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TECHNICAL NOTE

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AN EXPERIMENTAL STUDY OF THE IONIZATION OF LOW-DENSITY GAS FLOWS BY INDUCED DISCHARGES

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AN EXPERIMENTAL STUDY OF THE IONIZATION OF LOW-DENSITY GAS FLOWS BY INDUCED DISCHARGES

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SUMMARY

Induced discharges are advantageous for ionizing low-density flows in that they introduce no electrode contamination into the flow and they provide a relatively high degree of ionization with good coupling of power into the gas. In this investigation a 40-megacycle oscillator was used to produce and maintain induced discharges in argon and mercury-vapor flows. Methods for preventing blowout of the discharge were determined, and power measurements were made with an in-line wattmeter. Some results with damped oscillations pulsed at 1,000 pulses per second are also presented.

INTRODUCTION

The ionization of gas flows has various practical applications, such as for the study of real-gas effects or for the introduction of heat into the gas. The present investigation was initiated in order to obtain information needed for experiments in magnetohydrodynamics.

A variety of techniques for producing the ionization have been suggested (ref. 1), including ionization by an electron beam, by an arc or glow discharge in the stream, by a-c corona, and by a radio frequency discharge with electrodes outside the tunnel walls. Most of these methods have already been investigated. Results of investigations of a-c corona discharges are reported in reference 2; of radio frequency electrostatic discharges, in reference 3; and of the d-c discharges, in many sources (for example, refs. 4 and 5).

None of these techniques has proved to be completely satisfactory. The a-c corona requires a wire situated longitudinally in the flow, and the current is quite small; therefore, the degree of ionization is low. The glow discharge also has the disadvantage of providing small currents in addition to sputtering electrode material into the flow as a result of the large voltage drop in the cathode fall region. Impurities are also released by arc electrodes which may erode or evaporate, particularly at reduced pressure, where the boiling point is lowered. The problem of electrode contamination is eliminated when the discharge is maintained by a high-frequency field imposed by "electrodes" outside the flow tube, but the coupling of a large amount of power into the gas by this means involves a difficult impedance matching problem (ref. 3).

High current induced discharges with good coupling of energy into the gas have previously been produced in a nonmoving gas. This investigation was concerned with the problems involved in obtaining and maintaining induced discharges in a moving gas.

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While this research program was in progress, a report was published (ref. 6) which describes a mercury-vapor flow system that utilized an induced discharge. The present report extends considerably the qualitative information needed in the design of equipment for ionizing flows by induction.

DESCRIPTION OF INDUCED DISCHARGE

In order to obtain this type of discharge, high-frequency current is produced in a coil surrounding the flow tube, which is constructed of quartz or some other dielectric material, and the alternating magnetic field associated with this current generates an electromotive force (emf) in the gas. When conditions are such that this induced emf drives a current in the gas, the current flows in a closed loop opposite in direction to the current in the primary coil. This short-circuiting of the current in the gas establishes a low resistance path with resulting large currents.

When the current in the primary coil is relatively low, a rather dull glow appears in the tube as a result of the high-frequency electrostatic field created between the ends of the coil. As the current in the coil is increased, this electrostatic discharge increases in intensity until at some critical value, which depends on several factors - including current frequency, the gas pressure, and tube dimensions - the glow switches discontinuously to an intense high-current discharge which is of electromagnetic origin. The induced discharge is more localized in the region of the coil than the electrostatic discharge.

A considerable quantity of experimental information concerning induced discharges in stationary gases is available. MacKinnon (ref. 7) demonstrated conclusively that the dull glow was electrostatic and the brilliant discharge was electromagnetic in nature. His experiments also demonstrated that considerably less average power was required to start an induced discharge with pulsed current than with continuous-wave current. More recent researches include measurements of skin effect (ref. 8) and the experiments of Cabannes with the noble gases (ref. 9). Cabannes studied the radiation from the discharge, noting both spark and arc lines, and determined that less than 2 percent of the power dissipated in the discharge was emitted as radiation at pressures in the low millimeter range and below. He measured the power lost as heat to the walls calorimetrically and then, by using the methods of induction-heating theory, computed the conductivity of the gas from the power dissipated. His results indicated an approximately linear relationship between the magnitude of the current flowing in the gas and its conductivity (i.e., the emf created in the gas is almost constant after breakdown), which is also a characteristic of arc discharges.

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There is, in fact, a rather close analogy between induced discharges and low-pressure arcs. Both are intense high-current discharges that require a low maintenance voltage after starting. The problem of inducing a discharge in a moving gas is somewhat similar to starting an arc transverse to the flow. It is apparent that the flow considerably complicates the starting problem, since breakdown will not occur as long as ionization is swept away faster than it is produced.

This study was, for several reasons, qualitative in nature. Such considerations as "blowout" of the discharge, the relative effectiveness of pulsed and continuous-wave exciting current, and choking of the flow have been studied; but discharge parameters such as optimum breakdown pressure, conductivity of the gas, and so forth were not determined for several reasons. In the first place, virtually all of the discharge parameters depend strongly on many factors - including the nature of the gas, its pressure, the geometry of the discharge tube, and the velocity - so that the task of tabulating the effect of varying each of these factors would be formidable. Furthermore, the characteristics of a discharge are so sensitive to small traces of contamination that the degree of purity required for a precise quantitative study was considerably beyond the capability of the apparatus used. Finally, the design and operation of equipment for studies of gas-dynamic phenomena should, in general, not have to rely on precise knowledge of the discharge parameters since such equipment should inherently be rugged and versatile in its application.

APPARATUS AND PROCEDURE

The flow system that was used for the investigations of induced discharges in argon is shown diagrammatically in figure 1 and a photograph of part of the apparatus is shown as figure 2. The use of a blowdown system is, of course, undesirable for low Reynolds number flows, but available pumping equipment was not adequate for producing a continuous supersonic flow. The nozzle would not operate supersonically at stagnation pressures less than about 10 mm Hg, and the operating time was only about 30 seconds. The nozzle exit diameter was about 19 mm, the same as the inside diameter of the discharge tube.

A d-c arc of 3 or 4 amperes could be struck between a cathode in the settling chamber and the nozzle, which acted as the anode. This arc rendered the flow visible. Observation of the angle of the shock on a thin plate mounted in the stream indicated a Mach number of about 1.5. The use of this d-c arc for preionization is discussed in a subsequent section.

