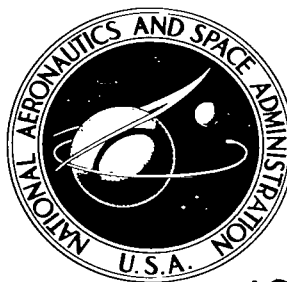


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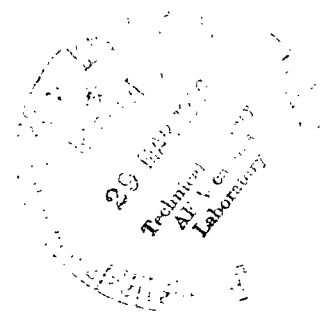
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SUMMARY

Velocity measurements have been made in the Mach 12 test section of the Langley 1-foot (0.305-meter) hypersonic arc tunnel at free-stream static pressures as low as 40 microns of mercury at 155° K. An electrical discharge apparatus was used to produce two short high-voltage pulses spaced 5 microseconds apart in the flow. These pulses produced a single variation in the stream luminosity that was detected by photomultipliers. For a range of tunnel stagnation conditions, the velocities, as determined by the discharge technique, varied from 2500 m/sec to 3170 m/sec. The differences between the measured velocities and the velocities calculated by assuming equilibrium flow down the nozzle varied from 0 percent to -4.2 percent, with an average difference of -2.2 percent. If known vibrational nonequilibrium effects are taken into consideration, the agreement is much better than -2.2 percent.

INTRODUCTION

As part of an experimental program to obtain a better understanding of the flow in a Mach 12, electric-arc-heated wind tunnel, measurements of the flow velocity in the test section have been made. The technique used was a variation on the tracer-spark technique; however, the photographic techniques, such as those reported in references 1 to 3, were not used because of the experimental difficulties connected with producing a spatially well-defined electrical discharge at low static pressures, which exist in the test section of the tunnel. The tunnel is operated at stagnation pressures between 15 and 25 atmospheres and free-stream static pressures in the test section are from about 40 to 80 microns of mercury. Other velocity-measuring techniques such as photoelectric techniques to observe the random fluctuations in a plasma arc (refs. 4 and 5) were not appropriate to the conditions in the Langley 1-foot (0.305-meter) hypersonic arc tunnel. The random fluctuations in this tunnel were found to have durations too long to be of use in determining stream velocity. The velocity-measuring technique, which is described in reference 6, consisted of discharging a small capacitor in the throat of a supersonic arc jet to produce a variation in stream luminosity that was detected by photoelectric techniques at a location just downstream of the throat region. This method exhibited good

repeatability and agreed well with the velocity determined by pressure probe measurements. However, the method did not appear feasible in the Langley 1-foot (0.305-meter) hypersonic arc tunnel because of the large distance between the throat and the test section (nearly 1.83 m). There would be a time delay of approximately 1 millisecond which is greater than the lifetime of the excited species before the electrical disturbance traversed the distance between the throat and the test section.

The velocity-measuring technique described herein utilized a relatively weak double-pulse electrical disturbance fired between two electrodes at the upstream end of the test section. The two pulses were spaced 5 microseconds apart and produced a single variation in stream luminosity which was detected by a photoelectric technique.

These velocity measurements are compared with the predicted velocities in the test section of the tunnel for a range in stagnation enthalpies between about 3.48×10^6 to 5.578×10^6 J/kg.

SYMBOLS

e	base of Napierian logarithm
h	enthalpy, J/kg
\dot{m}	mass-flow rate, kg/sec
p	pressure, N/m ²
R	universal gas constant, 8.314 J/mol-°K
T	temperature, °K
V	velocity, m/sec
θ	characteristic vibrational temperature, °K

Subscripts:

c	cold flow (arc off)
h	hot flow (arc on)
s	sonic throat
l	free stream
t	stagnation conditions

