Slanting of a Magnetically Stabilized Electric Arc in Transverse Supersonic Flow

CHARLES E. BOND
The University of Michigan, Ann Arbor, Michigan, and The University of Illinois, Urbana, Illinois
(Received 6 August 1965; final manuscript received 8 November 1965)

Experimental observations are presented which indicate the existence of a convective interaction mechanism affecting the direction and stability of electric current in a flowing gas. The observations were made of an electric arc confined in transverse supersonic flow by means of a nonuniform magnetic field mutually orthogonal with the freestream velocity field and the applied electric field. The positive column exhibits remarkable stability when allowed to slant across the applied electric field, approximately parallel to the freestream Mach line. The direction of slant is the Hall direction, cathode root downstream, but the magnitude of the slant angle does not appear to vary with the Hall parameter $\omega_e\tau_e$. At the Mach numbers investigated, 2.0, 2.5, and 3.5, the inclination of the stable arc to the freestream is near the Mach angle, which is near the angle corresponding to a maximum in the discharge parameter $E_{\parallel}/P_s$, the ratio of parallel component of electric field to pressure at the upstream boundary of the arc. Under conditions where the column could not assume its characteristic slant angle, a highly unstable discharge was observed.

I. INTRODUCTION

THE interaction between convective streaming and charge diffusion in the presence of a magnetic field is fundamental to gaseous conduction of electricity under conditions which exist in many $\mathbf{j} \times \mathbf{B}$ channels. The electric arc in transverse flow provides an opportunity for the experimental study of such interaction. This paper presents experimental observations of a highly stable dc arc magnetically confined in transverse supersonic flow as described in Refs. 1–3.

Most experimental investigations of the electric arc under the influence of transverse forced convection have made use of an experimental setup known as the rail accelerator. With this experimental setup, the arc is moved along parallel rail electrodes through a quiescent gas by means of a magnetic field normal to the plane of the electrodes. Both the conducting column and the points of contact, or arc roots, must move with respect to the rails. Conditions at the surface of the cathode have a strong effect on the arc velocity,[4–18] and the arc column is characterized by wild spatial fluctuations.[13,19–21]

Rail-accelerator experiments have contributed to basic understanding of arc root processes and have provided the major source of fundamental information on the moving arc. But because the column of the moving arc fluctuates so erratically, often forming loops and spirals, it has not been possible with the rail accelerator to obtain meaningful measurements of such elementary properties of the convective arc as column voltage gradient and electrical conductivity or to make fundamental observations of the nature of the convective interaction in the absence of root influences.

An alternative approach to experimental study of the electric arc under the influence of transverse forced convection consists of holding the arc stationary in a stream of moving gas. Smith and Early[22] investigated the feasibility of uniform supersonic heating by an electric arc. Using a small Mach 4 wind tunnel, they found that the arc followed a path through the tunnel boundary layer for all the electrode and magnetic field conditions investigated. Guile and Mehta[8] reported the oscillating motion of ac arcs on rail electrodes mounted in a subsonic