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The apparatus used for the mercury-vapor experiments is shown diagrammatically in figure 3. A vapor pressure of about 30 mm Hg is generated by the boiler, and the pressure ratio across the nozzle is maintained by condensing the mercury on water-cooled surfaces in a manner exactly analogous to the operation of a diffusion pump. The flow system is therefore somewhat similar to that described in reference 6, except that it was modeled more closely after the original Langmuir diffusion pump. All the metal components were made of stainless steel. The use of a d-c arc or a directly heated tungsten coil in the settling chamber is required, not only to superheat the vapor to prevent condensation on expansion through the nozzle, but also to prevent the vapor from condensing on the walls of the settling chamber. By use of the arc to visualize the shock angle, the Mach number was again determined to be about 1.5. (See fig. 4.) For heating the flow, the heater coil was preferred because a weak arc does not adequately heat the walls of the chamber, and a strong arc would introduce too much electrode material into the flow.

The oscillator used for continuous-wave studies was a 40-megacycle electron-coupled oscillator with a maximum power output of about 1,500 watts. An in-line wattmeter was used to measure the power directed toward the load and the power reflected. Since the wattmeter was designed for a 50-ohm line, the output of the oscillator had to be matched to this impedance by a π-resonant network, but as the load was actually less than 50 ohms, another impedance-matching circuit was required to match the load to the line.

An attempt was made to compare the continuous-wave discharge with that obtained by pulsing the current. For this investigation, a line-type pulse generator was constructed. This pulser utilized diode charging, capacitance of 0.1 microfarad or less for energy storage, and a type 1907 hydrogen thyratron for a trigger. No pulse-forming network was used. A 4-kilowatt commercially built spark gap unit was also used as a pulse supply. Its repetition rate was 2,000 pulses per second with a ring frequency of 400 kilocycles. The peak pulse current in these discharges was of the order of 2,000 amperes.

In order to obtain an indication of the decay of the ionization from pulsed discharges in mercury vapor, the decay of the light intensity from the discharge was studied by use of oscillographic records obtained with a type 931 photocell tube. This tube does not measure the total radiation, but has high sensitivity only in the visible range. However, it has been shown in reference 10 that the visible radiation in the mercury-vapor afterglow is approximately proportional to the total radiation and that it gives a relative indication of the electron concentration.

RESULTS AND DISCUSSION

When the argon was held stationary in the 19-mm tube and the coil was fed by the 40-megacycle oscillator, the discharge behaved in a manner similar to that reported by Cabannes (ref. 9). At a power level of about 50 watts an electrostatic discharge was obtained at pressures in the range of 50 microns to several millimeters of mercury. (See fig. 5.) This figure indicates an apparent tendency of the plasma to pull away from the wall at the coil. This effect is caused by the refractive effect of the radial component of the magnetic field at the ends of the coil on the longitudinal motions of the electrons and ions. Since the degree of ionization is quite low in the relatively weak electrostatic discharge, this effect has a negligible influence on the body of the gas. As the power was increased, the discharge became brighter, the circuit being kept tuned for maximum brightness, and on reaching the requisite degree of conductivity (which varies with pressure), it switched discontinuously to the very bright induced discharge. This discharge was localized in the region of the coil but appeared uniformly bright throughout the radius of the tube (fig. 6). Under these conditions, Cabannes assumed a distribution of ionization over the radius of the tube given by the Bessel function J_0.

However, when the pressure was kept above about 0.5 mm, and the discharge was produced in a large-diameter tube (75 mm), it appeared somewhat similar to the discharges in mercury vapor and in iodine vapor described by MacKinnon (ref. 7). The current flowed in a discrete ring near the outer periphery of the tube. This effect is clearly seen in figure 7. This current ring was a bright but relatively transparent blue color, whereas the rest of the gas in the tube emitted a pale pink glow. The two bright vertical lines in the photograph are an optical effect due to the curvature of the glass cylinder.

The formation of the discrete current ring is undesirable from the standpoint of ionizing a flow, since the flow along the axis would attain a much lower degree of ionization than the gas near the wall, that is, in the boundary layer. The effective use of the induction technique for ionization therefore appears to require either pressures in the millimeter range, or small-diameter tubes or ducts having an annular geometry. All of the flow experiments reported herein utilized a 19-mm tube with static pressures of several millimeters.

The Problem of Blowout

When the flow was initiated, the induced discharge was blown out, but the electrostatic discharge remained. This effect was anticipated, since the emf induced in the gas is not large (ref. 7) and considerable ionization must exist in the gas for breakdown into an induced discharge to occur. The flow represents a major loss mechanism for removing the ionization, reducing it to a level below that necessary for maintaining the induced discharge.

The problem of blowout was solved initially by introducing ionization into the coil region from a weak preionizing arc in the settling chamber. The small amount of electrode material released by this weak arc, although potentially affecting strongly the discharge parameters, should be negligible for most experiments of gas-dynamic interest. Figure 8 shows the induced discharge in the argon flow.

Some preionization was obtained from the electrostatic discharge, which is maintained even in the presence of the induced discharge. When the nozzle block was grounded, this electrostatic discharge was augmented to such an extent that the separate preionizing arc was no longer necessary. This result is significant because it indicates that the induced discharge is not so tenuous as it at first appears. It is, in fact, an inherently stable discharge because of the simultaneous presence of the electrostatic discharge as a sustaining mechanism.

In the mercury-vapor flow it was unnecessary to use a preionizing arc or to ground the nozzle to maintain the discharge with the oscillator, although grounding the nozzle helped to start the discharge. This result is not surprising, since mercury vapor, in addition to having a lower ionization potential than argon, has a sound speed which is only about 40 percent that of argon, so that the velocity of the mercury-vapor flow was much lower than the argon flow. The other parameters (nozzle shape, stagnation pressure, etc.) were approximately the same.

Difficulty of Working With Nitrogen and Air

An attempt was made to reproduce these results in air and in nitrogen, since these gases are of more immediate aerodynamic interest than argon or mercury vapor. They are, however, considerably more difficult to work with than the monatomic gases. At pressures higher than about 1 millimeter, the characteristic brightness of the nitrogen plasma was prominent in the electrostatic discharge. As the power was increased, the electrostatic discharge became brighter and its relative intensity became greater in the region of the coil; therefore, the precise point of transition to the induced discharge was difficult to determine.