v vibrational mode
V measured velocity

APPARATUS AND PROCEDURE

A diagram of the Langley 1-foot (0.305-meter) hypersonic arc tunnel is shown in figure 1, and a description of the tunnel can be found in reference 7. A schematic diagram of the electrical apparatus for making velocity measurements is shown in figure 2, and a picture of this apparatus is shown in figure 3. The spark electrodes were 6.35-mm-diameter boron nitride rods with a 0.79-mm-diameter steel rod through the center. The electrodes were mounted in the tunnel (fig. 4) so that the discharge would be perpendicular to the line of sight of the photomultipliers. The power to the electrodes was supplied by a burst generator capable of producing bursts of pulses from 0 to 15 kilovolts in amplitude. The pulser is basically a series type, that is, a tube (hard vacuum) in series with the output is cut off until triggered. A stored charge can then be passed through the tube where it develops a voltage across the load. The photomultipliers used in this apparatus were of the type 931A. A transistorized emitter follower was used to match the high output impedance of the photomultiplier to the impedance of the coaxial cable connecting the output of the photomultiplier to the input of the dual-beam oscilloscope. The diagram for the emitter follower is shown in figure 5. The test chamber of the tunnel is equipped with two (12.7- by 27.9-cm) quartz windows, which are in recessed cavities in the wall of the tunnel. For this experiment one of the windows was removed and the velocity-measuring device was mounted in the window cavity. Three brass tubes of 1.27-cm diameter with three collimating slits 0.79 mm wide were used to limit the view of each photomultiplier to a strip 1.58 mm wide and approximately 1.90 cm high in the tunnel test section. Only two of the slits were used to measure stream velocity.

The following method was used to measure the stream velocity. A burst consisting of two 15-kV, 1-microsecond pulses spaced 5 microseconds apart was applied to the electrodes. The first pulse produced a path of ionized gas across the electrodes. This ionized gas travels with the stream velocity. The second 1-microsecond high-voltage pulse is applied 5 microseconds later. Due to the small amount of ionized residue of the first pulse, the second pulse will strike through the path of the displaced first pulse. This phenomenon, demonstrated in reference 3, enhances the luminosity of the gas, since the second pulse appears as a well-defined glow discharge rather than a diffused glow. This luminous disturbance is carried along with the stream and detected by the photomultipliers. The dual-beam oscilloscope is triggered by a synchronized pulse from the burst generator. Since the first photomultiplier is located nearer the spark electrodes than the second, the traces on the dual-beam oscilloscope indicate a time displacement of the luminosity. This time difference and the distance between the slits were used to calculate the stream velocity.

The traces of the dual-beam oscilloscope were photographed and some typical traces are shown in figure 6. Each photograph represents several velocity determinations since the burst repetition rate was 60 bursts/sec and shutter

time was 1/25 second. The time difference was measured by cutting the picture in half and superimposing the wave shapes. As a check, the time was also measured by determining the time between peaks of the light intensity. Three to eight photographs were made for each tunnel run; of the measurements made from these photographs, the last measurement was used to determine the velocity, since the best estimate of the tunnel operating conditions can be determined at this time.

RESULTS AND DISCUSSION

Direct velocity measurements were made in hypersonic airflow. The static pressure for the different tests varied from about 40 to 70 microns of mercury. For a range of tunnel stagnation conditions, the velocities varied from 2500 m/sec to 3170 m/sec. The differences between the measured velocities and the velocities calculated with the assumption of equilibrium flow down the nozzle varied from 0 to -4.2 percent, with an average difference of -2.2 percent. (See fig. 7.)

The enthalpy at the sonic throat was calculated by using the following formula:

$$h_t = 1.51 \times 10^2 \left[\left(\frac{p_{t,h} \dot{m}_c}{p_{t,c} \dot{m}_h} \right) (T_{t,c})^{1/2} \right]^{2.50} \quad (1)$$

This method is discussed in references 8 and 9 and the results of an experimental check made by using a calorimeter are presented in reference 10.

The free-stream velocity was calculated by assuming an equilibrium expansion of the test air from the sonic throat to the test section. In a Mach 12 flow the velocity is related to the enthalpy by

$$h_t = \frac{0.500V_1^2}{0.969} \quad (2)$$

The preceding equation is a fit of total enthalpy to free-stream velocity over the range of conditions in this report and is shown as the solid line in figure 7. Since all the experimental points in figure 7 fall above the equilibrium curve, it would appear that there could be some nonequilibrium effect in the expansion of the gas. Previous measurements of the vibrational temperature in the Langley 1-foot (0.305-meter) hypersonic arc tunnel are reported in reference 11. The amount of the enthalpy tied up in the vibrational mode was calculated from the following expression:

$$h_v = \frac{R\theta}{e^{\theta/T_v} - 1} \quad (3)$$

which is based on quantum mechanical considerations applied to a diatomic gas model as obtained from reference 12. Since the enthalpy tied up in the

vibrational mode is not available as velocity, this effect was subtracted from the stagnation enthalpy and a new velocity was calculated. The result of this calculation is shown as the dashed line in figure 7. The agreement with the experimental values are better if vibrational nonequilibrium effects are taken into consideration. Vibrational nonequilibrium would seem to explain the slightly lower values of measured velocity, if it were assumed that the effective stagnation enthalpy is decreased by the amount tied up in the vibrational mode. However, a close examination of the accuracy of the enthalpy measurements does not allow this explicit conclusion. A plot of h_t determined from the velocity measurements by using equation (2) is shown in figure 8. All the data points fall within the experimental error (± 10 percent) as reported in reference 10. Experimental values of vibrational temperature were not available above 4.299×10^6 J/kg. Therefore, it is not known whether the disagreement at higher enthalpies could entirely be explained by vibrational nonequilibrium.

