VELOCITY MEASUREMENTS IN THE
LANGLEY 1-FOOT (0.305-METER)
HYPERSONIC ARC TUNNEL

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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 $3.48 \times 10^6$ to $5.578 \times 10^6$ J/kg.

SYMBOLS

\begin{align*}
e & \quad \text{base of Napierian logarithm} \\
h & \quad \text{enthalpy, J/kg} \\
\dot{m} & \quad \text{mass-flow rate, kg/sec} \\
p & \quad \text{pressure, N/m}^2 \\
R & \quad \text{universal gas constant, 8.314 J/mol-\textdegree K} \\
T & \quad \text{temperature, \textdegree K} \\
V & \quad \text{velocity, m/sec} \\
\theta & \quad \text{characteristic vibrational temperature, \textdegree K} \\
\text{c} & \quad \text{cold flow (arc off)} \\
\text{h} & \quad \text{hot flow (arc on)} \\
\text{s} & \quad \text{sonic throat} \\
\text{l} & \quad \text{free stream} \\
\text{t} & \quad \text{stagnation conditions}
\end{align*}
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.)

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\[ \text{RESULTS AND DISCUSSION} \]

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The time difference was measured by cutting the picture
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 effec-
tive stagnation enthalpy is decreased by the amount tied up in the vibrational
mode. However, a close examination of the accuracy of the enthalpy measure-
ments 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 ($\pm 10$ percent) as reported in
reference 10. Experimental values of vibrational temperature were not available
above $4.299 \times 10^6$ 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 deter-
mine the time separation of a luminous region of gas and the separation dis-
tance 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 7.23 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 inde-
dependently. 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 repre-
senting 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 stagna-
tion 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.
REFERENCES


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.
Figure 5.— Schematic of pulse emitter follower.
Figure 6.— Typical oscilloscope traces of output of photomultipliers. Sweep from left to right. Scope gain on each channel is 0.5 V/cm.
Figure 7. - Variation of velocity with total stagnation enthalpy.

\[ h_t = \frac{V_t^2 \times 0.500}{0.969} \]

\[ h_t + 116 \times 10^3 \text{ J/kg} \]
Figure 8.- Comparison of enthalpy determined by sonic-throat equation and measured velocity.
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