[3] Gehring, J. W. and Warnica, R. L., "An Investigation of the Phenomena of Impact Flash and its Potential Use as a Hit Detection and Target Discrimination Technique," *Proceedings of the Sixth Symposium on Hypervelocity Impact*, The Firestone Tire and Rubber Co., Cleveland, Ohio, Vol. II, Pt. 2, 1963, pp. 627–681.
[4] Koehler, R. A., "Spectroscopic Study of the Impact Flash," M.S. thesis, 1965, Univ. of Western Ontario, London, Ontario, Canada.
[5] Jean, B., "Experimental Observations of Optical Radiation Associated with Hypervelocity Impact," *AIAA Journal*, Vol. 4, No. 10, Oct. 1966, pp. 1854–1856.
[6] Rollins, T. L. and Jean, B., "Impact Flash for Micrometeoroid Detection," CR-92122, May 1968, NASA.
[7] Jean, B. and Rollins, T. L., "Hypervelocity Impact Flash for Hit Detection and Damage Assessment," AFATL-TR-68-46, March 1968, U.S. Air Force, Eglin Air Force Base, Fla.
[8] Cook, A. M., "The Science of High Explosives," Reinhold, New York, 1959, pp. 259–262.
[9] Birkhoff, G. et al., "Explosives with Lined Cav ties," *Journal of Applied Physics*, Vol. 19, No. 6, June 1948, pp. 563–582.
[10] Walsh, J. M., Shreffler, R. G., and Willig, F. J., "Limiting Conditions for Jet Formation in High Velocity Collisions," *Journal of Applied Physics*, Vol. 24, No. 3, March 1963, pp. 349–359.

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# Convective Electric Arcs at Mach Numbers up to 6.5

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**Experimental observations are presented of supersonic convective electric arcs magnetically stabilized in sulfur hexafluoride. It is found that the arc column, moving at Mach numbers from 1.3 to 6.5, slants across the electric field lines at angles such that the crossflow Mach number ranges from 0.8 to 3.8. The experimental apparatus was a rail accelerator with one rail, usually the cathode rail, preheated to enhance arc stability. Observed values for the angle of slant are presented for three different preheat temperatures. The direction of slant was always such that the arc root at the heated rail led the remainder of the arc. At Mach numbers above 2.0 and preheat temperatures $T_R$ of 1700°C and 2200°C, the magnitude of the slant angle was given very nearly by $\cos^{-1}(T_1/T_R)^{1/2}$, where $T_1$ is the temperature of the gas ahead of the arc. For the preheat temperature of 1100°C, the slant angle has a maximum which is also given by $\cos^{-1}(T_1/T_R)^{1/2}$. Observations of the effective drag coefficient for the arc column are presented and discussed.**

## Introduction

FOR the convective electric arc in air, there exists a stable geometric configuration in which the plasma column slants across the electric field lines.[1–5] The connection between column slanting and arc stability was first discovered for the stationary blown arc in a supersonic wind tunnel,[1,2] and later confirmed for the moving arc in a thermionic rail accelerator.[5] It has been shown that the stable supersonic arc in air slants very nearly along a Mach line—i.e., the component of velocity normal to the arc column is approximately equal to the speed of sound in the undisturbed gas.

Experiments are discussed herein in which electric arcs moving through sulfur hexafluoride were observed. These arcs also slanted across the electric field lines, but at angles such that the normal component of velocity ranged from about 0.8 to 3.8 times the speed of sound in the undisturbed gas.‡

The experiments were conducted in a thermionic rail accelerator, in which the electric arc is established between parallel rail electrodes in a stationary gas and accelerated to equilibrium speed by a uniform impressed magnetic field normal to the electrode plane. The cathode rail was preheated to enhance thermionic emission and minimize the destabilizing influence of arc root phenomena.[1] Sulfur hexafluoride was used for the present experiments primarily because its low speed of sound permits observation of arcs at high Mach numbers by means of conventional high-speed photographic procedures.