[1] C. E. Bond, Ph.D. dissertation, University of Michigan (1964).
[2] C. E. Bond, AIAA J. **3**, 142 (1965).
[3] C. E. Bond and A. M. Kuethe, AGARDograph **84**, 935 (1964).
[4] P. E. Secker and A. E. Guile, Nature **181**, 1615 (1958).
[5] A. E. Guile, T. J. Lewis, and S. F. Mehta, Brit. J. Appl. Phys. **8**, 444 (1957).
[6] A. E. Guile, T. J. Lewis, and S. F. Mehta, Nature **179**, 1023 (1957).
[7] I. Gönenc, Elektrotech. Z. **A81**, 132 (1960).
[8] A. E. Guile and S. F. Mehta, Proc. Inst. Elec. Engrs. (London) **A104**, 533 (1957).
[9] P. E. Secker, A. E. Guile, and P. S. Caton, Brit. J. Appl. Phys. **13**, 282 (1962).
[10] P. E. Secker, *Ionization Phenomena in Gases* (North-Holland Publishing Company, Amsterdam, 1959), Vol. 1, p. 768.
[11] A. Eidinger and W. Rieder, Arch. Elektrotech. **43**, 94 (1957).
[12] P. E. Secker and A. E. Guile, Proc. Inst. Elec. Engrs. (London) **A106**, 311 (1959).
[13] L. P. Winsor and T. H. Lee, Proc. AIEE **75**, 143 (1956).
[14] A. E. Guile and P. E. Secker, J. Appl. Phys. **29**, 1662 (1958).
[15] T. J. Lewis and P. E. Secker, J. Appl. Phys. **32**, 54 (1961).
[16] A. E. Guile, T. J. Lewis, and P. E. Secker, Proc. Inst. Elec. Engrs. (London) **C108**, 463 (1961).
[17] T. J. Lewis and P. E. Secker, Nature **186**, 30 (1960).
[18] P. E. Secker, Brit. J. Appl. Phys. **11**, 385 (1960).
[19] M. L. Féchant, Rev. Gen. Elec. **68**, No. 9, 519 (1959).
[20] E. Kuhnert, Elecktrotech. Z. **A81**, 401 (1960).
[21] M. Angelopoulos, Elecktrotech. Z. **A79**, 572 (1958).
[22] H. L. Smith and H. C. Early, University of Michigan Engineering Research Institute Report 2154-3-F (1954).

airstream. Rother,[23] and Thiene,[24] measured and analysed the deflection of short low-current electric arcs between collinear electrodes, with a wind normal to the electrode axis. Fay,[25] and Bond,[1] have noted limitations incurred in the Thiene analysis by the assumption of a nondivergent electric field.

The present investigation employs a modified wind-tunnel approach to the study of the convective arc. The experimental setup[1–3] is based on the use of electrodes mounted in the freestream of a supersonic wind tunnel in such a way that the arc interaction passes through uniform supersonic flow. The aerodynamic effects on the arc are counterbalanced by a transverse magnetic field. Stability in streamwise arc location is provided by a monotonic downstream increase in transverse induction. To eliminate root constraints, and to allow motion of the arc to the position in the field required for column equilibrium, parallel rail electrodes are used.

The arc is dc, with currents ranging from 150–700 A. The arc length ranges from about 1–3 cm. The gas stream is unheated dry air, with Mach number ranging from 2.0–3.5 and isentropic stagnation pressure ranging from about 100–600 mm Hg.

II. EXPERIMENTAL SETUP

The experimental setup consists of two rail electrodes mounted in the region of uniform flow in a supersonic wind tunnel and oriented in a vertical plane parallel to the freestream (see Fig. 1). External coils provide a magnetic field essentially perpendicular to the plane of the electrodes. The coils are placed such that there is a monotonic increase in magnetic flux density from the upstream to the downstream end of the rails (Fig. 2).

The arc is initiated by the explosion of a wire between the conical electrode tips. Given the proper field-coil location, field-coil current, and tunnel stagnation pressure for the given Mach number, arc current, and arc length, the convective plasma resulting from the explosion of the firing wire moves downstream along the rails to an equilibrium position, where the convective arc remains until the arc current is shut off.

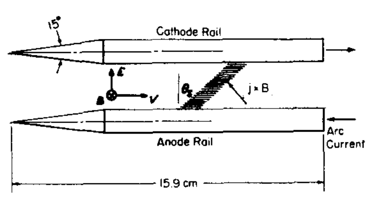

Fig. 1. Relative orientation of the velocity, magnetic, and electric fields.