ACCURACY

The accuracy of photoelectric techniques depends upon the ability to determine the time separation of a luminous region of gas and the separation distance between collimating slits, with the assumption that the time dependence of luminosity does not affect the distribution of the light intensity.

The distance between slits was determined by a series of measurements to be 7.234 cm with a maximum deviation between any two readings of 0.25 percent and an average deviation from the mean of 0.1 percent. The time difference as determined from the photograph traces was measured by several individuals independently. The maximum difference was 1 microsecond with an average difference from the mean of 0.3 microsecond.

Obviously an overall error cannot be applied to the technique since the time difference is not the same for each velocity measurement and therefore the percent error is different for each case. It was therefore decided to do a statistical analysis on each velocity measurement. A large number of readings were taken of the measurements and a standard deviation was obtained for each measurement obtained. However, since the velocity depends upon more than one measured quantity, the method of propagation of uncertainties was applied and the range of uncertainty is plotted in figures 7 and 8, with the circle representing the actual velocity data point. The same method of analysis was applied to the determination of total enthalpy by the sonic-throat method, and the results are plotted as a range of enthalpies in figures 7 and 8.

CONCLUDING REMARKS

Velocity measurements have been made in the Mach 12 test section of the Langley 1-foot (0.305-meter) hypersonic arc tunnel at free-stream static pressures as low as 40 microns of mercury at 155° K. For a range of tunnel stagnation conditions, the velocities, as determined by the discharge technique,

varied from 2500 m/sec to 3170 m/sec. The differences between the measured velocities and the velocities calculated with the assumption of equilibrium flow down the nozzle varied from 0 to -4.2 percent, with an average difference of -2.2 percent.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., November 17, 1965.

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DIAGRAM OF 1 FOOT HYPERSONIC ARC TUNNEL

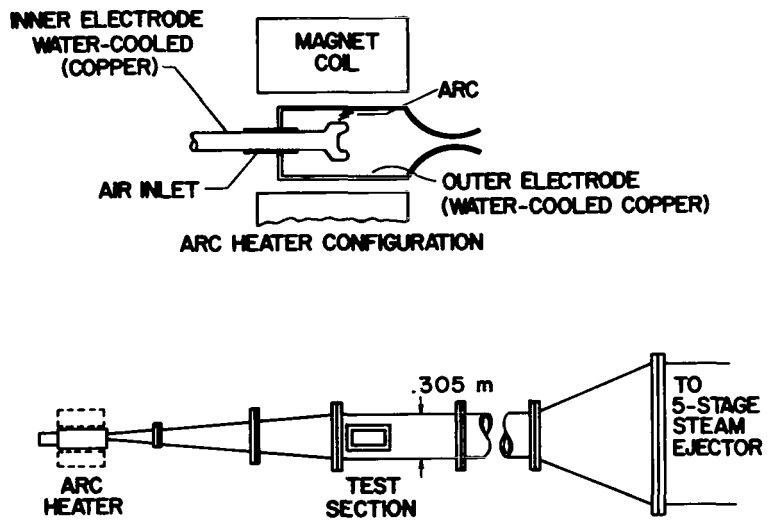


Figure 1.- Langley 1-foot (0.305-m) hypersonic arc tunnel.

