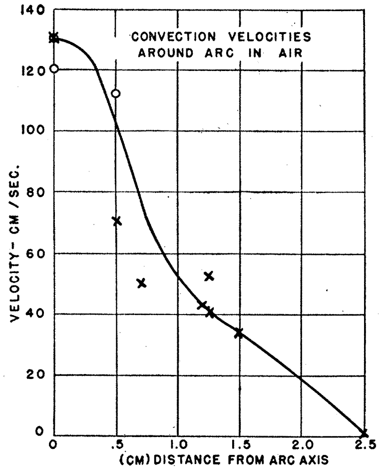

FIG. 1. Convection velocities around arc in air.

DISCUSSION

The measurements with C and BN dust are in good agreement and show velocities which

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[3] H. R. Hassé and W. R. Cook, Proc. Roy. Soc. **A125**, 196 (1929).

[4] C. G. Suits, Physics **6**, 315 (1935).

[5] J. A. Van Lund, who took many of the measurements in this paper, devised this method.

vary between 130 cm sec.$^{-1}$ in the arc core and 34 cm sec.$^{-1}$ at a distance of 1.5 cm from the arc axis. The air currents appear to be practically undisturbed at 2.5 cm, which may be taken as the point of zero velocity. The velocities on the arc axis are about two to three times as large as observed by Kenty for the Hg arc at the same pressure, although the lower density of air would lead to a velocity one-seventh as large for our case, according to Elenbaas' theory.[6] The essential difference in the geometry must be held accountable for this result, since in the Hg arc the rising gas column in the tube axis experiences a viscous drag from the descending velocity stream near the tube wall.

A study of Fig. 1 shows the difference between the convection currents near a solid body and near an arc. The velocity stream which is zero at the surface of the solid has a finite value at the boundary of the arc column. The amount of energy which is carried away by the movement of the gas in the region defined by the arc column is small compared to the total arc energy. The heat Δh, which is carried away by a laminar convection current in a cylinder of radius r and thickness dr, is given by

$$\Delta h = 2\pi r dr v C_p \Delta T \rho, \tag{1}$$

where v is the uniform velocity, C_p is the specific heat (in cal. g^{-1}), ΔT is the temperature above ambient, and ρ is the gas density. If T is large, and for a monatomic gas, the product $\Delta T\rho$ is constant and Δh does not depend upon the temperature. For a dissociating gas, ρ experiences a pure temperature effect and an effect due to thermal dissociation; in general, in a nonreactive gaseous mixture of i components the density ρ at the temperature T is given by:

$$\rho(T) = \frac{T_0}{T}\sum\frac{\rho_i p_i}{p_i} = \frac{\rho_0 T_0}{T}\sum\frac{M_i p_i}{p_i},$$

where p_i is the partial pressure and M_i is the molecular weight of the i the component; ρ_0 is the density of atomic hydrogen at the temperature T_0. The quantity

$$\sum M_i p_i / p_i = \bar{M},$$

where $\bar{M}$ is the weighted mean molecular weight. Also

$$C_p = C_{p_1}/\bar{M}$$

where C_{p_1} is the heat capacity in cal. per gram molecule. Hence

$$\Delta T C_p \rho = \Delta T \frac{C_{p_1}}{\bar{M}} \frac{\rho_0 T_0 \bar{M}}{T} \cong C_{p_1}\rho_0 T_0$$

if $\Delta T \cong T$. The quantity $\Delta T C_p \rho$ is thus constant to the extent to which the heat capacity per gram molecule is constant. This is not precisely true,[7] but in the following calculation we neglect the error. The convection heat Δh can therefore be simplified to

$$\Delta h = 2\pi r dr v a,$$

where $a = 0.124$ cal. cm^{-3} for air. To obtain the heat energy h_c in the arc core, we can integrate

$$h_c = 2\pi \int_0^{0.36} r v(r) dr \tag{2}$$

numerically to obtain

$$h_c = 6.8 \text{ calories.}$$

The total calories in the arc are 96, so that the core portion represents about 7 percent of the total. If we integrate between 0–2.5 cm to get the total convection heat flow h for the $v-r$ curve of Fig. 1, we find $h = 71.5$ calories or 75 percent of the total input. This agreement is satisfactory in view of the heat loss along the electrodes and some radiation loss.

