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TECHNICAL NOTE

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DIRECT VELOCITY MEASUREMENTS IN LOW-DENSITY PLASMA FLOWS

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SUMMARY

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The flow velocity is measured directly in a direct-current arc jet by creating a luminous disturbance in the flow and measuring its time of flight over a known distance with photoelectric detectors. This technique is applicable to flows with high stagnation temperatures and low discharge pressures. Measurements made in supersonic flows without arc heating correlated well with velocities computed from pressure probe measurements. Measurements made in supersonic plasma flows exhibited good repeatability at static pressures well below 1 mm Hg.

INTRODUCTION

The present investigation was undertaken to develop a reliable method for making direct velocity measurements in a low-pressure, high-temperature plasma flow. Because of the low pressures and high temperatures, use of conventional devices for measuring the velocity, such as pressure probes or schlieren optical systems, was not feasible. The pressure probes would burn up when subjected to the extremely high temperatures, and the schlieren system would not perform at the low static pressures.

Some method which can perform this task under these environmental conditions and yet be simple, reasonably accurate, and practically unlimited in time of operation is therefore required. The method described in this investigation fulfills these requirements.

One of the most important parameters for the evaluation of the performance of arc jets is the exhaust velocity. The velocity is directly related to the specific impulse and to the thrust (when the mass flow is known).

The technique used in this experiment is similar, in various respects, to the methods described in references 1 to 5. The schlieren method was employed in references 1 and 2, but it is not applicable at low static pressures. The method described in reference 3 employs photomultipliers to observe the time of flight for inherent luminous pulsations of the stream, introduced by random arc fluctuations, to travel a known distance in the flow direction. This method depends upon the existence of fluctuations of appreciable amplitude in the flow.

This latter method has also been employed in experiments described in reference 4 wherein the technique yielded values for stream velocities that varied from 5,000 to over 30,000 ft/sec. A wide variation in the velocity measurements obtained by a similar technique is also reported in reference 5. It is not known whether the broad distribution of measured velocities is an inherent characteristic of the measurement technique or whether it actually represents variations in velocities resulting from the arc fluctuations. Indeed, the presence of large arc fluctuations could result in large temperature-time variations in the throat thereby causing even larger variations of the exhaust velocity, especially when the flow is expanded supersonically.

The technique described in this investigation is to discharge a small capacitor in the throat of a supersonic nozzle thereby producing a variation in the stream luminosity that is carried in the direction of flow at the stream velocity. Two photomultipliers detect this variation and yield the velocity directly through a time-of-flight calculation. This method was developed primarily to measure directly the velocity in a direct-current (d-c) arc jet, and its applicability to other types of systems, such as alternating-current (a-c) arc jets, is not known.

SYMBOLS

a^* speed of sound in nozzle throat, m/sec

$\dot{m}$ mass flow, g/sec

p pressure, mm Hg

V velocity, m/sec

APPARATUS AND PROCEDURE

A schematic illustration of the d-c arc jet and expansion chamber is presented in figure 1. The arc is struck between the cathode and the nozzle throat. The arc circuit is electrically insulated from the remainder of the system.

Two different nozzle configurations were used in this investigation. An axially symmetric contoured nozzle, designed to operate in air at a Mach number of 4 with a static pressure of 40μ Hg, was used with argon, nitrogen, and helium. This nozzle had a 1/4-inch-diameter throat with an expansion length of 3.0 inches. The other nozzle was a short conical nozzle with a 1/8-inch-diameter throat and with an expansion length of 1.25 inches and was used with helium. In both nozzles the throat served as the arc anode with the inlet surface area electrically insulated with an alumina coating. The nozzles were water cooled and electrically insulated from the remainder of the equipment.

The cathode is an uncooled, 1/8-inch-diameter, thoriated tungsten rod with a pointed tip. It is mounted on the center line of the nozzle and electrically insulated with a sleeve of boron nitride. Thus, the arc is confined between the cathode tip and the nozzle throat.

The gas inlet tube in the settling chamber is mounted concentrically about the cathode and consists of a single-turn loop of 1/4-inch-diameter copper tubing with small orifices along the outside. This arrangement insures circumferential uniformity of the gas in the settling chamber.