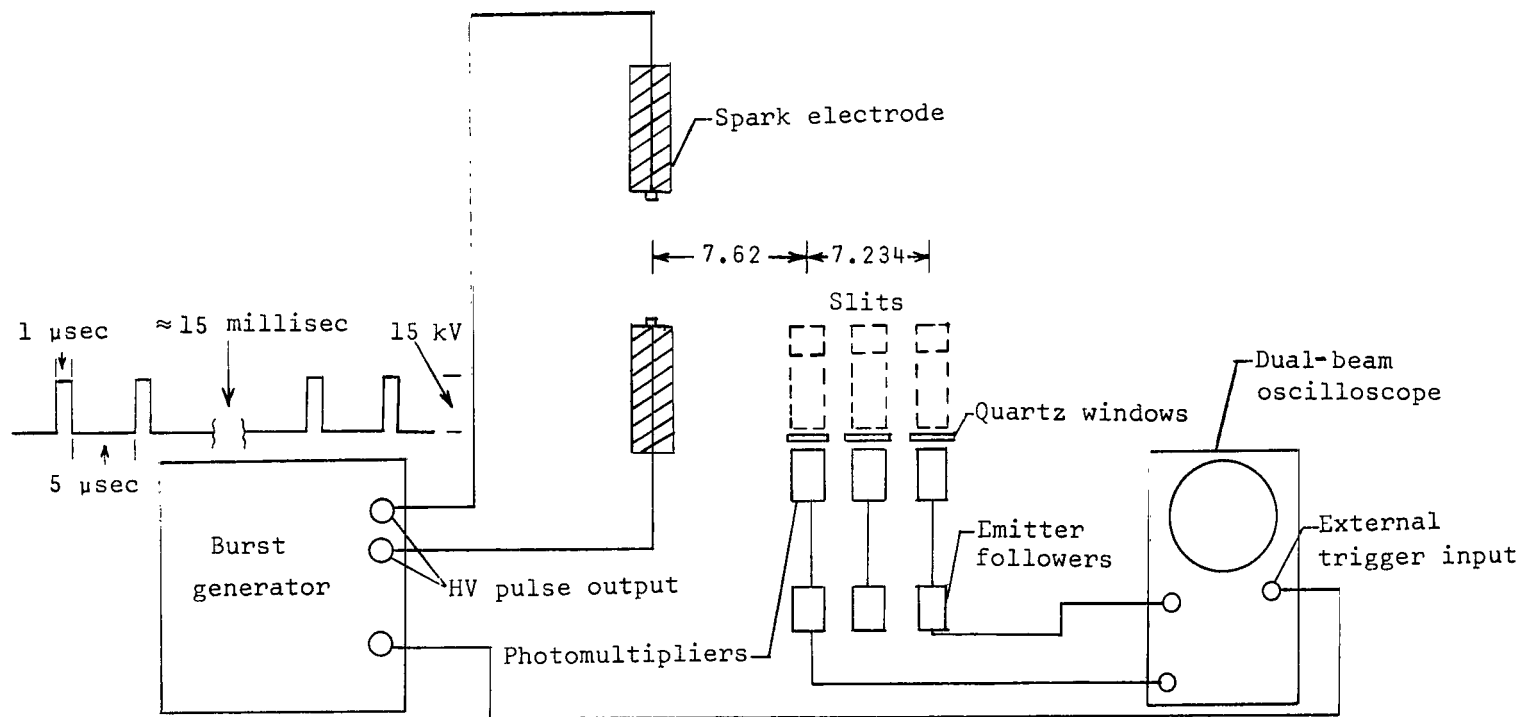


Figure 2.- Schematic diagram of electrical apparatus. (All dimensions are in centimeters.)