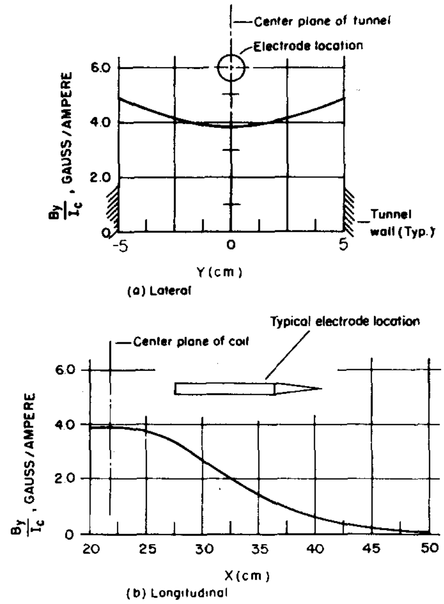

Fig. 2. Calculated spatial variation in transverse component of magnetic induction (per ampere of coil current).

Arc location, root induction, and arc slant were determined from measurements of the root location on the electrodes and from photographs of the reflection of the arc in the side wall of the tunnel. Stability of the positive column was determined from high speed motion pictures and oscillograph traces. Details of the experimental setup and procedures can be found in Refs. 1–3.

III. RESULTS

A. The Stable Arc

The balance between aerodynamic and electromagnetic effects on the arc column determines the configuration and streamwise location of the arc. The three configurations observed for the magnetically confined arc in supersonic flow are shown schematically in Fig. 3. Under those conditions where the confined arc could assume an orientation parallel to the freestream Mach line, without root interference, the column became quite stable. Separate frames of the motion pictures were superposable with only slight variations near the roots. The configuration for the stable arc, slanted with the anode root upsteam of the cathode root, is illustrated by configuration B, Fig. 3. In configura-

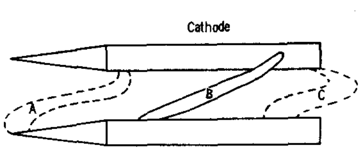

Fig. 3. Schematic drawing of observed arc column configurations.

[23] H. Rother, Ann. Physik **20**, 230 (1957).
[24] P. Thiene, Phys. Fluids **6**, 1319 (1963).
[25] J. A. Fay, Phys. Fluids **7**, 621 (1964).

tions A and C, Fig. 3, the discharge was highly unstable (see below).

High speed (Fastax) motion pictures of the stable arc show no lateral fluctuations in the column, and it appears certain that what fluctuations exist must be less than a few percent of the diameter. The observed fluctuation in voltage ($\pm 4\%$) is very small for a convective arc. The spatial fluctuation of the column is so slight that if it were not for the obvious slant, it would be difficult to determine from the motion picture alone that the column is immersed in supersonic flow. The fluctuating loops which were observed by Angelopoulos[21] and the spirals which were reported by Féchant[19] are properties of the moving arc which evidently can be avoided in the wind-tunnel experiment.[2]

Figure 4 is a single frame from the Fastax film. The anode root (bottom) is contracted for a distance of about $\frac{1}{2}$ cm above the anode surface. The cathode root (top) is also contracted and is curved around the cathode, striking the surface at around 120–150° from the generatrix nearest the anode. This phenomenon is probably caused by the circumferential component of the Lorentz force associated with the streamwise component of the magnetic induction on either side of the electrode plane.[1,2]

Figure 5 is a photograph of a stable arc reflected in a glossy black Plexiglas tunnel side-wall. It is evident in Fig. 5 that the positive column between the two root constrictions is approximately straight. The width of the column is also roughly constant over the column length. The positive column of the arc appears to have little tendency to extend in the downstream direction through its own heated wake. This observation is confirmed by the concentrated nature of the electrode markings generally left by the roots of the stable arc.[1]

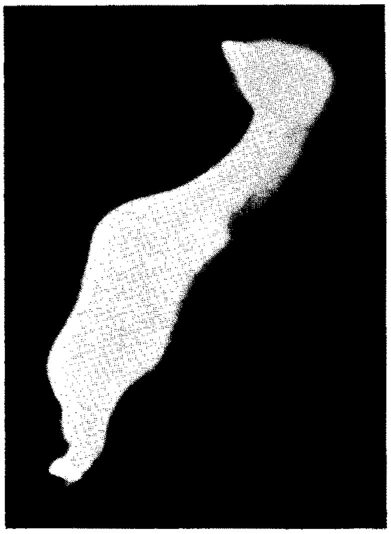

FIG. 4. Single Fastax frame of stable arc. M = 2.5, P_{t_1} = 512 mm Hg, I = 132 A, g = 2.8 cm. Camera speed about 3000 frames/sec.