Side-view photographic observations showed that the magnitude of the angle of slant increased with cathode rail temperature. For the highest rail temperature employed (2200°C), the arc column approached the Mach slant and was most stable and straight. Stable convective columns of considerable length were observed, the length-to-width ratio ranging up to about 50.

Head-on observations showed 1) that in the stable mode, the convective arc column in $SF_6$ remains remarkably straight and in the plane of the electrodes, 2) that the luminosity width of the stable arc column (measured normal to the electrode plane) is greater than the arc thickness,§ 3) that the column width does not vary appreciably along the length of the stable supersonic column as it does for the low-subsonic column in nitrogen[4] and 4) that in the unstable mode, the arc column fluctuates out of the electrode plane.

Highly unstable arcs were obtained when both electrodes were unheated. Column stability was greatest with a heated

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‡ A further paper[6] is now in publication which reports a fine sawtooth structure for the arc column in $SF_6$, and indicates that the column mechanism tending to produce a crossflow Mach number of unity is locally effective in $SF_6$.

§ Reference 7 reported a similar cross-sectional shape for arcs in air at crossflow Mach numbers around 0.05, as did Ref. 3 for crossflow Mach numbers around 1.0. See also Ref. 8.

cathode rail. A relatively stable, slanted arc column was also observed with a heated anode rail and cold cathode rail. The direction of slant was always such that the arc root at the heated rail led the other root, indicating that the direction of column slanting in the thermionic rail accelerator is related to the effects of the higher temperature and lower density of the gas near the heated rail. The arc Mach number ranged from 1.3 to 6.5, the ambient pressure from 4 to 140 torr, and the magnetic induction from 900 to 4900 gauss.

## Experimental Setup

The thermionic rail accelerator is described in Ref. 3. It consists of a rail accelerator with one rail preheated to preclude the destabilizing influence of arc root phenomena. An electric arc between parallel rail electrodes is moved down the rails by the Lorentz force associated with a uniform impressed magnetic field.

The electrodes are mounted in a vertical plane, with the heated rail above the unheated rail. The impressed magnetic field is essentially normal to the electrode plane. Each rail electrode is a solid cylinder about 85 cm in length and about 1.3 cm in diameter. The heated rail is made of carbon, the unheated rail of oxygen-free, high-conductivity (OFHC) copper. For some (unstable) arcs, OFHC copper was used for both electrodes.

Arc behavior was observed by means of a high-speed camera, a recording oscillograph, and an oscilloscope. Rail temperatures were measured with a radiation pyrometer.

The estimated experimental errors are as follows: ambient pressure $p$, $\pm$ 5%; heated-rail temperature $T_R$, $\pm$ 60°C; magnetic induction $B$, $\pm$ 5%; arc current $I$, $\pm$ 5%; arc Mach number $M$, $\pm$ 6%; arc slant angle $\theta$, $\pm$ 2°, apparent arc luminosity thickness $t$, $\pm$ 20%; arc drag coefficient (calculated) $C_D$, $\pm$ 50%.

## Arc Behavior

Using a heated rail, arcs of varying degrees of stability were produced. The stable arc column (Fig. 1) maintained a constant geometric shape during its travel down the rails. The voltage fluctuated around $\pm 8\%$ as the arc traversed the accelerator.

The stable column invariably slanted across the electric field lines. In those cases where the slant angle was such that the crossflow Mach number was significantly greater than unity, the over-all column geometry was stable, but small fluctuating kinks in the column were observed.[6] Arc velocity increased when the magnetic field was increased or the ambient pressure decreased.

The arc column was generally straight, with some curvature near the heated rail. The curved portion of the column did not extend as far from the heated rail as was the case in air.[5] The photographs usually showed an enlarged luminous region near the heated rail, evidently a region for the establishment of multiple arc roots. The arc column near the unheated rail sometimes stretched along the rail (Fig. 1), or around to the side of the rail.