The expansion chamber is equipped with a 6-inch-diameter quartz window for observing and photographing the flow. Also installed in the chamber are 1-inch-diameter lucite rods (light pipes) inserted through "O" rings. Each lucite rod

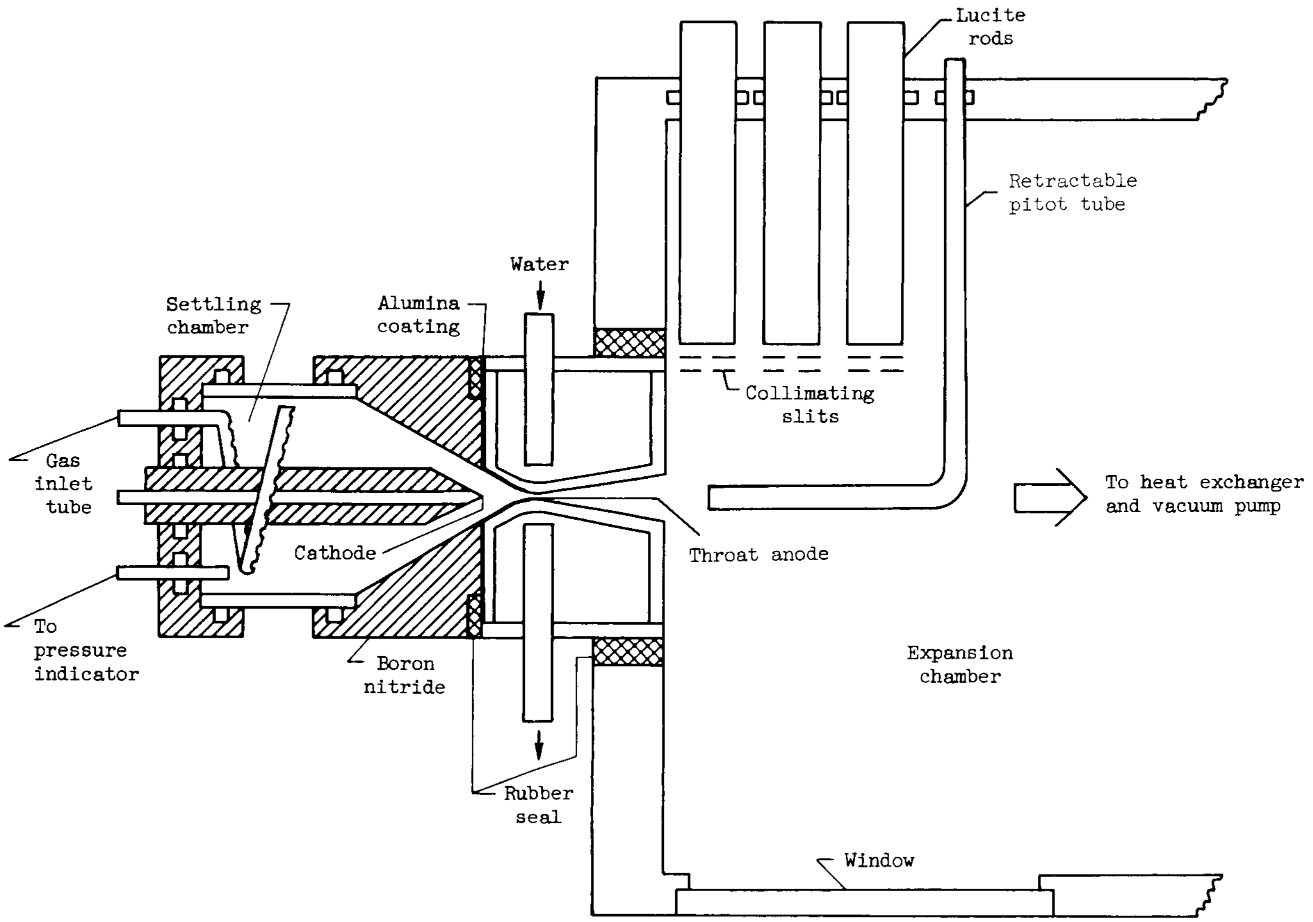


Figure 1.- Direct-current arc jet and expansion chamber.

is terminated with collimating slits 1/32 inch wide for observing 0.5 centimeter along the center line of the flow. The plasma is expanded in the chamber and exhausted into the heat exchanger and vacuum system. The vacuum pump is a mechanical booster having a capacity of 3,000 to 3,500 cu ft/min over the operating range, which provides the high-capacity pumping speed necessary to maintain a supersonic flow.

A schematic illustration of the electrical apparatus is shown in figure 2. The d-c arc power supply is a 100-kilowatt machine with a constant-current output and a rapid response to any preset current level. It employs high-current silicon rectifiers with saturable reactor controls and provides a well-filtered output over a range up to 100 amperes at an open-circuit voltage of 1,000 volts. External filter chokes and a ballast resistor are provided to protect the power supply from high-voltage transients and to stabilize the arc.