The ionizing efficiency (ref. 11) in nitrogen is considerably lower than in the monatomic gases, since the electrons use a large part of the energy that they gain from the field in exciting the vibrational levels of the molecules and in dissociating them. This action may be desirable for the purpose of making studies of real-gas effects in the flow; but, from the standpoint of obtaining a good conductivity in the gas and maintaining the induced discharge, it represents a major loss of available power. Since the voltage gradient in the positive column of nitrogen arcs and glow discharges is much greater than that in argon discharges (ref. 12, pp. 234-235 and 327), it is reasonable to expect that the induced emf required to break down and maintain an induced discharge in nitrogen may be several times that required in argon.

In air, the situation is somewhat similar to that in nitrogen in regard to the energy dissipated in dissociating molecules and exciting vibrational levels. Furthermore, the attachment of electrons to oxygen atoms and molecules results in greater volume ionization losses.

Induced discharges could be obtained in both air and nitrogen in the absence of flow, but when the flow was initiated the discharge reverted to the electrostatic type. With increasing power, the electrostatic discharge became rather bright within the coil, but even at the maximum power input (about 1,200 watts), the induced discharge had failed to reappear. As the appearance of the discharge at this point was similar to that of the electrostatic discharge in the stationary gas near the transition point, it is believed that with somewhat more power the induced discharge could have been produced and maintained in the nitrogen flow.

Power Measurements

With an induced discharge in the argon flow, measurements were made of the power delivered to the primary coil producing the induced discharge and of the power reflected back to the oscillator. About

15 percent of the power was reflected, this value being virtually constant within the experimental error.

Of course, not all of the remaining 85 percent of the power was delivered to the gas. Some of this power was dissipated in heating the circuit elements, but this loss was relatively small, since these elements became only moderately warm when the circuit was kept properly tuned.

The radiation loss can be estimated. The coil diameter was about 0.05 meter and the wave length 7.5 meters. The radiation resistance of a single turn loop under these conditions is only about 6×10^{-4} ohms (ref. 13), so that even at 25 amperes the power radiated from the entire coil should be quite small. The radiation from the tuning condenser should be negligible. The ohmic and radiation losses together are estimated to be about 5 percent of the available power but, even if as much as 10 percent were lost, 75 percent would still be delivered to the gas.

This method of obtaining a measurement of the power delivered to the gas is, of course, far from ideal, but it should be pointed out that an accurate measurement is difficult to obtain. The calorimetric technique used by Cabannes would be difficult, if not impossible, to adapt for use with a flowing gas. Furthermore, the region of flowing water between the coil and the discharge tube implies a very poor coupling condition, and Cabannes' measurements indicate that cooling of the wall may actually alter the discharge parameters.

Chuan (ref. 3) measured the power dissipated in a low-density nitrogen flow by a discharge in the stream. He used a thermocouple to determine the rise in the temperature of the stream. The major weakness of this method is that the temperature measured would ordinarily be much higher than the actual gas temperature, since the heat released by recombination or deionization on surfaces in the flow may be considerable, even so great as to melt small wires of tungsten or other refractory materials (ref. 5).

Effect of Discharge on Flow Parameters

The effect of the discharge on the velocity and Mach number is an important gas-dynamic consideration. In some discharges, particularly at higher pressures, a large part of the energy imparted to the charged particles by the electrical field is communicated to the rest of the gas as heat. At the pressures and powers used in these experiments, the gas-temperature rise is small, but it is not negligible.

For a static temperature of the mercury-vapor flow of 450° K and a mass flow of roughly 1.5 grams per second, the temperature would only have to be raised by 35° to choke the flow at a Mach number of 1.5. Since the heat capacity C_p of mercury vapor is only 0.025 cal/g-$^{\circ}$K approximately 1.12 cal/sec or 5 watts is required to choke the flow. If, in the argon system, a mass flow of 1 g/sec and initial temperature of 300° K are assumed, about 11.5 watts are required to choke the flow.

The flow will not necessarily be choked by the discharge, although choking will result if only a small fraction of the power delivered to the gas is converted to heat. At low pressures the gas temperature in a discharge is a function of the pressure and depends weakly, if at all, on the discharge current. The temperature never exceeds a few hundred degrees if the pressure is sufficiently low (ref. 12, p. 291), so that a supersonic flow can be maintained if the temperature in the settling chamber is sufficiently high.

Experiments With Pulsed Discharges

MacKinnon (ref. 7) found that an induced discharge could be produced with less average power in a stationary gas with pulsed current in the primary coil than with continuous-wave current. Experiments with the spark-gap unit and with the line-type pulser were intended to determine whether a similar effect occurred in the case of the flowing gas.

With the spark-gap unit, a very brilliant induced discharge could be induced in stationary mercury vapor, but with flow no induced discharge could be obtained by this method, either in argon or in mercury vapor. This failure was attributed mostly to the internal construction of the unit, which was such that it was difficult to tune the circuit for a varying load.

With the hydrogen thyratron pulser, which was designed so that the circuit inductance and capacity could easily be changed, induced discharges were obtained under rather restricted conditions in both argon- and mercury-vapor flows. The leads had to be kept short and heavy and the nozzle had to be grounded. Also, at high repetition rates of 1,000 pulses per second or more, the capacitance had to be less than about 0.1 microfarad. At repetition rates of around 1,000 pulses per second, the electrostatic discharge appeared at power levels of a few hundred watts. Almost 3,000 watts average power were required to initiate and maintain the induced discharge.

The fact that considerably more power was required to obtain the induced discharge in the flow with the pulsed current than with continuous-wave current is significant, since it is contrary to the results obtained by MacKinnon with discharges in stationary plasmas.

An attempt was made to obtain a comparison of the pulsed discharge in the flow with that in a stationary gas by comparing the pulse shapes and light intensity decay under both conditions. As has already been noted, the form of the light intensity decay curve indicated approximately the decay of the ionization. Oscillographs taken with an induced discharge in a closed tube (stationary gas), with an induced discharge in the flow, and with an electrostatic discharge in the closed tube are shown in figures 9(a), 9(b), and 9(c), respectively. The amplitudes of the light intensity curves are not comparable, since the photocell had to be moved toward or away from the discharge tube according to the brightness of the discharge. The first several cycles of the pulse ringing are not observable in figures 9(a) and 9(b). They can be seen on the oscilloscope screen, however, and their amplitudes are considerably greater than the pulse amplitudes that produce the electrostatic discharge (fig. 9(c)).