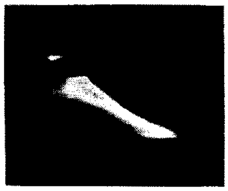

FIG. 5. Polaroid photograph of arc reflection. M = 2.5, P_{t_1} = 404 mm Hg, I = 280 A, g = 2.8 cm.

A fluctuating arc, characterized by erratic changes in arc shape and orientation, was observed whenever the magnetic field was so strong that the arc struck to the tip-cone of the anode, or so weak that it struck to the cathode base (configurations A and C, respectively, Fig. 3). The observed motions of the fluctuating arc were often directed normal to the electrode plane, and were accompanied by large fluctuations ($\pm 15\%$) in arc voltage.

B. Column Slanting

One of the most noticeable characteristics of the stable arc, apart from its stability, is the slanting of its positive column. Measurements of root location indicate a well-defined angle of arc slant repeatable within about $\pm 5°$. The Fastax photographs (see Fig. 4) confirm the fact that the column is slanted and is approximately straight. The apparent angle of slant is considerably foreshortened in these photographs. Figure 5, which shows the arc from a position almost directly to the side, demonstrates that the column is approximately straight and is slanted. The slant angle in this photograph is also foreshortened somewhat.

Figure 6 shows a plot of measured slant angle determined from the root locations versus arc current. Figure 7 shows θ_s versus freestream stagnation pressure at M = 2.5. It can be seen that there is no variation in slant angle with either current or pressure.

Measurements of the magnitude of the slant angle show that the stable arc lies nearly parallel to the freestream Mach line (see Sec. IVE).

C. Induction for Stable Confinement

The arc root locations can in most cases be posi-

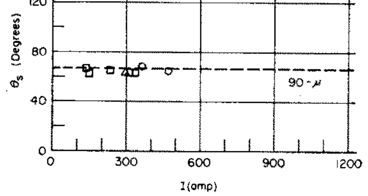

FIG. 6. Slant angle versus arc current.

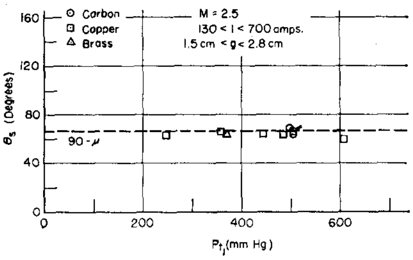

FIG. 7. Slant angle versus stagnation pressure.

tively determined from markings left on the electrodes after the run.[1] The magnetic induction at the arc roots can then be determined from measurements made of the external induction without the arc, inasmuch as the induction at the cathode surface due to the current in the electrodes is not more than 5% of the external induction. The induction required for dynamic equilibrium at the arc column is similarly indicated by column location. From Fig. 2 it can be seen that along the slanted arc there is a considerable variation in local magnetic induction.

Figure 8 shows the average magnetic induction required for the magnetically confined steady arc B_m as a function of current. It is seen that over the range of the experiments B_m is independent of current. Dashed lines of constant IB_m are shown. For the stable arc the Lorentz force per unit length increases with current throughout the given range of current.

Figure 9 shows the magnetic induction required for the stably confined arc as a function of the static pressure in the undisturbed stream p for electrode spacings of 1.5 and 2.8 cm. The lower curve gives the column induction B_m, and the upper curve gives the cathode-root induction B_c. These data tend to support the conclusion given in Refs. 1 and 2, that column effects, rather than root effects, govern the arc position.