Stable arcs were established for three different rail temperatures, 1100°, 1700°, and 2200°C. Increasing the temperature of the heated cathode rail increased the arc Mach number $M$ and the column slant-angle $\theta$ (measured between the arc axis and the impressed electric field). Comparisons between observations made with interelectrode spacings of 3 cm and 7 cm indicated no differences between arcs of different lengths established under the same conditions of cathode temperature, magnetic field, and gas pressure.

For some runs the polarity of the electrodes was reversed, so that the heated carbon rail became the anode, and the cold copper rail the cathode. A relatively stable, slanted arc configuration was observed, with the arc root at the heated anode

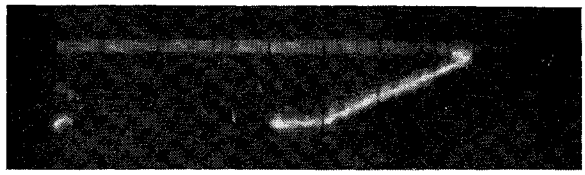

**Fig. 1 A slanted supersonic arc in $SF_6$. The electric field is vertical. The direction of arc motion is from left to right. In the photograph, the incandescent carbon cathode rail is visible, the cold copper anode rail is not. The dark vertical lines are window-markings, 5 cm apart. The experimental conditions are: Mach number, 3.2; slant angle, 67°; crossflow Mach number, 1.2; ambient pressure, 40 torr; arc current, 180 amp; magnetic induction, 4.6 kgauss; interelectrode spacing, 7 cm; cathode preheat temperature, 1700°C.**

rail leading the cathode root. The heated-anode arcs were similar in behavior to the heated cathode arcs, except that the arc column had less curvature near the heated anode and fluctuated more near the cold cathode.

For a nominal arc current of 200 amps, the apparent arc luminosity thickness $t$ (measured in the electrode plane, normal to the column), was constant at about 0.4 cm for pressures from 40 to 140 torr. Below 40 torr, $t$ increased with decreasing pressure. At pressures around 4 torr, the arc column was very diffuse, and seemed to slant partially in the cathode-root-trailing direction, even when a heated cathode was used—indicating some influence of the Hall effect. Additional observations of arc behavior are given in the Introduction.

## Aerodynamic Drag

An effective drag coefficient for the arc column is given by the Lorentz force divided by the product of the crossflow dynamic pressure and the arc frontal area. This can be written

$$C_D = IB/(\rho V_c^2 d/2) = 2IB/\gamma p M_c^2 d$$

where $I$ is the arc current, $B$ the impressed magnetic induction, $\rho$ the freestream density, $p$ the pressure, $V_c$ the crossflow velocity, $M_c$ the crossflow Mach number, $d$ the arc diameter, and $\gamma$ the ratio of specific heats.

For an arc of noncircular cross section, the significant dimension to be used in place of $d$ in the preceding equation is the effective arc width. Unfortunately, the arc width was not observed for most of the arcs reported herein. On the basis of the few observations available, it can only be assumed that arc luminosity width for the low Mach number arcs is probably around 1.5 to 2.0 times the measured luminosity thickness $t$. At the higher Mach numbers, the measurements of $t$ itself are in some doubt.¶ Figure 2 presents values of $C_D$ based on the assumption $d = t$, along with an indication of the effect of the assumption $d = 2t$. Figure 2 also shows the coefficient of drag for an unheated solid circular cylinder.[9] For an elliptical cross section with the same frontal area, the $C_D$ is approximately 20% greater.[10]

The data shown in Fig. 2 does not contradict the previous observation,[3,4,7] made in air at low-subsonic and near sonic crossflow Mach numbers, that the $C_D$ for the arc column agrees fairly closely with the $C_D$ for a solid cylinder. It should be noted, however, that such agreement between arc and cylinder does not allow the prediction of arc crossflow velocity for arbitrary conditions, since there is as yet no way to predict arc size, which in general depends on the energetics of the inter-

¶ At high crossflow Mach numbers, the interpretation of these data will be considerably affected by the assumptions made relating to the fine structure of the column.[6] Whatever assumptions are made, it appears likely that the high Mach number data represented in Fig. 2 will be affected as follows: the effective arc thickness will be reduced, the local cross flow Mach numbers will be reduced, and the effective drag coefficient will be increased.