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Figure 9(a) indicates that the power couples well into the discharge, as the ringing in the circuit is rapidly damped out. When the induced discharge was produced in the flow, however, much of the power was dissipated in the circuit ringing (fig. 9(b)) which indicates that the conductivity never did become very good. Since the pulse decays more slowly, it is possible for the induced discharge to be maintained longer. The light decay (fig. 9(b)) indicates that the induced discharge lasts about 30 microseconds, but after the discharge is extinguished the light intensity drops rapidly (in about 25 microseconds) to the reference line. In the closed tube (fig. 9(a)), on the other hand, virtually all the power appears to have been dissipated after a few cycles of the ringing and so the discharge is not maintained longer than 5 or 10 microseconds; but the light decay is much more gradual, being nearly linear for about 50 microseconds and then beginning an asymptotic approach to the reference line.

In the electrostatic discharge, the light intensity decays much more rapidly than in the induced discharge, as might be expected, with virtually all the power being dissipated in the circuit ringing.

CONCLUDING REMARKS

Induced discharges could be maintained in low-density argon-and mercury-vapor flows at velocities near a Mach number of 1. The coupling of power into the gas by this means appeared to be relatively good, and a clean, well-ionized flow was produced: The advantages of using pulsed current in the primary coil, as observed in studies with stationary gases, were not evident when the gas was flowing.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., May 11, 1960.

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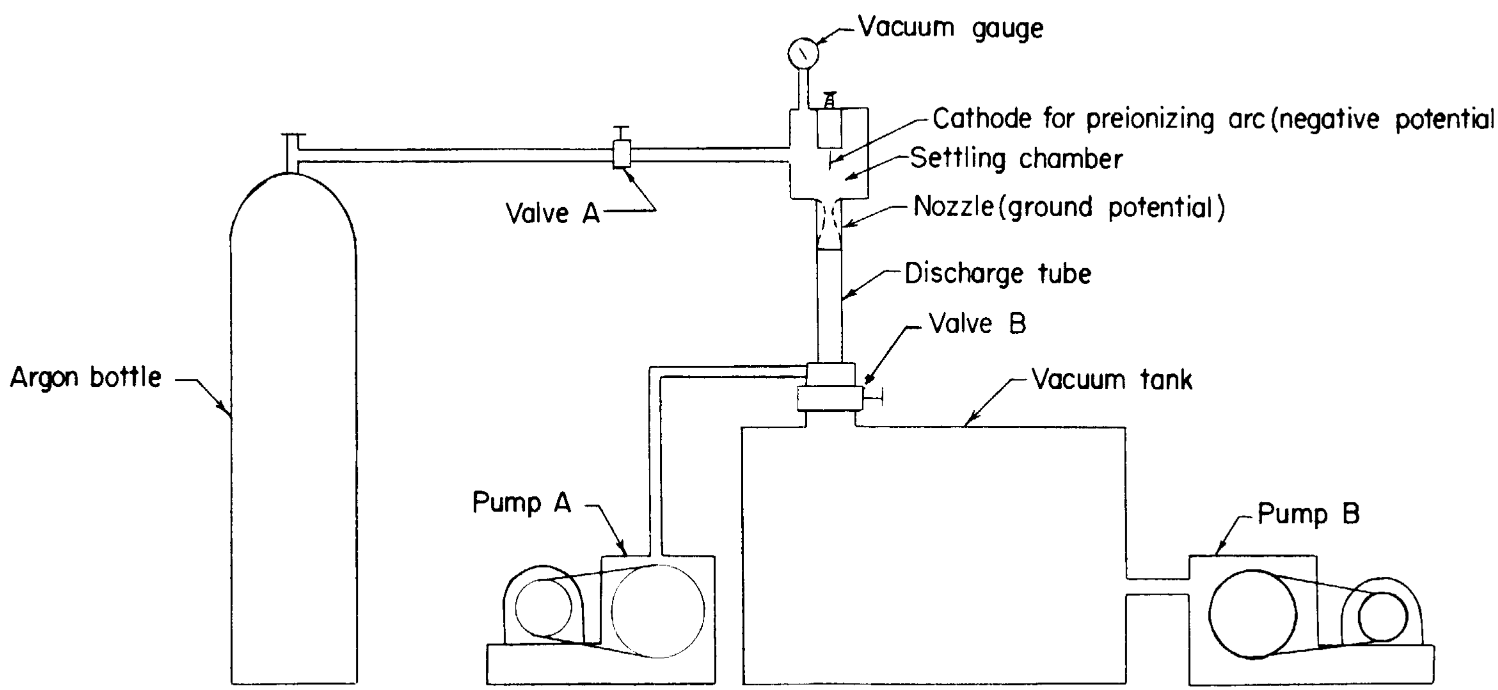

Figure 1.- Schematic diagram of argon flow apparatus.

