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PERFORMANCE OF A MASS-FLUX PROBE IN A MACH 3 STREAM

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16. Abstract

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SUMMARY

The characteristics of two similar (0.23-cm-diam inlet) mass-flux probes in a Mach 3 gas stream with a nominal Reynolds number per meter of 5×10^8 are presented. Both probes agreed with the calculated mass flux of the gas stream to within 1 percent. The major source of error in mass-flux determination for the probe size used was due to uncertainty in the geometric inlet area.

The probe is insensitive to angle of attack up to about 20° if the capture area is based on the projected geometric capture area of the probe. When used as a total-pressure tube (aspiration off), the probe is insensitive to angle of attack up to about 25°.

INTRODUCTION

Experimental work in fluid mechanics usually involves measurements of total pressure, static pressure, total or static temperature (or enthalpy), and flow direction. Many techniques and devices are available to make these measurements in low-temperature, low-velocity streams. However, for more severe environments such as high-temperature, supersonic flows, investigators are continuously searching for new methods of measuring stream parameters which would help to more thoroughly describe the flow field.

One such device, in which there has been a renewed interest, is the use of a probe to measure the mass flow rate per unit area ρV of various streams. Figure 1 is a schematic drawing of a mass-flux probe system. The probe consists essentially of a tube with a supersonic inlet pointed into the gas stream. Sufficient pressure drop must be provided across the inlet to "swallow" the shock and ingest the stream flow tube. The mass flow rate through the probe is then determined at a mass-flow-rate measuring station. The mass flow rate per unit area ρV can then be determined with knowledge of the cross-sectional area of the stream tube entering the probe inlet. The probe may also serve as a pitot tube when the system valve is closed, and pressure sensed in the usual manner.

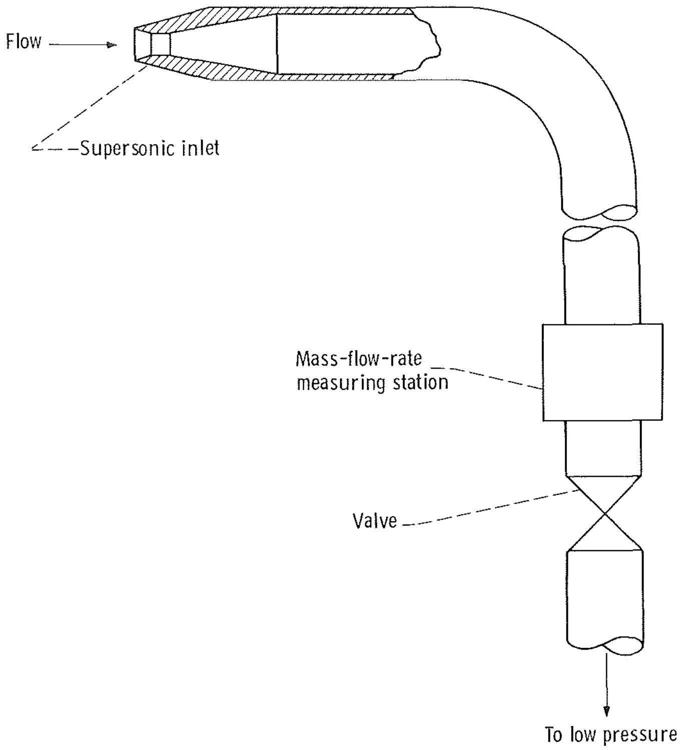


Figure 1. - Mass-flux-probe system.

Such a mass-flux probe can be applied to stream-profile surveys of arc tunnels, to combustion studies in advanced turbojet and ramjet engines, and to mass-flow-ratio determination in inlet tests. Some advantages of such a device are

(1) The real-gas effects are small.

(2) It is useful for mass-weighting a temperature profile to obtain enthalpy distribution.

(3) Separate quantities ρ and V can be obtained when it is used in conjunction with, or alternately, as a total-pressure probe.

The principal problem in using a mass-flux probe arises from the fact that the effective capture area is rarely equal to the actual geometric capture area. The former area depends both on probe design and on stream conditions. Most of the efforts of previous investigators have been directed toward an examination of the ratio of effective capture area to geometric capture area.

One of the earliest uses of the mass-flux probe was in the studies of boundary layers of supersonic flows, carried on by Coles (ref. 1) in the early 1950's. Measurements made with a small, sharp-lipped-inlet probe were used primarily to calculate a temperature profile rather than to assume a theoretical temperature profile in the boundary layer. The results encouraged Liccini (ref. 2) in 1955 to apply this experimental method to a Mach 5 to 6.8 stream. The results of his work with rectangular and circular inlet geometries indicated errors up to 9 percent in the capture-area ratio over the Reynolds number range surveyed. Both investigators (refs. 1 and 2) indicated that the ratio of effective capture area to geometric capture area decreased with decreasing Reynolds number. Coles (ref. 1) hypothesized that this effect may have been caused by the presence of viscous effects at the lower Reynolds number or by fluctuations in flow direction in the turbulent boundary layer.