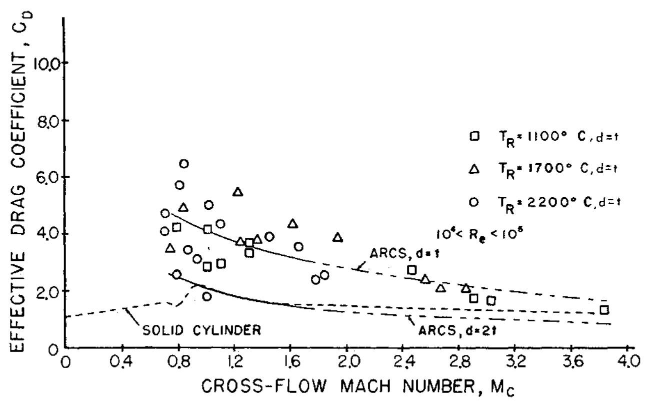


**Fig. 2 Effective drag coefficient for the slanted convective arc in $SF_6$.**

action as well as the dynamics. It should also be noted that the present $SF_6$ observations may be affected by arc root phenomena (see end of next section).

## Column Slanting

Figure 3 shows the variation with Mach number $M$ of the arc slant angle $\theta$ (measured near the cold rail), for three values of heated-rail temperature $T_R$. It can be seen that for the higher rail temperatures, where arc root constraints[11] are presumably less, the angle of slant is nearer the Mach slant, $(90° - \mu)$. Here $\mu$ is the Mach angle, defined by

$$\cos(90° - \mu) = 1/M$$

In sulfur hexafluoride, the Mach slant angle is very nearly equal to the slant angle $\theta_E$ at which a maximum occurs in the value of the ionization parameter, $E_{||}/p_s$, where $E_{||}$ is the component of electric field parallel to the arc column, and $p_s$ is the pressure at the leading boundary of the arc. It can be shown that $\theta_E$ is given by

$$\cos\theta_E = (1/M)[2/(\gamma + 1)]^{1/2}$$

For $SF_6$, with $\gamma = 1.1$, $\theta_E$ is effectively equal to $(90° - \mu)$ and is therefore not shown in Fig. 3.

Figure 3c includes measurements of slant angle for the electric arc column in air.[2,3,5] It can be seen that, for air, measurements obtained in the rail accelerator[5] are in good agreement with those obtained in the supersonic wind tunnel.[2,3] It can also be seen that, over the range of comparison, the slant angle observed for $SF_6$ in the rail accelerator (rail temperature, 2200°C) agrees well with the observations for air.

The observations, first, that the direction of slant reverses with reversal of the polarity of the heated electrode, and second, that the arc column is usually curved near the heated electrode, suggest the possibility that the magnitude of the slant angle may be dictated by the temperature distribution near the heated electrode. This possibility is ruled out, however, by the fact that stable slanted arcs are observed in the wind tunnel even in the absence of freestream temperature gradients,[1,2,3] and by the fact that the column appears not always to be curved near the heated electrode. It is surprising, therefore, that an angle of slant which is in specious agreement with the experimental values can be calculated as follows.

If we assumed an arc column of constant frontal area and constant effective drag coefficient along the column, then, since the velocity, the pressure, and the Lorentz force are also constant along the column, we would have

$$\cos^2\theta/T = \text{const along the column}$$

$\theta$ and $T$ are here the local angle of slant and freestream temperature, respectively. Hence, as the column passed through the temperature variation near the heated rail, the local slant angle $\theta$, would vary accordingly. If we further assumed the column to be parallel to the electric field at the heated rail, we would obtain

$$\cos\theta = [T_1/T_R]^{1/2}$$

where $\theta$ and $T_1$ are measured near the cold rail. This value of slant angle, indicated by the dotted lines in Fig. 3, compares very closely with the maximum values of $\theta$ measured at the three cathode rail temperatures employed.