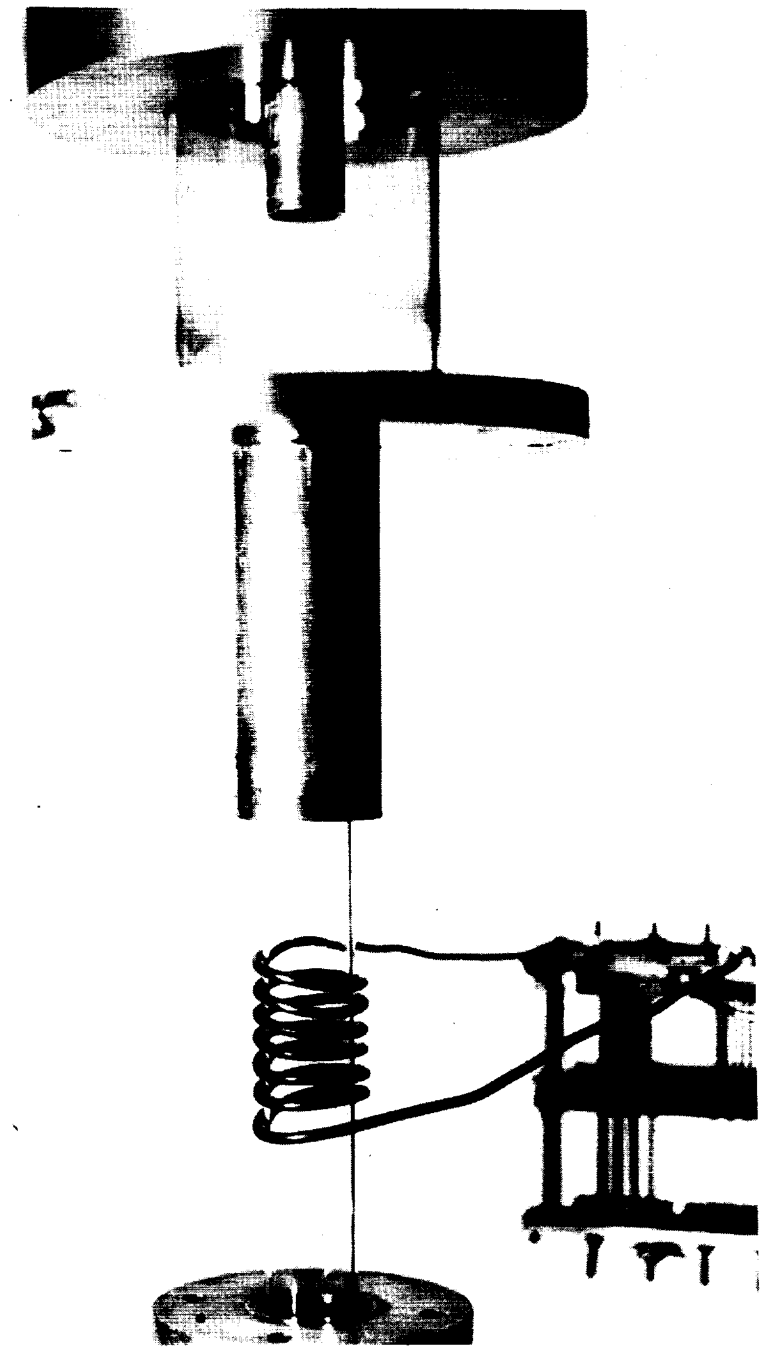

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Figure 2.- Settling chamber, nozzle, and discharge tube of argon flow apparatus.

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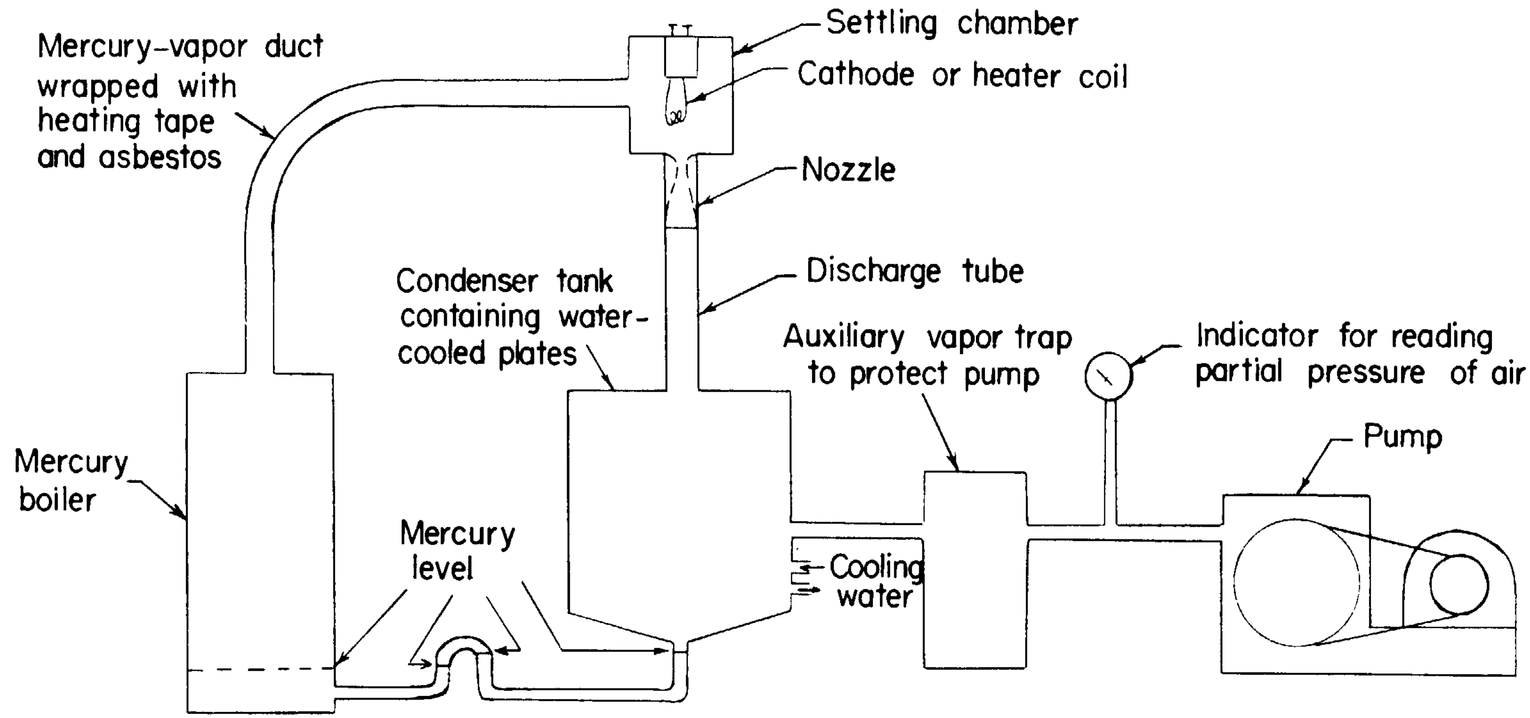

Figure 3.- Schematic diagram of mercury-vapor flow system.