Stalker (ref. 3) applied a mass-flux probe and total-head tube to deduce the velocity of a Mach 4 to 5.5 high-temperature (1800 to 3200 K) shock tunnel facility. Disagreements between this velocity and the calculated nozzle velocity based on equilibrium flow ranged up to 15 percent.

Van Camp et al., and Kroutil (refs. 4 and 5) used mass-flux probes to determine the exit-flow profiles of two arc-jet nozzles. The integrated mass flow rate thus obtained ranged from 80 to 97 percent of the mass flow rate determined with an orifice in the pipe supplying gas to the tunnel. The effective probe capture area deduced from this comparison is uncertain because arc-jet nozzle area was not clearly defined because of boundary-layer effects.

Huber (ref. 6) in 1966 presented a study of design considerations for mass-flux probes and other sensors for high-temperature applications. Considerations of inlet geometries, cooling passage configurations, cooling requirements, etc., are included in his paper. He also contends that viscous effects on some inlet shapes could cause the effective capture area to be different from the geometric capture area.

Anderson and Sheldahl (ref. 7) used a mass-flux probe having a 2.5-centimeter-diameter inlet in a low-density plasma and report that radial surveys of local mass flux captured by the probe agreed with an independent measurement of the total mass flow through their system.

Crites and Czysz (ref. 8) in 1968 reported on several miniature mass-flux probes (0.15- and 0.39-cm-diam inlets) used in a hypersonic impulse tunnel. The characteristics of the probe inlets were determined by comparing the stream velocity obtained from measurements with the mass-flux probe and a total-head tube, with the velocity obtained from measurements with a stagnation-point-heat-flux gage and a total-head tube. It is stated that, for small inlets in hypersonic flow conditions characteristic of hotshot tunnels, lip geometries may cause deviations in the capture area from the geometric inlet area of as much as 30 percent. This deviation, at the lower Reynolds number, is in the opposite direction from that reported by references 1 and 2. It is also reported that use of a simple double-bevel lip with Reynolds number per meter greater than 1.5 million will insure that the capture area and geometric area are equal to within 5 to 8 percent. The problem of an inlet lip operating in a rarefied-flow regime is also discussed.

In a previous publication by the present authors (ref. 9), the accuracy of a mass-flux probe system using two inlet designs (0.70 cm diam) was determined by exposing them to a well-defined Mach 2.5 stream. One inlet was sharp-lipped and had both the internal and external lip surfaces beveled at 15°. A second inlet, which had only an external 15° bevel, was initially sharp and then was progressively blunted to various degrees. This single-beveled inlet had an effective capture area up to 4 percent greater than the geometric capture areas, while the double-beveled sharp-lipped inlet gave perfect agreement within the accuracy of the experiment (1/2 percent).

In references 1 to 8 the mass-flux probes reported were developed for a particular application and were usually evaluated in the flow systems associated with that application. As a result, the reported accuracy of the mass-flux probe as a diagnostic tool has been obscured because of uncertainty in the flow conditions in which it was used. Reference 9 and the present work were undertaken to evaluate mass-flux probes in well-defined streams in order to have a better understanding of the accuracy of the instrument.

The present investigation is a continuation of the work presented in reference 9. A mass-flux probe system with a double-beveled, sharp-lipped inlet is used in a size (0.23 cm diam) which is more suitable for current propulsion experiments. The absolute accuracy in a well-defined gas stream is presented for both alined flow and for angles of attack up to 30°. The test gas was nitrogen at near room temperature, with a Mach number of 3, and a nominal Reynolds number per meter of 5×10^8.

APPARATUS AND TESTS

Nitrogen-Gas-Flow Apparatus

A schematic drawing of the test apparatus is shown in figure 2. Nitrogen gas supplied from a portable gas trailer was throttled from 160×10^5 newtons per square meter (N/m^2) (160 atm) to the desired operating pressure. Operating pressures in the plenum upstream of the free-jet nozzle varied from 40×10^5 N/m^2, which is the minimum to establish designed flow in the free-jet test section, to 62×10^5 N/m^2. The mass flow rate through the system was 0.5 kilogram per second (kg/sec) at the higher pressure level. The supersonic nozzle has an exit diameter of 1.3 centimeters (cm) and a throat-to-exit length of 4.2 cm. It was a contoured nozzle designed for an exit Mach number of 3.00. A 25-cm-entrance-diameter conical collector section attached to an exhaust system was used to collect the gas from the free-jet test section, at a station 70 cm downstream of the nozzle exit.