The d-c spark supply provides a variable voltage up to 6,000 volts for charging a small capacitor. The switch is a double-pole, double-throw, high-voltage switch operated by a-c solenoids. It is used to charge and discharge the capacitor and to isolate the spark power supply circuit from the d-c arc power supply. Synchronization of the dual-beam-oscilloscope sweep with the capacitor discharge is provided by a small pickup coil mounted adjacent to the

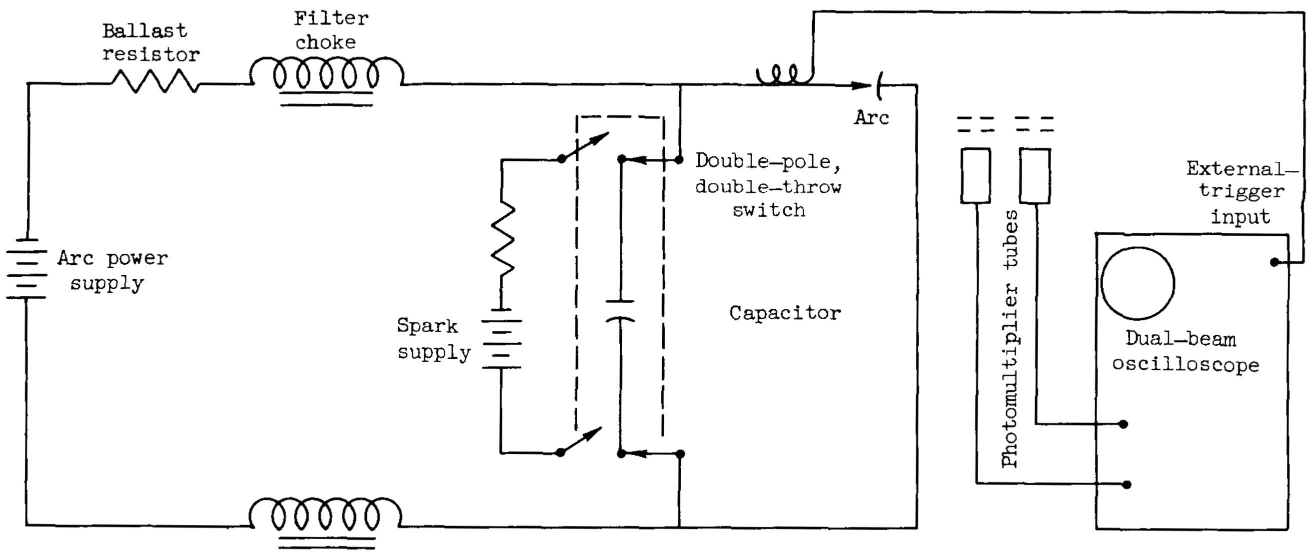


Figure 2.- Electrical circuit.

cathode. The coil consists of several turns of insulated wire and is connected to the external-trigger input of a dual-beam oscilloscope. The rise time of the oscilloscope was adequate for recording the photomultiplier outputs. Type 931A photomultiplier tubes are used as detectors and are connected to the oscilloscope preamplifier inputs.

Total pressure was measured in the settling chamber with an aneroid-type gage. This aneroid gage indicates the settling-chamber pressure within an error of 2 percent. Pitot pressure was measured in the supersonic flow with a thermocouple-type gage. This thermocouple gage is estimated to indicate the pitot pressure within 5 percent when used in air. The gage was recalibrated for each gas.

The method used to measure the velocity of the cold flow is as follows: A small capacitor (0.03 microfarad) is charged to a high d-c potential (usually 2,500 volts) by means of the switch. The switch is then thrown to disconnect the spark power supply and to discharge the capacitor between the cathode and the throat anode. The capacitor discharges in the form of a spark with a rise time less than 1 μsec, creating a luminous disturbance which persists for some time in the flow. This luminous disturbance is carried along in the flow at the stream velocity and is observed at various downstream stations by means of the photomultipliers and collimating slits. The dual-beam-oscilloscope sweep is triggered by the voltage induced in the pickup coil at the instant the capacitor discharges. Since the photomultiplier located nearer the nozzle exit observes the change in luminosity before the second, the respective traces of the photomultiplier outputs indicate a time displacement on the oscilloscope screen. This time lapse together with the physical displacement between the collimated slits is used to compute the velocity directly.

The operation of the arc jet is as follows: The gas is metered into the settling chamber through the inlet tube. The arc is established at some preset current level and confines itself to the region of the throat anode. As the gas passes through the throat it is heated to an extremely high temperature by the arc. The plasma is then expanded supersonically into the expansion chamber.

The method used to measure the velocity of the plasma is the same as that for cold flow. The arc column provides a low impedance path for the capacitor discharge current. The capacitor discharges into the arc column in the throat and produces a change in the ionization level of the arc, which results in a change in luminosity that persists for some time in the flow.