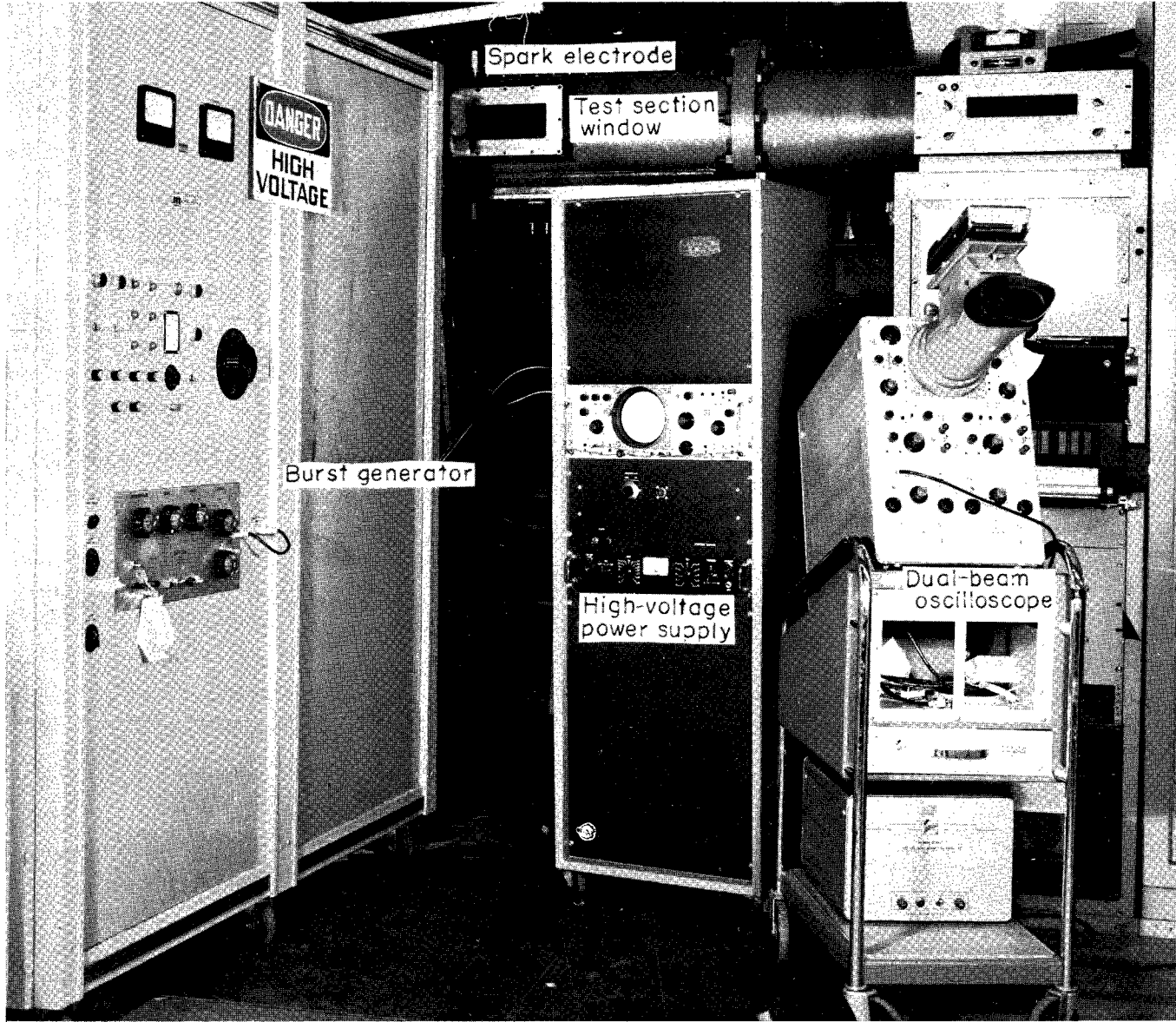


Figure 3.- Photograph of electrical apparatus.