Figure 2 also shows, schematically, a mass-flux probe in the test section and its associated measuring system. A calibrated circular-arc critical-flow nozzle (0.37-cm-diam exit) was used to measure the mass flow rate through the probe. At a line pressure of 62×10^5 N/m^2, the mass flow rate through the critical-flow nozzle was 0.015 kg/sec.

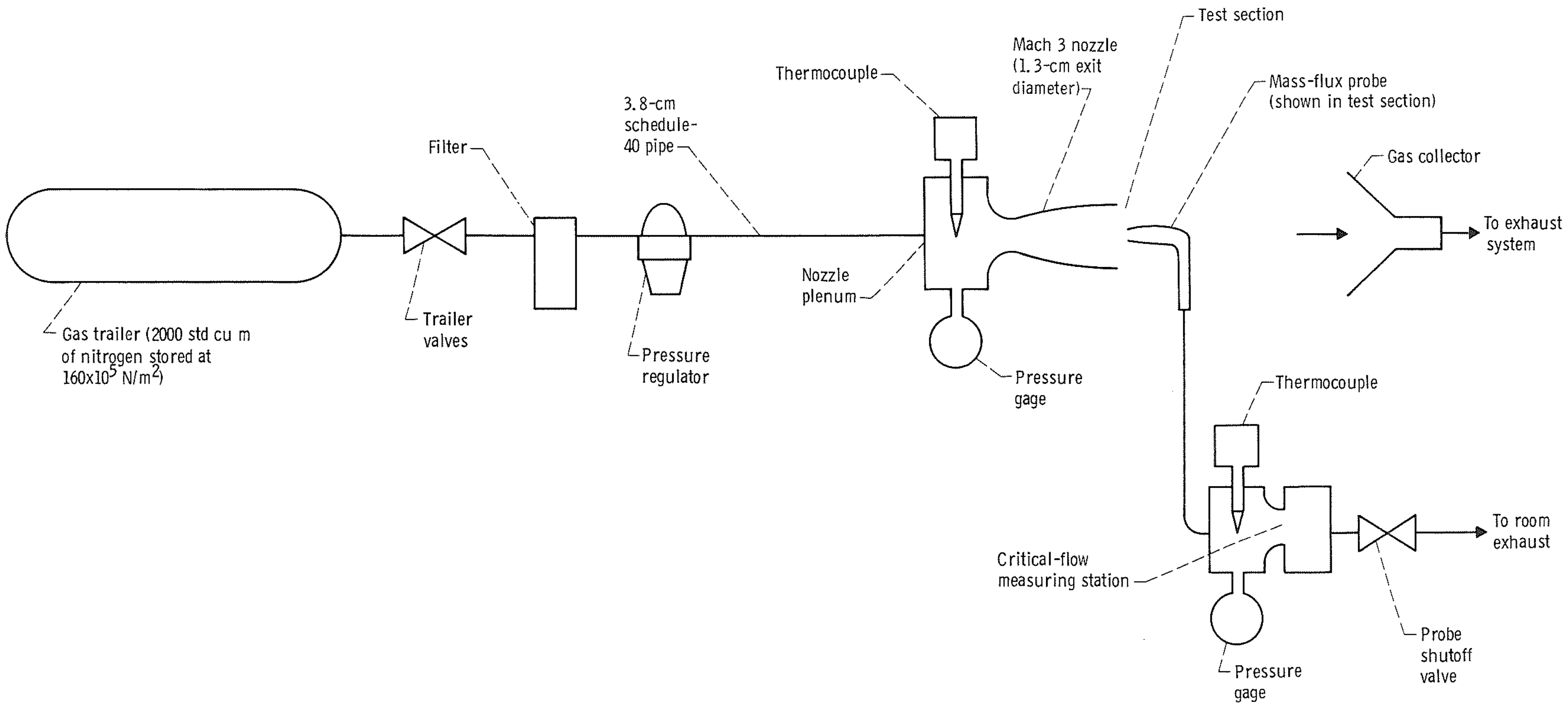


Figure 2. - Nitrogen-gas-flow apparatus with mass-flux-probe installation.

A valve downstream of the measuring nozzle can be closed to allow the mass-flux probe to be operated as total-head tube when required.

Thermocouples were used to measure gas temperatures. System pressures were measured with precision Bourdon-tube gages having direct-reading dials.

The first 5 minutes of any given run were used to stabilize the system temperature. Thereafter, flow conditions could be changed, with stabilization occurring in less than 1 minute.