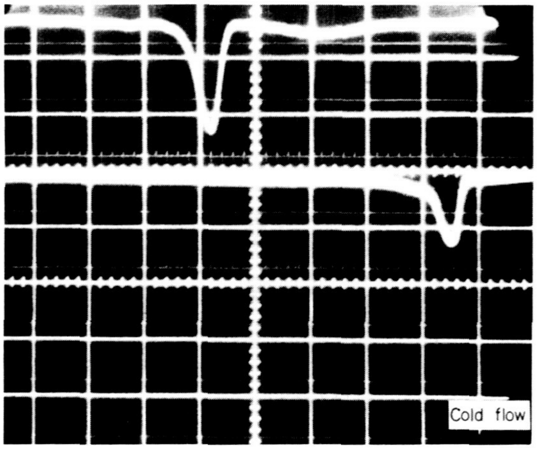
A Polaroid camera is used to photograph the oscilloscope traces. Some typical photographs are shown in figure 3. The photographs for cold flow were made without an arc in the throat. Those for hot flow were made with an arc. The negative pulses represent the change in light intensity level created by the spark. The time of flight of the disturbance is measured as the distance between these negative peaks. The error involved in measuring this distance between peaks depends on several factors such as the detector separation, the pulse shape, the oscilloscope sweep rate, and the stream velocity.

Velocity measurements were computed from total and pitot pressure measurements of the flow for comparison with photomultiplier measurements in cold flow. The total pressure is taken to be the pressure in the settling chamber. The ratio of pitot pressure to total pressure was used to find the value of V/α^* from compressible flow tables. The value of α^* was known since the stagnation temperature could be determined accurately in the absence of an arc. The velocity was then computed and compared with that obtained with photomultipliers.

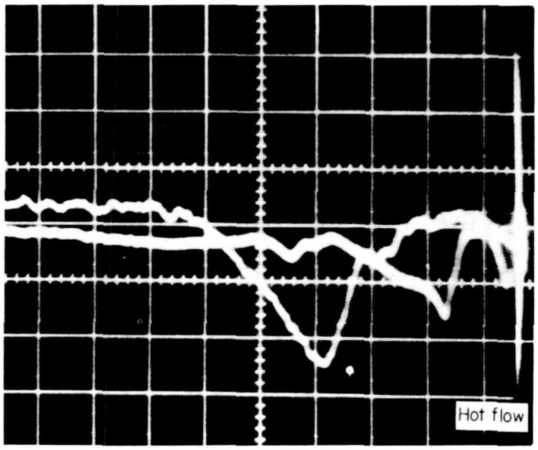
RESULTS AND DISCUSSION

Results of Cold-Flow Measurements

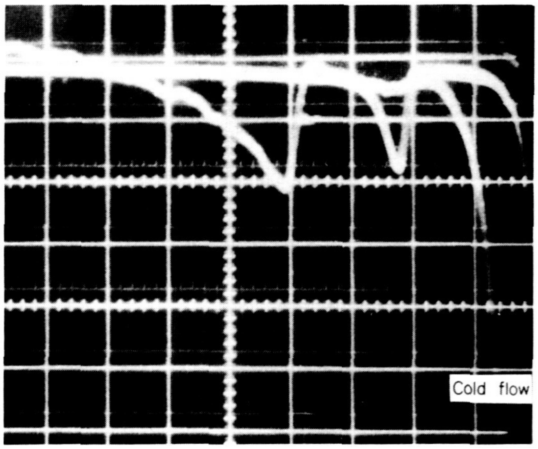
Figure 4 presents the velocity obtained from pressure measurements and from photomultipliers plotted against settling-chamber pressure for argon and for nitrogen.



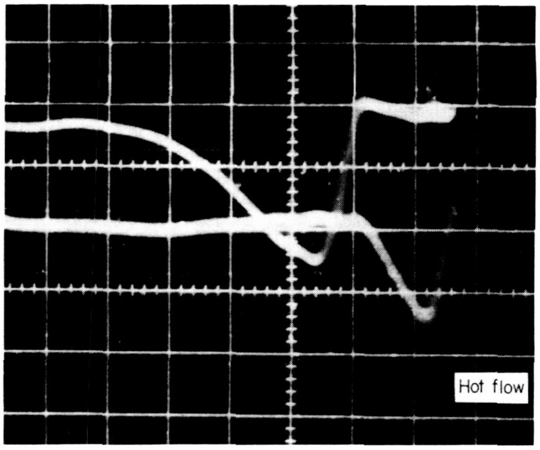
(a) Gas, argon; 1/4-inch-diameter nozzle; photomultiplier spacing, 12 centimeters; oscilloscope sweep rate, 50 μsec/cm; settling-chamber pressure, 125 mm Hg.



(b) Gas, argon; 1/4-inch-diameter nozzle; photomultiplier spacing, 12 centimeters; oscilloscope sweep rate, 20 μsec/cm; $\dot{m}$ = 0.735 g/sec; arc current, 85 amperes.