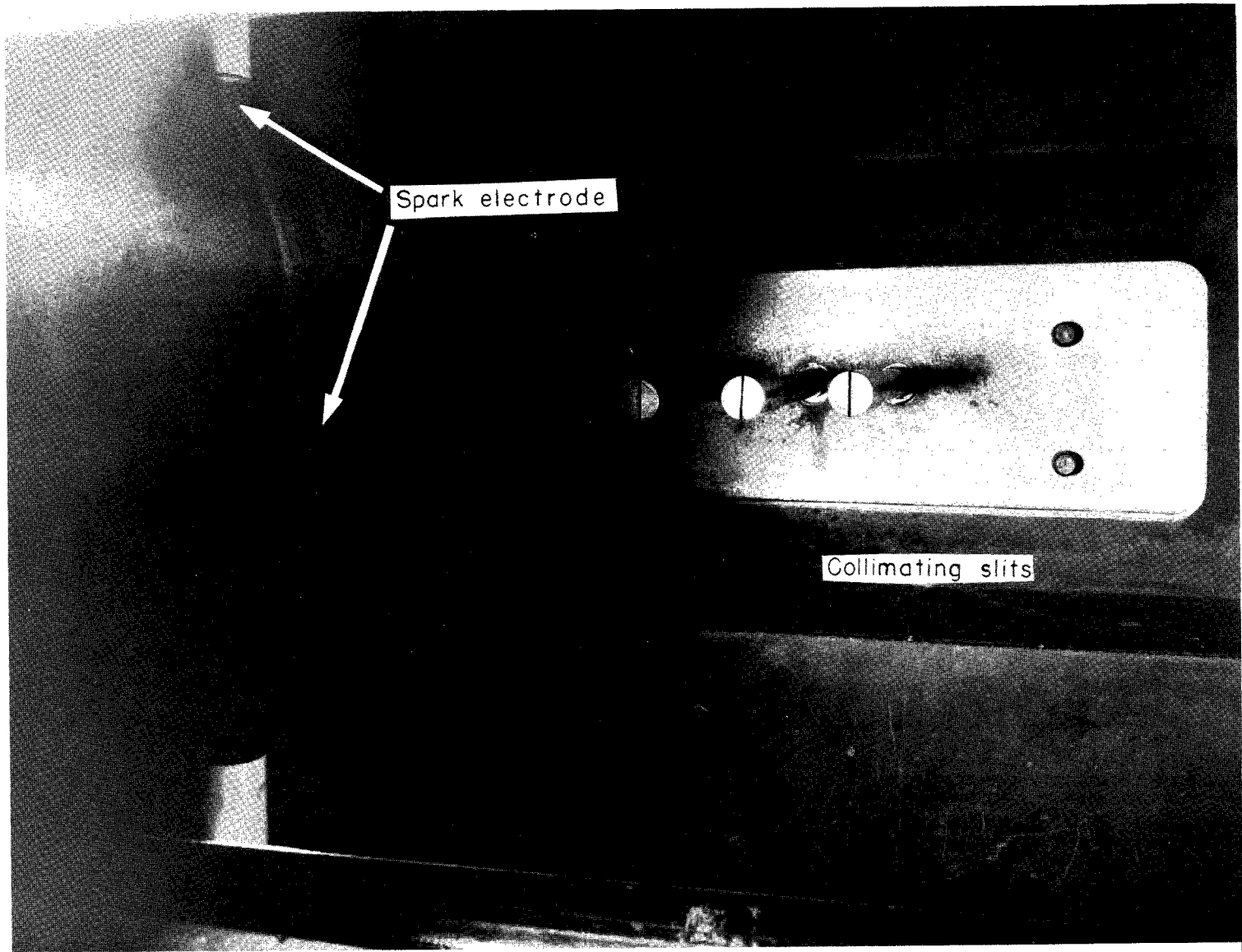


Figure 4.- Photograph of electrodes and slits.

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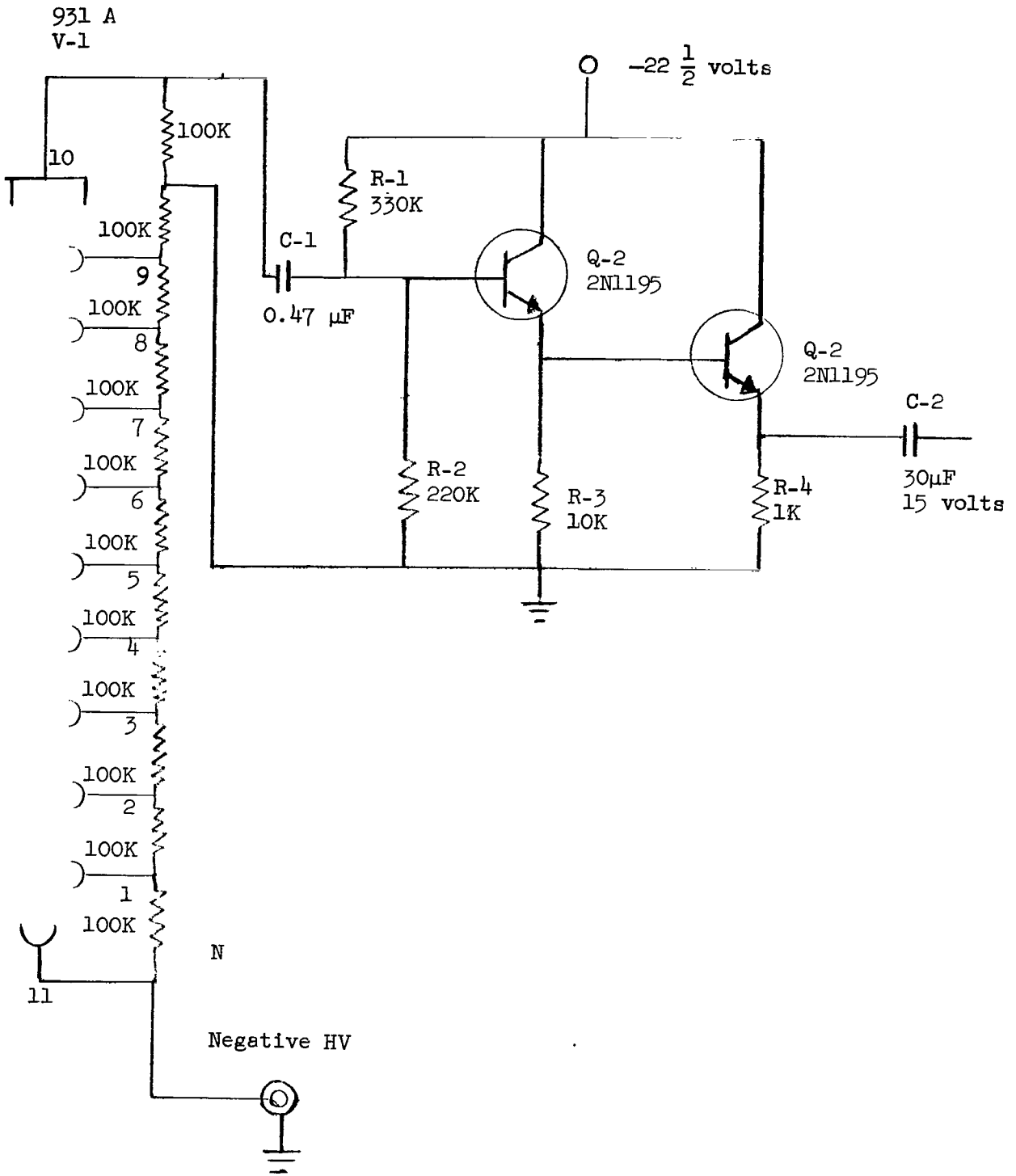
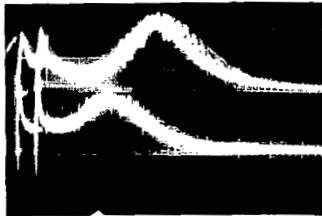