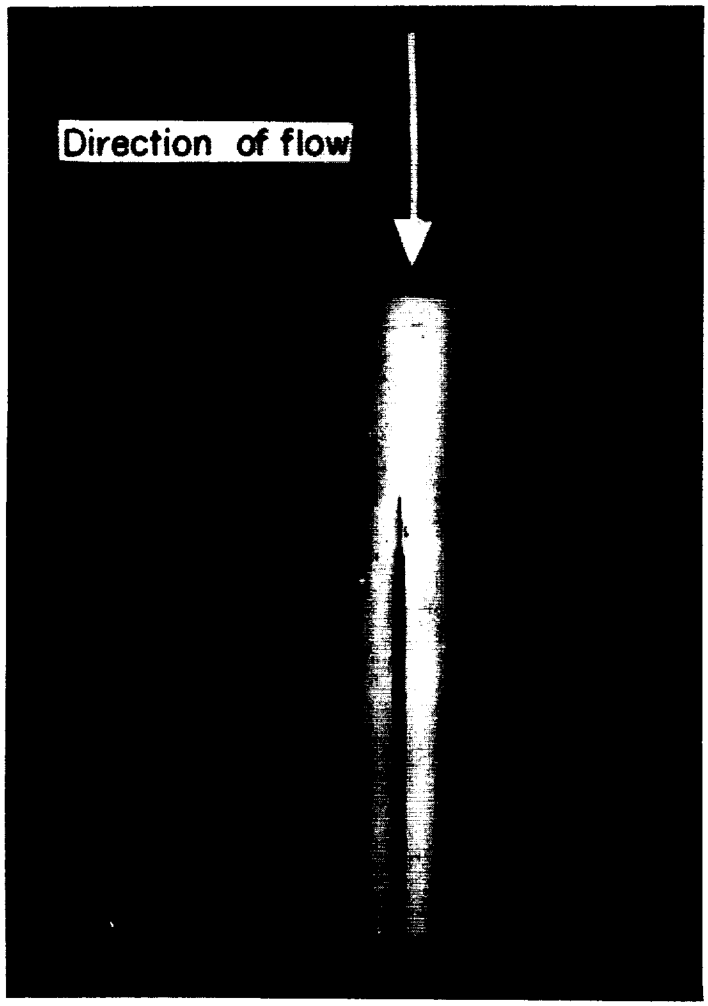

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Figure 4.- Shock wave on blade in mercury-vapor plasma flow.

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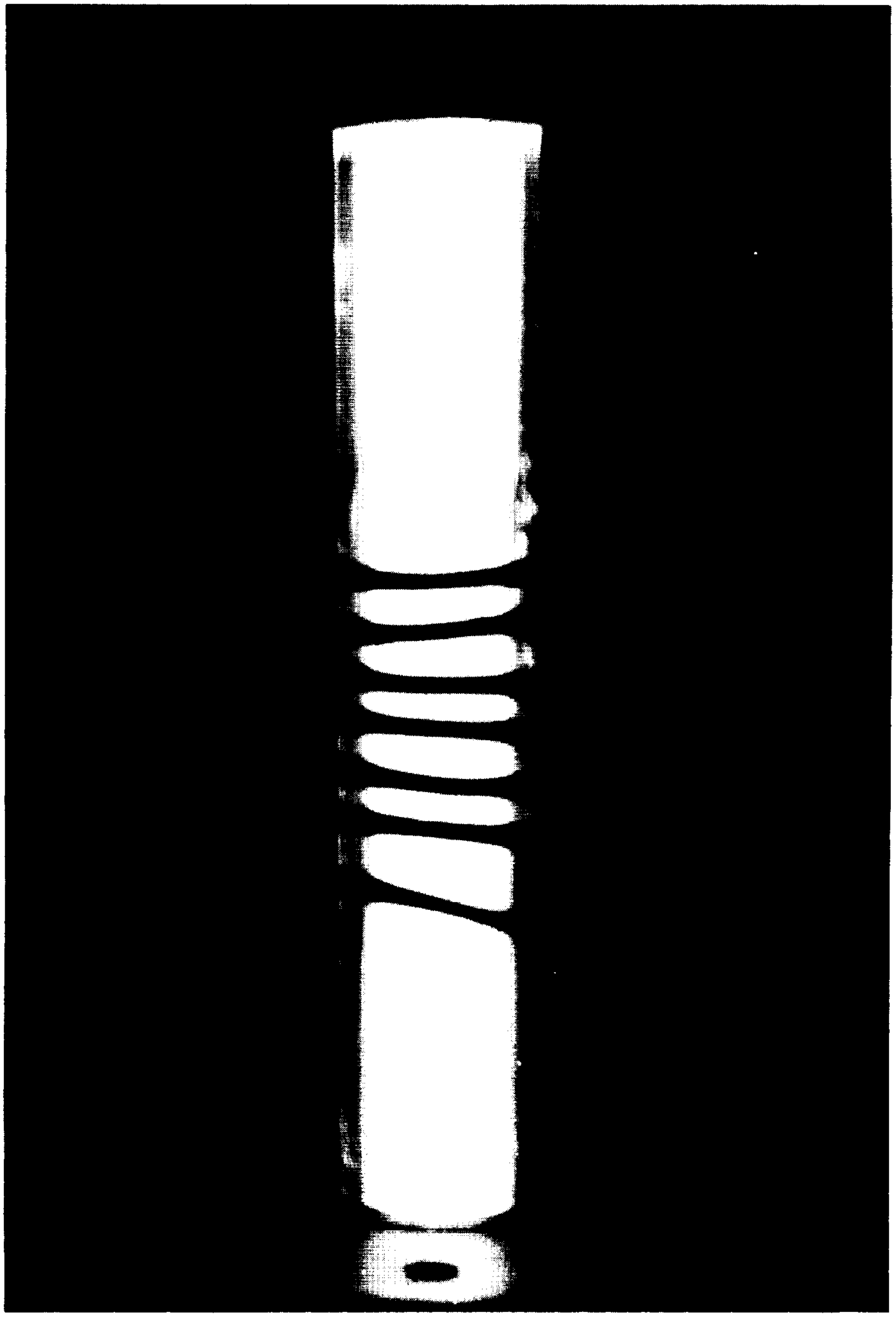

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Figure 5.- Electrostatic discharge due to voltage developed across coil in argon with no flow.