(c) Gas, helium; 1/4-inch-diameter nozzle; photomultiplier spacing, 6 centimeters; oscilloscope sweep rate, 20 μsec/cm; settling-chamber pressure, 30 mm Hg.



(d) Gas, helium; 1/8-inch-diameter nozzle; photomultiplier spacing, 6.5 centimeters; oscilloscope sweep rate, 5 μsec/cm; $\dot{m}$ = 0.143 g/sec; arc current, 50 amperes.

Figure 3.- Typical oscilloscope traces of the outputs of two photomultipliers displaced longitudinally along the direction of flow. The oscilloscope sweep is from right to left.

With argon, the total pressure was varied from 20 to 125 mm Hg and the Mach number varied from 4.45 to 5.50. The static pressure varied from 60 to 580μ Hg. The velocities measured directly with the photomultipliers varied from 558 to 572 m/sec. The velocities computed from the pressure measurements varied from 522 to 534 m/sec. The difference between the velocities obtained by the two methods ranged from 4.5 to 8 percent.

With nitrogen, the total pressure was varied from 20 to 140 mm Hg while the Mach number varied from 4.16 to 4.85. The static pressure varied from 86 to 575µ Hg. The velocities measured with the photomultipliers varied from 700 to 750 m/sec. The velocities computed from pressure measurements varied from 697 to 718 m/sec. The difference between the velocities obtained by the two methods varied from 0.14 to 6.25 percent.

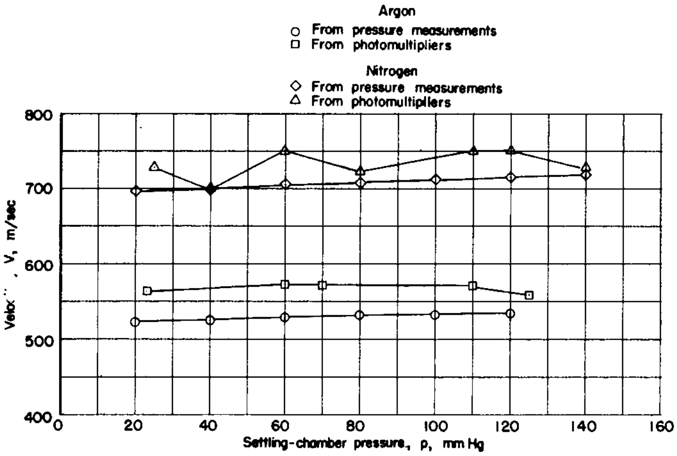


Figure 4.- Comparison of gas velocity obtained from pressure measurements and from photomultipliers in cold argon and nitrogen. 1/4-inch-diameter nozzle.

It was not possible to obtain a sufficient pressure ratio across the 1/4-inch-diameter nozzle to produce a supersonic flow in hydrogen. However, a spot check was made by using helium at a total pressure of 30 mm Hg. The velocity measured with the photomultipliers was 1,667 m/sec, and the value inferred from pressure measurements was 1,644 m/sec. The difference in the velocities was 1.4 percent.

In consideration of the inaccuracies of measurements, the velocities obtained with photomultipliers are reasonably consistent with those calculated from pressure measurements.

Factors Influencing the Accuracy of Photomultiplier Measurements

Obviously, the accurate measurement of velocity by the photomultiplier method depends on the ability to identify, by its luminosity, a small region of the flowing gas. This identification is made possible by the fact that the luminosity, which is actually spread out over some region, reaches a peak at some point in that region.

Actually the spark disturbance appears to be initially localized but spreads out by diffusion and by expansion in the nozzle, with the leading edge traveling somewhat faster than the stream velocity and the trailing edge slightly slower. However, the center of the disturbance, as indicated by the luminous peaks, should travel at approximately the stream velocity.

In order to investigate whether the discharge of the measurement spark interfered with the flow sufficiently to alter the measured velocity, the spark energy was increased by a factor of 25. No effect of the variation of the spark energy on the velocity was detected.

It at first appeared that, if the spark technique were to be used in a hot plasma flow, the spark energy might have to be increased to such an extent that the measured velocity might possibly be altered from that of the stream. However, it was found that, even with an intense arc in the throat, no additional spark energy was required to measure the velocity. It was merely necessary to increase the oscilloscope preamplifier gains to distinguish the peaks of the photomultiplier outputs.

With the arc in the throat, there is an appreciable radial temperature gradient, which may actually be of the order of several thousand degrees per centimeter, with a consequent radial variation in the exit velocity. If the measurement spark discharges through the path of least resistance, as might be expected, the discharge would occur in the hottest part of the arc column. Thus, the disturbance detected by the photomultipliers would be carried by the fastest part of the stream, and consequently the velocities measured would be the maximum over the cross section.