Figure 5.- Schematic of pulse emitter follower.



(a) Photomultiplier spacing, 3.485 cm; oscilloscope sweep rate, $10\mu\text{sec}/\text{cm}$. (Approximately 5 retraces of scope.)



(b) Photomultiplier spacing, 7.234 cm; oscilloscope sweep rate, $10\mu\text{sec}/\text{cm}$. (Approximately 3 retraces of scope.)

Figure 6.- Typical oscilloscope traces of output of photomultipliers. Sweep from left to right. Scope gain on each channel is $0.5\text{ V}/\text{cm}$.

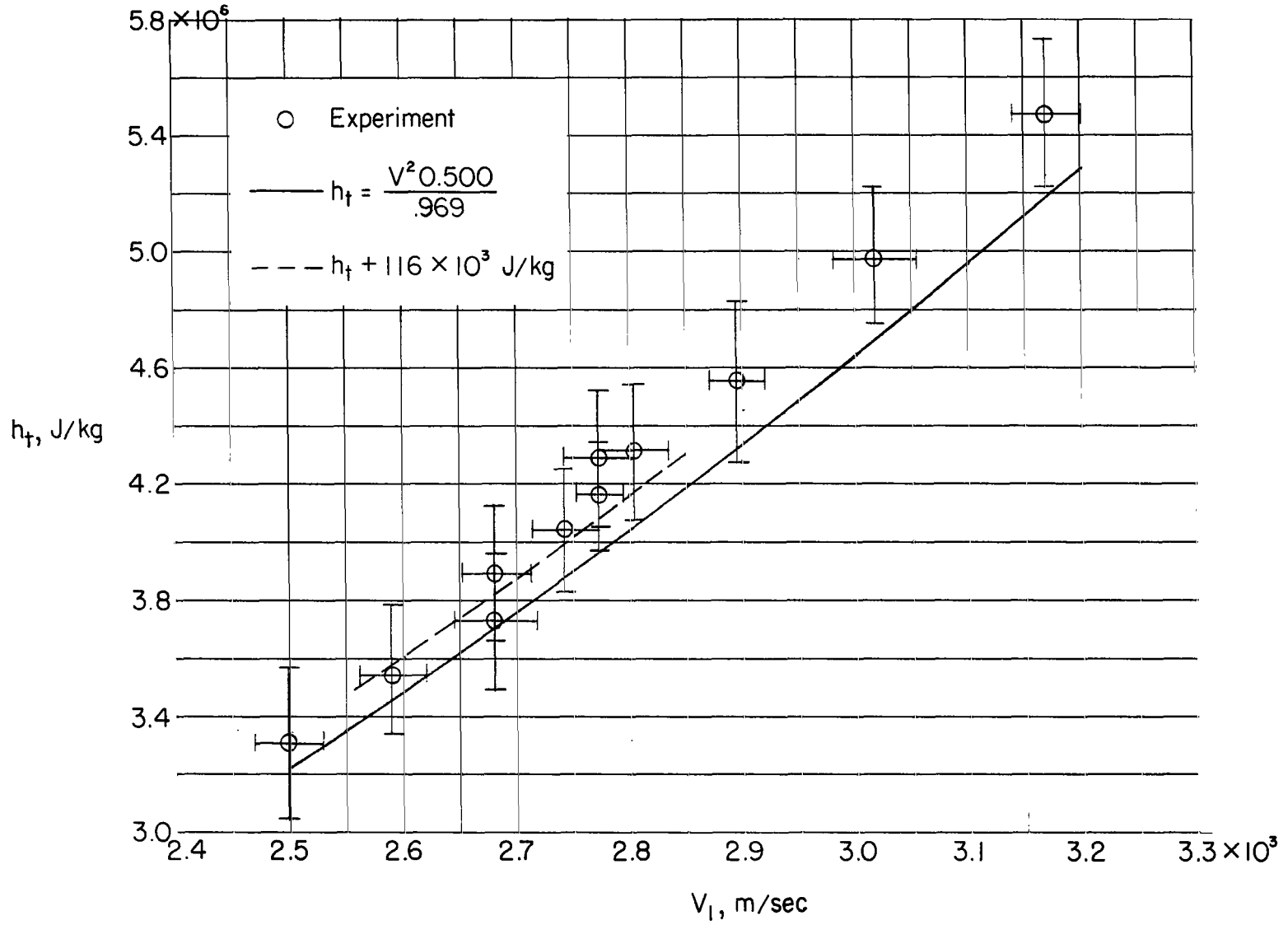


Figure 7.- Variation of velocity with total stagnation enthalpy.