D. Voltage–Current Characteristics

The achievement of a steady arc column makes possible meaningful measurements of the column

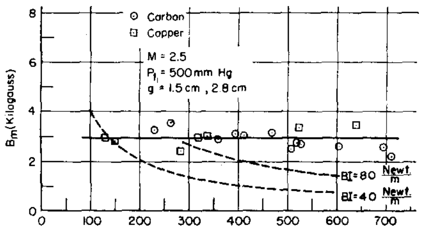

FIG. 8. Variation of mean column induction with arc current.

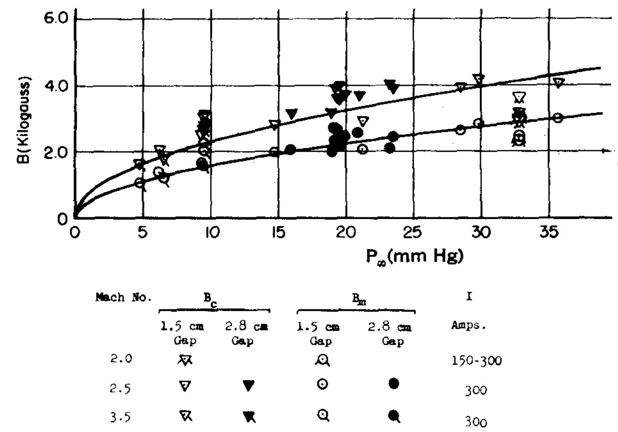

FIG. 9. Magnetic induction versus ambient pressure.

voltage gradient for the convective arc. Figure 10 gives voltage–current characteristics for the steady arc on carbon electrodes. After correction for column slant, these data indicate, for $P_{t_1} = 510$ mm Hg at Mach 2.5, a column gradient of about 14 V/cm, independent of arc current. A total fall voltage (anode and cathode) of about 30 V is indicated. The electrical conductivity of the column is difficult to determine because of uncertainties in determining the conducting cross section photographically, but estimates based on the available photographs indicate that the average conductivity is around 10 mho/cm for $P_{t_1} = 510$ mm Hg at Mach 2.5.

IV. DISCUSSION OF ARC SLANTING

A. Summary of Observations

The observations reported here, while not sufficient to determine the cause of slanting, can nevertheless form a basis for discussion of some of the possible influences. The principal experimental observations of the stable arc in a supersonic airstream are: (1) The arc is inclined to the freestream at an angle near the Mach angle; (2) the slant angle is independent of the arc current, the stagnation

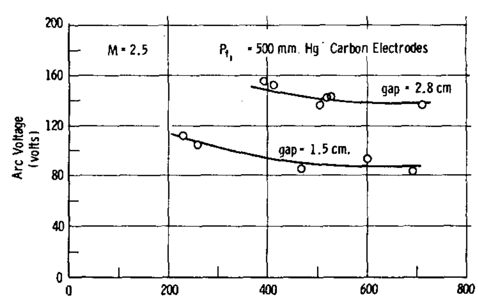

FIG. 10. Voltage–current characteristics for the stable arc.

pressure, and of the local magnetic induction; (3) the sign of the slant angle reverses with polarity reversal such that the anode root is always upstream of the cathode root, while the magnitude of the slant remains unchanged.

B. Fluid Mechanical Effects

Whether fluid mechanical effects have an important influence on the magnitude and direction of the arc slant is largely conjecture until more is known of the fluid mechanical structure of the arc. The Mach angle is the angle of lines along which small pressure disturbances must propagate. A bow shock will not form ahead of an infinite solid cylinder yawed at the Mach angle. These facts, however, do not constitute an explanation for the slanting, and in particular, they do not help to explain why the cathode root is always downstream of the anode root.

The fact that the arc slant is near the Mach angle is not a conclusive indication of fluid-mechanical causes, since an angle of slant near the observed angle is also derivable from maximization of the ionization parameter at the leading boundary of the arc plasma (see Sec. E).

Any presumed influence of nonuniformities in the airstream, which might conceivably initiate a slant of the arc near the Mach angle, is ruled out by the observations that the direction of slant reverses with arc polarity and that the column location changes with field-coil location.