Results of Hot-Flow Measurements

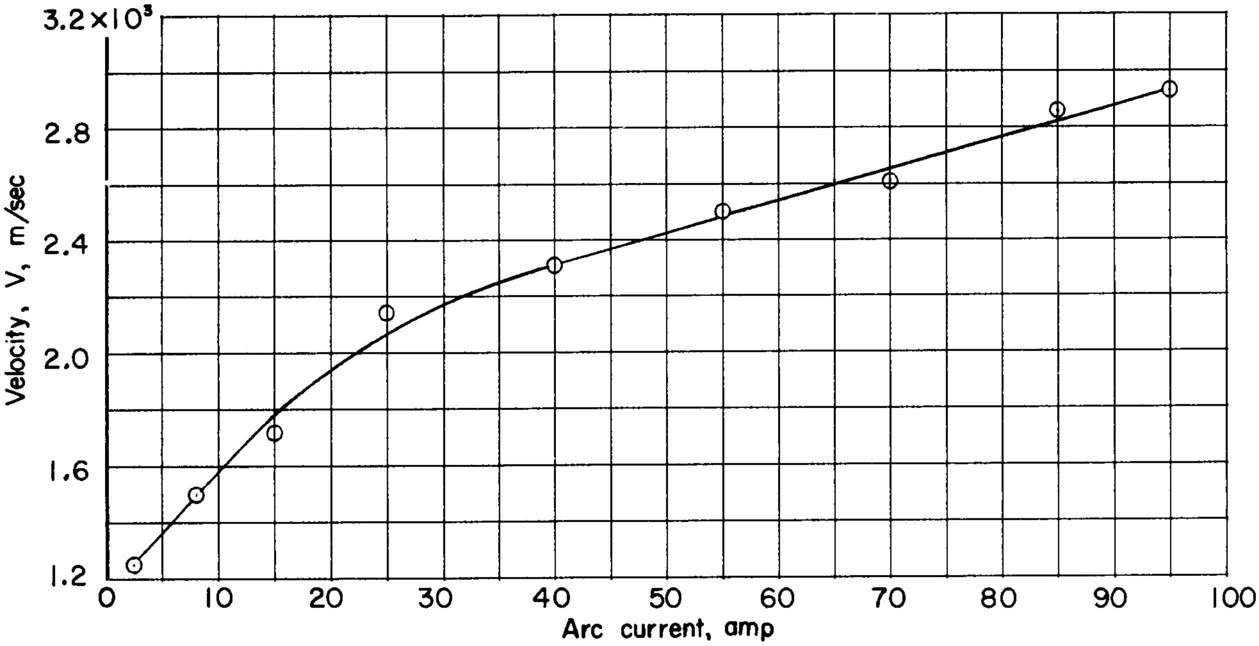
Measurements were made in low-density (in all cases static pressures were less than 1 mm Hg) hot plasma flow with nitrogen, helium, and argon using the contoured nozzle with the 1/4-inch-diameter throat, and with helium using the conical nozzle with the 1/8-inch-diameter throat. Plots of the measured velocity as a function of arc current are presented in figure 5. The velocity is higher in helium with the smaller throat, than with the 1/4-inch-diameter throat, because the throat temperature is higher as a result of the greater arc-current density. The measurements exhibited good repeatability.

The measurements of figure 5 were made with a very stable, low-noise-level arc. It was possible to stabilize the arc at very low current levels by using a small-diameter cathode. Arc instabilities were sometimes initiated by firing the measurement spark with the arc at very low currents.