The slanting of the subsonic column as observed in air[4,5] (Fig. 3), evidently cannot be related to any column mechanism so far proposed.[2] In particular, there is for the subsonic column no slant angle for which the crossflow Mach number is unity, or for which the ionization parameter is a maximum. Nor can subsonic column slanting be related solely to temperature gradients, since 1), column slanting has been observed in a subsonic wind tunnel where there was no freestream temperature gradient,[4] and 2), the angle predicted from the temperature gradient in the rail accelerator is considerably greater than the angle observed. Finally, the column-widening mechanism mentioned in Ref. 4, though physically plausible, also yields a calculated slant angle which is considerably

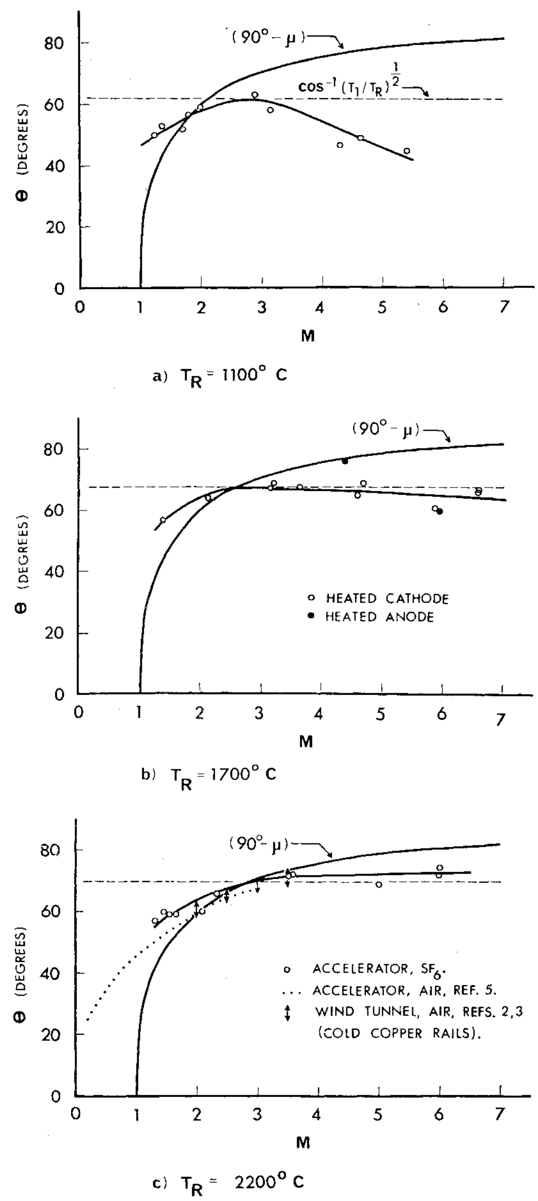


**Fig. 3 Variation of slant angle with Mach number and cathode rail temperature.**

greater than that observed in Ref. 5, since with the assumed mechanism, slanting due to the temperature gradient must be included in the calculation.

It should be noted that for the subsonic column, arc root phenomena cannot be ruled out as possible contributing factors in column slanting. In the rail accelerator, both roots of the convective arc must move over the electrode surfaces; the absence of root effects on a given column configuration is best inferred from agreement with wind-tunnel observations, provided such observations have themselves been shown to be free of root effects. For the supersonic wind tunnel, there is strong experimental evidence that the slanting of the stable column in air is independent of root phenomena (Ref. 1, p. 144; for more detail, see Ref. 12). For the subsonic wind tunnel, there seems as yet to be little such evidence.

Only when it has been demonstrated that column behavior is free of root or electric-field constraints is it sufficient to look to column processes alone for possible causes of slanting, or to consider a balance between column drag and the magnetic Lorentz force as the determinant of arc velocity. This statement applies not only to the subsonic arc column generally, but also to the supersonic column in $SF_6$.