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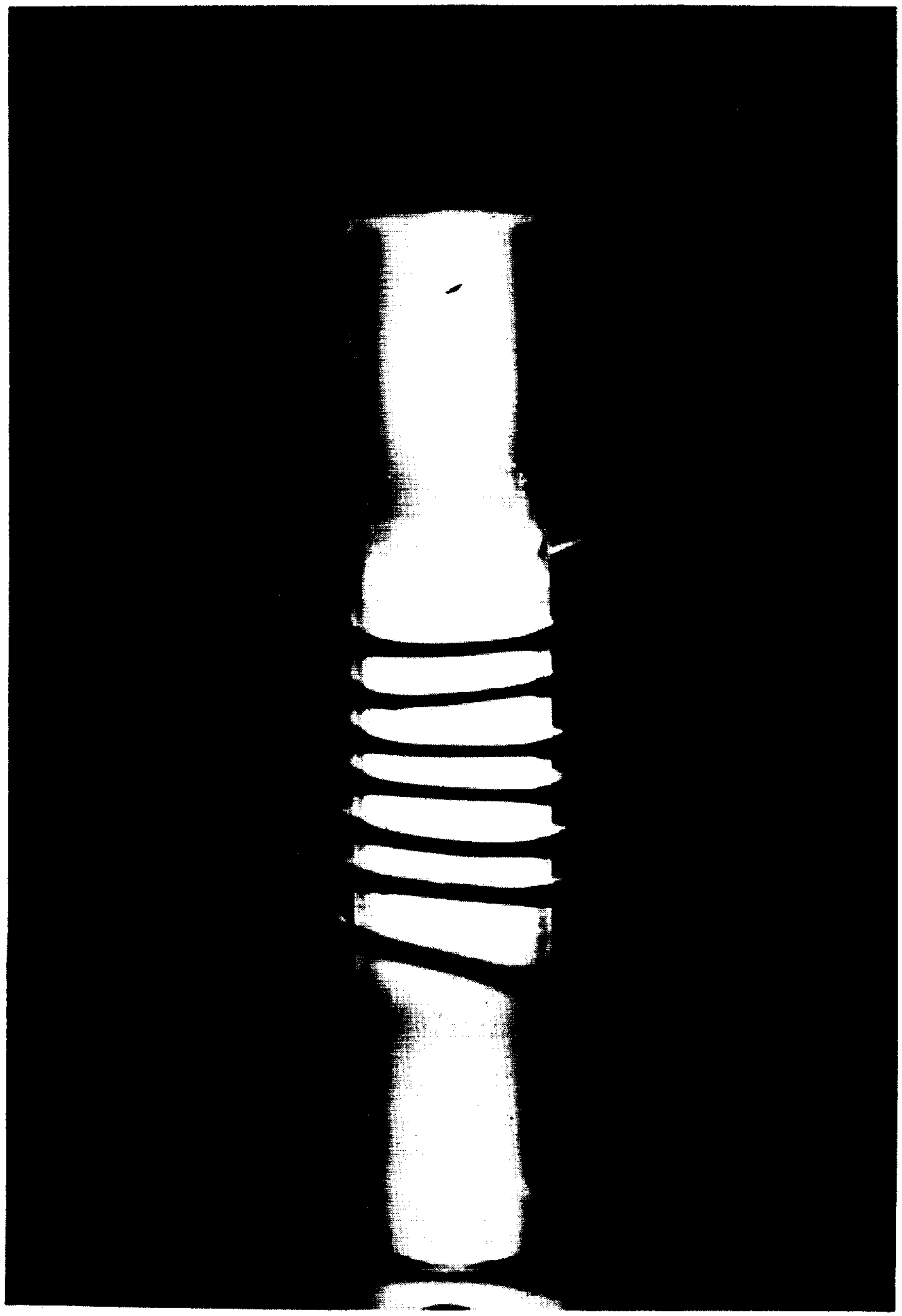

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Figure 6.- Induced discharge in argon with no flow.

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Figure 7.- "Ring" discharge in argon at 1.0 mm Hg pressure with no flow.

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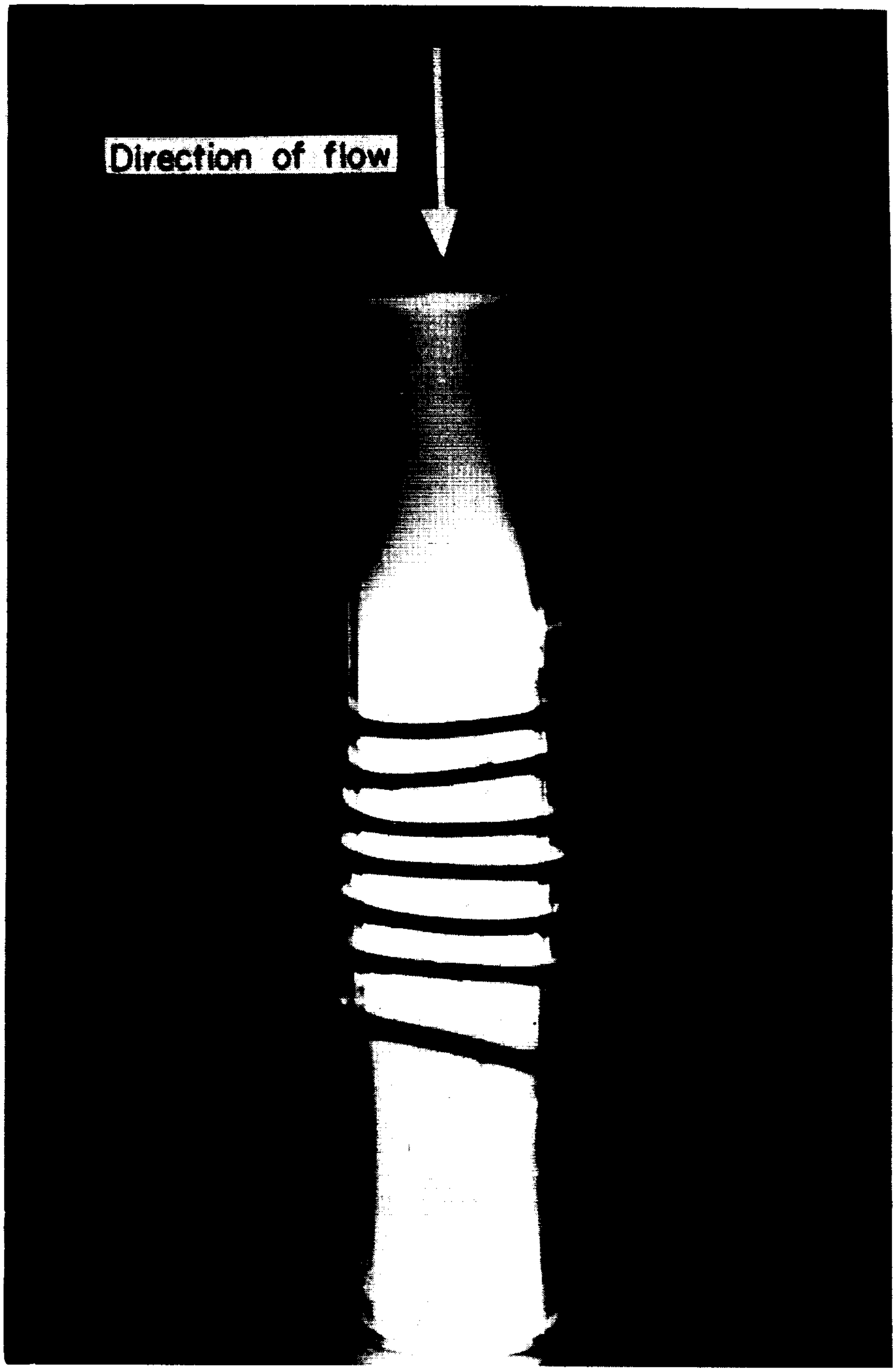