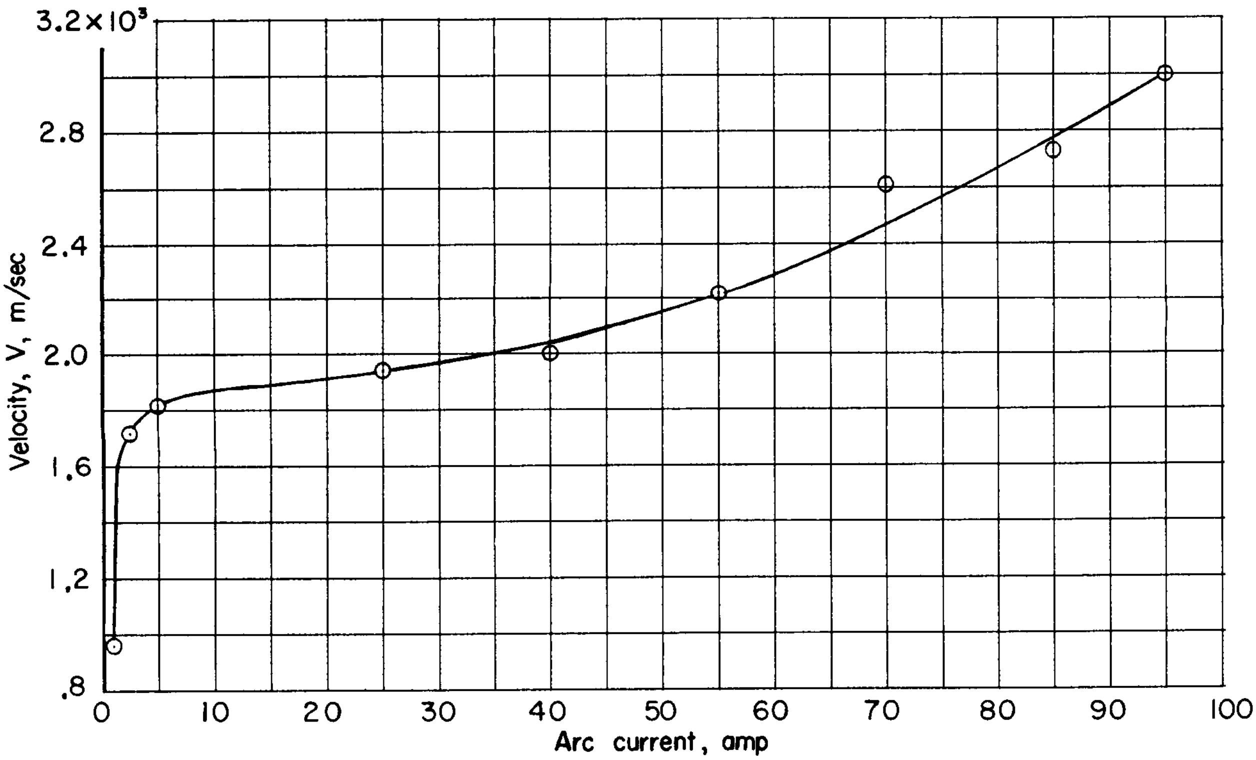
Some adverse effects were noted at low arc currents where large-scale fluctuations existed in the arc. The velocity measurements did not repeat well and the arc fluctuations were accompanied by a variation in the settling-chamber pressure. The fluctuations sometimes coupled into the oscilloscope trigger circuit and thus produced erratic sweeps and upset the measurements.

General Discussion

A number of attempts were made to measure the velocity of the supersonic plasma flows by injecting the measuring spark at various locations in the flow. No light intensity variations could be detected in the supersonic plasma when the spark was discharged well upstream in the settling chamber. When the spark was discharged between point electrodes located at the nozzle exit where the static pressure was well below 1 mm Hg, the spark discharge column was not constricted but was so diffuse that the collimated detectors observed directly part of the discharge column unless they were located at a great distance from the nozzle exit. This situation is undesirable since it is advantageous to measure the velocity as near the nozzle exit as possible. The injection of the spark into the nozzle throat was thus found to be the optimum arrangement.