## Conclusions

1) It is possible to produce stable supersonic electric arcs in sulfur hexafluoride. 2) The convective arc in $SF_6$ slants across the electric field at angles such that the crossflow Mach number ranges from 0.8 to 3.8. 3) In the thermionic rail accelerator, the direction of column slanting in $SF_6$ is such that the arc root near the heated electrode leads the remainder of the arc. 4) The magnitude of the angle of slant observed in $SF_6$ increases with cathode rail temperature. The angle is empirically given very nearly by $\cos^{-1}(T_1/T_R)^{1/2}$ for the cathode preheat temperatures of 1700°C and 2200°C at Mach numbers from about 2.0 to about 6.5, but falls considerably below this for the cathode temperature of 1100°C at high Mach numbers, and for all rail temperatures at Mach numbers below about 2.0. 5) For the given rail temperatures, the magnitude of the slant angle at high Mach numbers was considerably less than either the Mach slant, given by $\cos^{-1}(1/M)$, or the angle for maximum $E_{||}/p_s$, given by $\cos^{-1}\{1/M[2/(\gamma+1)]^{1/2}\}$. 6) For the arc column moving through $SF_6$ at low supersonic Mach numbers, the effective drag coefficient, when based on the dimensions of the region of high luminosity, is comparable to that of a solid cylinder.

## References


[1] Bond, C. E., "Magnetic Confinement of an Electric Arc in Transverse Supersonic Flow," *AIAA Journal*, Vol. 3, No. 1, Jan. 1965, p. 142.

[2] Bond, C. E., "Slanting of a Magnetically Stabilized Electric Arc in Supersonic Flow," *The Physics of Fluids*, Vol. 9. No. 4, April 1966, p. 705.

[3] Nicolai, L. M., and Kuethe, A. M., "Properties of Magnetically Balanced Arcs," *The Physics of Fluids*, Vol. 12, No. 10, Oct. 1969, p. 2072.

[4] Winograd, Y. Y. and Klein, J. F., "Electric Arc stabilization in Crossed Convective and Magnetic Fields," *AIAA Journal*, Vol. 7, No. 9, Sept. 1969, p. 1699.

[5] Bond, C. E. and Potillo, R. W., "Stability and Slanting of the Convective Electric Arc in a Thermionic Rail Accelerator," *AIAA Journal*, Vol. 6, No. 8, Aug. 1968, p. 1565.

[6] Bond, C. E., "The Sawtooth Column of the Supersonic Electric Arc in Sulfur Hexafluoride," Project SQUID Report ILL-20-PU, Dec. 1969, Univ. of Illinois; *AIAA Journal*, to be published.

[7] Roman, W. C. and Myers, T. W., "Experimental Investigation of an Electric Arc in Transverse Aerodynamic and Magnetic Fields," *AIAA Journal*, Vol. 5, No. 11, Nov. 1967, p. 2011.

[8] Goldstein, M. E. and Fay, J. A., "Shape of a Magnetically Balanced Arc," *AIAA Journal*, Vol. 5, No. 8, Aug. 1967, p. 1510.

[9] Gowen, F. E. and Perkins, E. W., "Drag of Circular Cylinders for a Wide Range of Reynolds Numbers and Mach Numbers," TN 2960, June 1953, NACA.

[10] Trilling, L. and Clark, J. W., "The Aerodynamic Force Coefficients of Yawed Slender Configurations at High Mach Numbers," *Journal of the Aeronautical Sciences*, Vol. 24, No. 12, Dec. 1957, p. 913.

[11] Guile, A. E., Lewis, T. J., and Secker, P. E., "The Motion Cold-Cathode Arcs in Magnetic Fields," *Proceedings of the Institution of Electrical Engineers (London)*, Vol. 108, May 1961, pp. 463–470.

[12] Bond, C. E., "The Magnetic Stabilization of an Electric Arc in Transverse Supersonic Flow," Ph.D. dissertation, 1964, Univ. of Michigan; released as Rept. ARL 65-185, Oct. 1965, Aerospace Research Labs., U. S. Air Force.