The convection currents arise from a buoyancy force F_b on the heated air of the form

$$F_b = \pi r^2 g h \Delta\rho, \tag{3}$$

where πr^2 is the area of a cylindrical section of height h, $\Delta\rho$ is the gas density difference due to temperature; and are restrained by a viscous force F_v of the form

$$F_v = 2\pi r h \eta dv/dr, \tag{4}$$

where η is the viscosity and dv/dr the velocity gradient at the surface of the cylinder of radius r. The flat top to the $v-r$ curve of Fig. 1 is no

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[6] W. Elenbaas, Physica 3, 484 (1936).

[7] See C_p for O_2 and N_2 in Table I, "Determination of Arc Temperature from Sound Velocity Measurements, II." H. Poritsky and C. G. Suits, Physics 6, 190 (1935).

doubt caused by the increase of η at the high core temperature. We can equate (3) and (4) at the arc boundary,[8] where $r=0.36$, $dv/dr=130$, and solve for η with the result that

$$\eta=0.0018 \text{ poises.}$$

By Hassē and Cook[4] the temperature of air corresponding to a viscosity of 0.0018 is 7000°K. This concept, therefore, leads to reasonable values of extrapolated viscosity in the correct range of measured arc temperatures, or, conversely, can be viewed as a direct measure of viscosity at high temperature, showing agreement with the extrapolated data of Hassē and Cook. It should be noted that both $\Delta\rho$ and η depend upon temperature. However, when T is large, the dependence of $\Delta\rho$ upon T is negligible in the present instance.

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[8] The arc "boundary" as a measurable is discussed in detail in a paper now in preparation.

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The Probability of Ionization of Mercury Atoms by Collision with Low Velocity Electrons[1]

MAURICE E. BELL*
George Eastman Laboratory of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts

(Received September 27, 1938)

INTRODUCTION

THE study which is briefly reported here was undertaken late in 1934 and completed in May 1937, with the principal object in mind of establishing beyond any doubt the true form of the ionization probability curve of mercury vapor in the immediate neighborhood of the ionization potential. The two schools of thought are well typified by the experimental results of E. O. Lawrence[2] on the one hand, and of P. T. Smith[3] on the other. Lawrence has maintained that the ionization function rises rapidly with increasing electron energy at the ionization potential and then falls, after which an "ultra-ionization" potential is reached giving rise to another rapid increase in ionization probability followed by another decrease, and so on. The opinion typical of the opposing group is well represented by a quotation from Smith's paper which follows: "The curve indicates that the ionization does not rise sharply at the ionization potential, the rapid rise occurring almost a volt above this potential. Curves obtained with a poor velocity distribution did, however, show a more rapid rise at 10.40 volts." The results here reported are in excellent agreement with Lawrence's experimental findings, although complete agreement with his theoretical deductions is not implied. As will be illustrated below, an apparent ionization was found below the ionization potential of mercury which cast some doubt over the detailed validity of the work, since it was not certain whether this apparent ionization was caused by some impurity, the mercury molecule, or photoelectric emission from the ion collector. Since it was within the range of possibility that this unknown mechanism was also responsible for the maximum and minimum in the ionization curve, it was considered necessary to repeat the work with a more elaborate tube. This work has served as a forerunner of the much more extensive study made by W. B. Nottingham and reported in the paper following this one.

EXPERIMENTAL APPARATUS

After experimenting with a tube design very similar in principle to that used by Lawrence, except that all metal parts were made of tantalum and no wax joints were used, this was abandoned because of the small intensity of electrons

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[1] A complete report of this research is on file in the library of the Massachusetts Institute of Technology.

* On the Research Staff of the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pennsylvania.

[2] E. O. Lawrence, Phys. Rev. **28**, 947 (1926).

[3] P. T. Smith, Phys. Rev. **37**, 808 (1931).