C. Hall Effect

At first glance the Hall effect appears to be the most likely cause of arc slanting. However, as is pointed out below, some of the observations do not appear to be reconcilable with this explanation.

The macroscopic behavior resulting from the Hall effect is profoundly influenced by the plasma configuration. For an infinite uniform plasma, the tangent to the angle between the current and electric field is given by the Hall parameter $\omega_e\tau_e$. An analogous relationship must exist between $\omega_e\tau_e$ and any presumed Hall slanting for the present case, since macroscopic Hall behavior must ultimately derive from microscopic particle trajectories, which in turn are strongly influenced by $\omega_e\tau_e$.

There is, however, evidence that the slant angle does *not* vary with $\omega_e\tau_e$. For example, the sideview photograph of Fig. 8 indicates that the column is straight in the central region, away from the immediate neighborhood of the roots. Yet this straight portion of the column spans a region in which B_y, and presumably $\omega_e\tau_e$, changes by a factor of about 2 (see Fig. 2).

Another indication that the slant angle θ_s does not vary with $\omega_e\tau_e$ is that θ_s does not vary with arc current. The gas temperature of a nonconvective arc varies with arc current,[26] and this temperature variation results in changes in collision frequency. If the temperature variation of a convective arc is comparable with that of a stationary arc, one would expect a variation in slant angle with arc current. However, the experimental data of Fig. 6 show the slant angle to be independent of arc current.

The fact that θ_s does not vary with P_{t_1} (see Fig. 7) is not as significant as might first appear. Even though τ_e should be roughly proportional to the inverse plasma density, which might in turn be expected to vary roughly as the freestream pressure, the decrease in τ_e with pressure could be cancelled by the increase in B (and thus in ω_e) required to confine the arc at the higher pressure (see Fig. 8).

Finally, it should be mentioned that the observed reversal of slant direction with electrode polarity would be expected if the slanting were governed by the Hall effect. While the Hall angle is independent of the direction of the electric field, it is dependent on the sense of **B**, which, to confine the arc, must be reversed along with the polarity; thus the Hall angle will change sign with reversal of electrode polarity.

D. Differential Root Forces

Minorsky,[27] in an early investigation of retrograde cathode-spot motion at very low pressures in mercury, observed a slanted arc column with the cathode root preceding the anode root. The retrograde tendency does *not* provide a satisfactory explanation for slanting in the present case, since the observed slant angle is unaffected by factors on which retrograde motion is strongly dependent, namely, pressure, current, and flow and material conditions at the cathode surface.

E. Leading Edge Ionization

The ratio E/P is a well-known similarity parameter for electric discharges. Its importance derives from the fact that it is roughly proportional to the average energy acquired by an electron between collisions,[28]

$$E/P \sim \lambda E \sim eV,$$

[26] L. A. King, *Colloquium Spectroscopicum International* (Pergamon Press, Inc., London, 1956), Vol. 6, p. 152.
[27] M. N. Minorsky, J. Phys. Radium 9, 127 (1928).
[28] L. B. Loeb, *Basic Processes of Gaseous Electronics* (University of California Press, Berkeley, California, 1960).

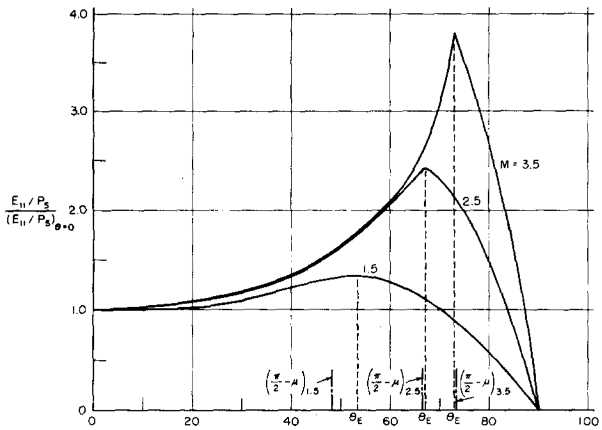

FIG. 11. Ionization parameter for arc with slant θ.

where λ is the mean free path of the electron, e is the electron charge, and V is voltage.