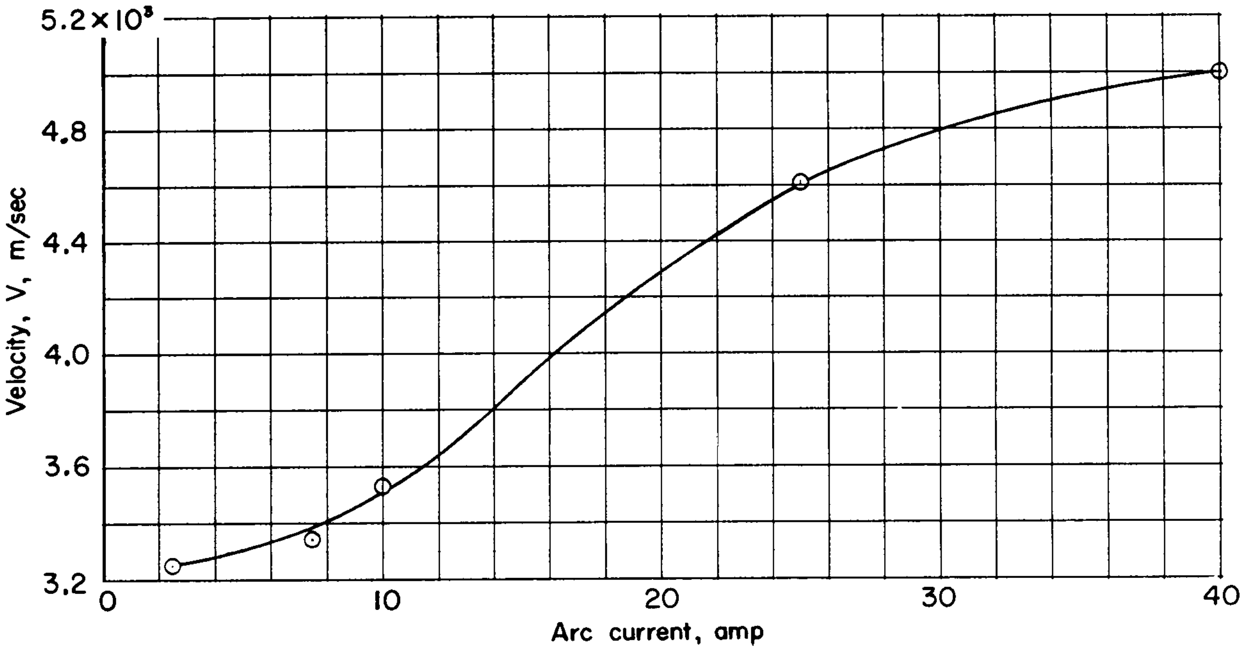


(a) Variation of velocity with arc current in argon. $\dot{m}$ = 0.735 g/sec; 1/4-inch-diameter throat.

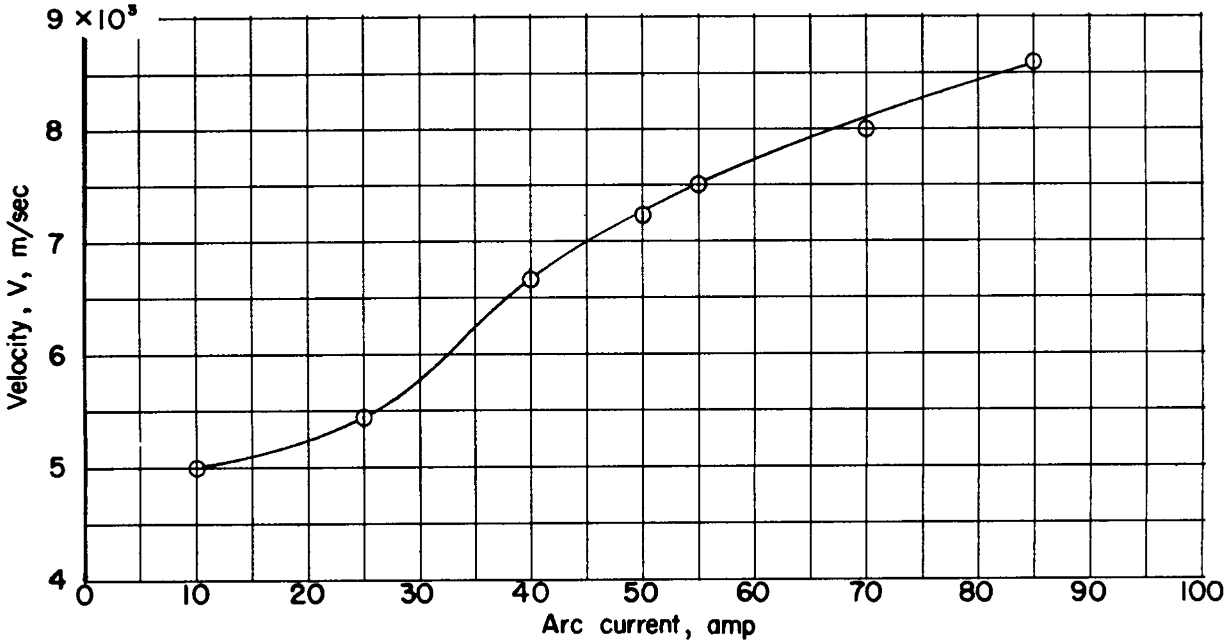


(b) Variation of velocity with arc current in nitrogen. $\dot{m}$ = 0.673 g/sec; 1/4-inch-diameter throat.

Figure 5.- Representative results of velocity measurements in plasma flows.



(c) Variation of velocity with arc current in helium. $\dot{m}$ = 0.191 g/sec; 1/4-inch-diameter throat.



(d) Variation of velocity with arc current in helium. $\dot{m}$ = 0.143 g/sec; 1/8-inch-diameter throat.

Figure 5.- Concluded.

The configurations used in many plasma systems, such as chemical jets or arc jets with the arc heater in the settling chamber, differ from that used in the present investigation. However, it is believed that this technique could be applied successfully in such systems if provisions were made to discharge the measuring spark in the nozzle throat.

CONCLUSIONS

Direct velocity measurements have been made in various gases in cold supersonic flows and in high-velocity plasma flows.

1. Measurements made in supersonic cold gas flows correlated well with velocities computed from pressure probe measurements.

2. The measured velocities in plasma flows exhibited good repeatability.

3. This technique has demonstrated the ability to measure directly the velocity of supersonic plasma flows at static pressures well below 1 mm Hg.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., February 6, 1963.

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