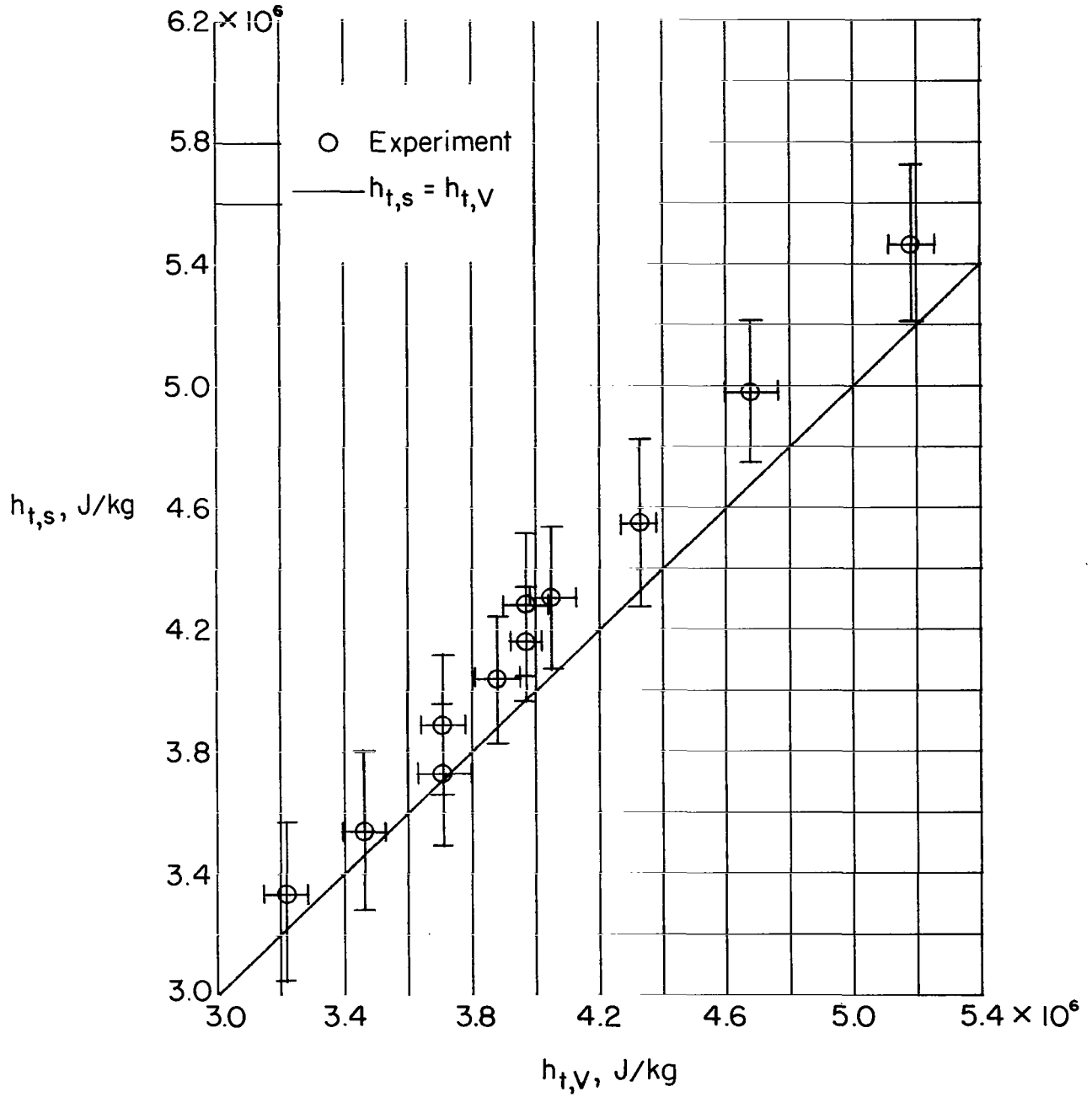


Figure 8.- Comparison of enthalpy determined by sonic-throat equation and measured velocity.

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