Two concomitants to arc slanting are the decrease in the pressure at the leading boundary of the arc P_s and the decrease in the component of the electric field parallel to the column $E_{\parallel}$. Since $E_{\parallel}$ and P_s both decrease with increasing slant angle θ_s, it becomes of interest to calculate how $E_{\parallel}/P_s$ varies with θ_s. Figure 11 shows the results of such a calculation. P_s was evaluated as that pressure which would exist at the stagnation point of an infinite solid cylinder inclined at an angle $\frac{1}{2}\pi - \theta$ to the flow. It is seen from Fig. 11 that for a given Mach number there is an angle θ_E for which $E_{\parallel}/P_s$ is a maximum.

A remarkable feature, indicated in Fig. 12, is the close agreement between θ_E and the angle $(\frac{1}{2}\pi - \mu)$ where μ is the Mach angle. The experimentally observed column slant angles for Mach 2.0, 2.5, and 3.5 are also shown in Fig. 12 with their approximate ranges of uncertainty. An hypothesis, based on Fig. 12, that the parameter $E_{\parallel}/P_s$ might be the dominant influence in determining the slant of the arc, would account approximately for the magnitude but not for the direction of the slant.

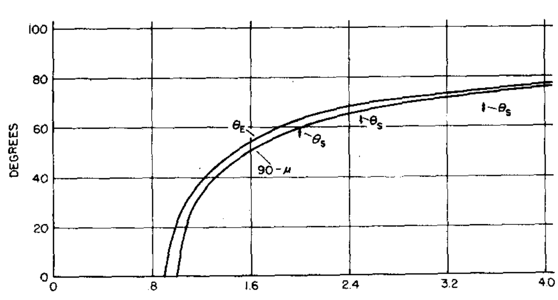

FIG. 12. Variation of Mach angle, angle of maximum $E_{\parallel}/P_s$, and arc slant angle with Mach number.

The direction of slant is, however, consistent with the hypothesis that the tangential velocity component of the incoming neutrals must be in the same direction as the electric drift of ions, with which they are coupled by collisions.

V. CONCLUSIONS

The following conclusions may be drawn.

(1) The positive column of a dc electric arc magnetically confined in transverse supersonic flow exhibits remarkable stability when allowed to slant across the electric field, parallel to the freestream Mach line.

(2) The discharge becomes highly unstable when the plasma column cannot assume its characteristic slant angle. This occurs whenever the field-coil location and current are such that for a given pressure and Mach number the arc must attach to the base or the tip of an electrode.

(3) The slant of the stable arc is in the Hall direction, but the slant angle appears to be independent of the Hall parameter $\omega_e\tau_e$ within the range of the experiments. Thus the Hall effect does not appear to account for the magnitude of the slant.

(4) The column slant angle, as determined from root location and from photographs, is near that of a Mach line in Mach 2.0, 2.5, and 3.5 flow. This angle of slant is nearly equal to the angle corresponding to a maximum in $E_{\parallel}/P_s$, the ratio of parallel component of electric field to pressure at the upstream boundary of the arc. The observed direction of the slant, with the anode root upstream, is such that the positive-ion drift always has a component in the direction of flow of the incoming neutrals.

(5) The slant angle is not affected by changes in arc current, freestream pressure, or local magnetic induction.

ACKNOWLEDGMENTS

The author wishes to express his gratitude for the suggestions and encouragement of Professor Arnold M. Kuethe, who also contributed for this paper some recent data on slant angle and stabilizing induction. The author is grateful for helpful suggestions by J. L. Amick, H. C. Early, A. F. Messiter, Jr., W. C. Roman, P. H. Rose, E. Soehngen, and R. A. Wolfe, and for the assistance of R. L. Harvey and particularly J. A. Bennett in experimental observation and data reduction.

The investigation reported here was sponsored by the Aerospace Research Laboratories, Office of Aerospace Research, United States Air Force, Contract No. AF 33(657)-8819.