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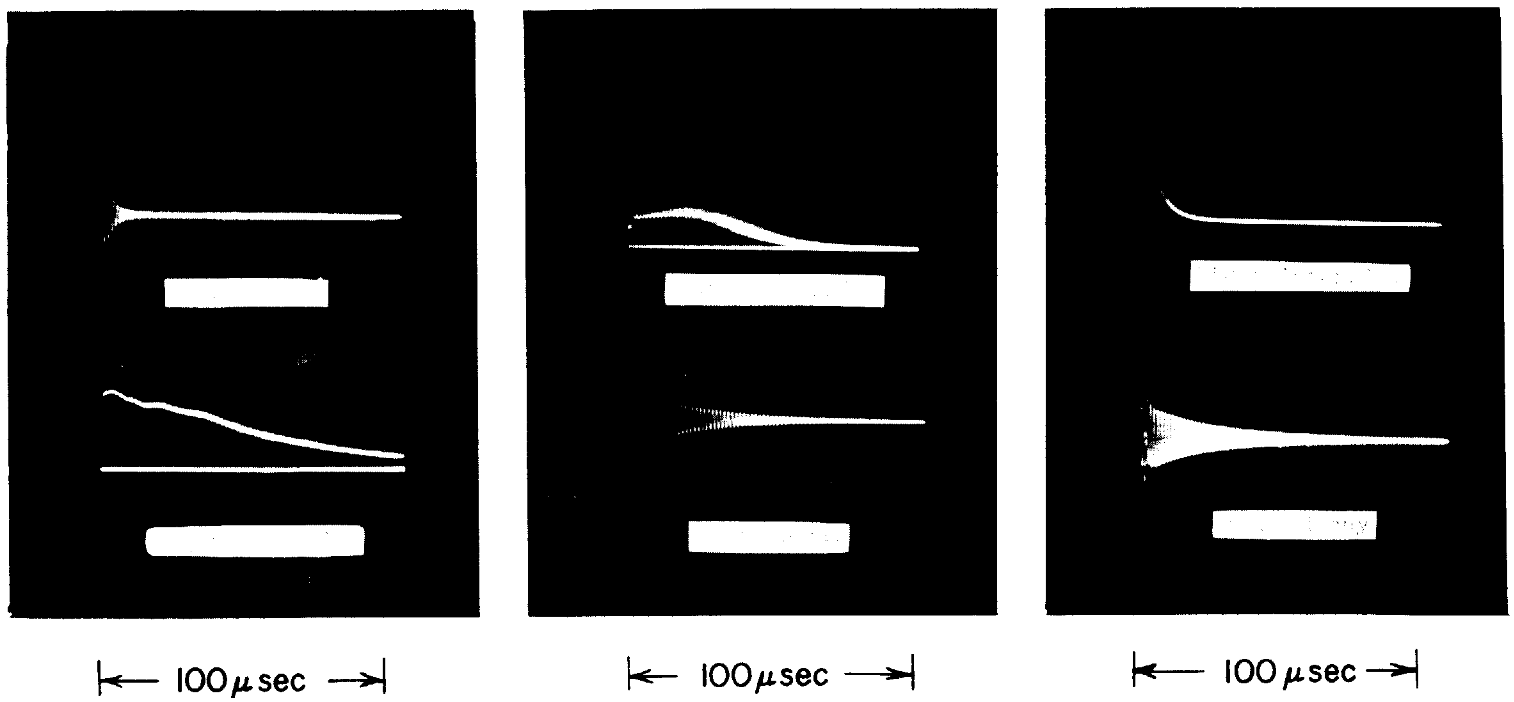
Figure 8.- Induced discharge in argon flow.



(a) Induced discharge in stationary gas.

(b) Induced discharge in flow.

(c) Electrostatic discharge.

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Figure 9.- Pulse decay and light intensity decay oscillographs for discharges in mercury vapor.

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AN EXPERIMENTAL STUDY OF THE IONIZATION OF LOW-DENSITY GAS FLOWS BY INDUCED DISCHARGES. R. L. Barger, J. D. Brooks, and W. D. Beasley. September 1960. 21p. OTS price, $0.75. (NASA TECHNICAL NOTE D-431)

Induced discharges are advantageous for ionizing low-density flows in that they introduce no electrode contamination into the flow and they provide a relatively high degree of ionization with good coupling of power into the gas. In this investigation a 40-megacycle oscillator was used to produce and maintain induced discharges in argon and mercury-vapor flows. Methods for preventing blowout of the discharge were determined, and power measurements were made with an in-line wattmeter. Some results with damped oscillations pulsed at 1,000 pulses per second are also presented.

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I. Barger, Raymond L.
II. Brooks, Joseph D.
III. Beasley, W. D.
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