Test-Section Survey Sensors

In order to utilize the Mach 3 free jet to determine the performance of mass-flux probes, the test-section flow conditions first had to be defined. Measurements were therefore made with a set of test-section survey sensors to determine these flow conditions. The set of survey sensors (fig. 3) consists of a total-pressure tube, a static-pressure wedge, and a high-recovery thermocouple. The sensors are stainless steel, using silver solder in construction. The support for each probe consists of an 11° half-angle wedge. The total-pressure tube is square-ended with an outside diameter at the tip of 0.076 cm and an inside diameter of 0.061 cm. The static-pressure wedge has a span of 0.51 cm, a base thickness of 0.24 cm, and a half angle of 9.7°. One static-pressure tap (0.037 cm diam) is located 0.46 cm from the leading edge on both wedge surfaces. This tap location is slightly upstream of the intersection of shock waves, which could originate at the wedge corners, as a result of fabrication imperfections, for a stream Mach number of 3. At the high pressures and velocities of the present tests, real-gas effects of flow calculations are not negligible. Therefore, a wedge instead of a cone was used for static-pressure measurements, because it is easier to calculate real-gas effects for the wedge than for the cone. The thermocouple consists of a

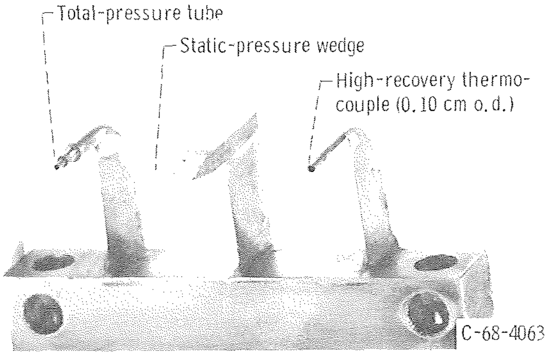


Figure 3. - Test-section survey sensors.

0.076-cm-diameter swaged assembly with 0.013 cm Chromel-Alumel wire. A single 0.10-cm-diameter shield encloses the thermocouple. Rectangular slots in the shield, adjacent to the base of the thermocouple wire, allow a continuous flow of gas past the thermocouple junction. The ratio of exit-slot area to shield inlet area is 1.5.

The survey probes were used to establish the flow conditions and profiles at the exit of the free-jet nozzle. While plenum conditions upstream of the nozzle were held constant, the survey sensor set was moved across the nozzle exit, and, at the same time, the pressure and temperature profiles were plotted on recorders. A complete survey took approximately 10 minutes.

Mass-Flux Probes

Stainless-steel mass-flux probe. - Figure 4 shows the stainless-steel mass-flux probe. It consists of a double-beveled inlet (0.234 cm diam) (fig. 5(a)) followed by a

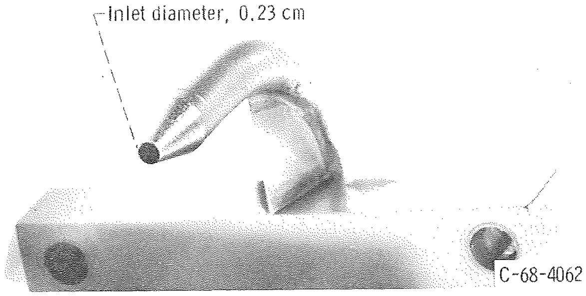
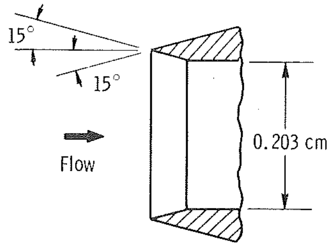
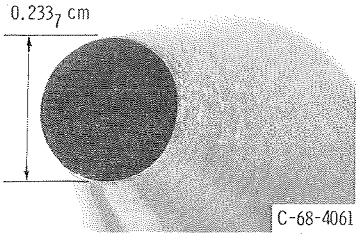


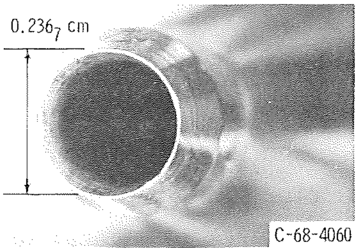
Figure 4. - Stainless-steel mass-flux probe.



(a) Cross section of inlets.



(b) Stainless-steel inlet.



(c) Platinum inlet.

Figure 5. - Details of mass-flux-probe inlets.

0.203-cm-diameter straight section 0.20 cm long, followed by a 10° half-angle diffuser which expands to the 0.56-cm-inside-diameter tube. The inlet (fig. 5(b)) has a lip thickness of approximately 0.004 cm. An 18° half-angle wedge is faired into the front of the aspirating tube for additional support.

The ratio of inlet area to throat area for the probe is 1.33. This contraction ratio will theoretically allow the probe to pass the shock and swallow the flow down to a Mach number of 2.6. However, once the shock has been swallowed, the stream Mach number can, for this probe, be reduced to about 2 before the shock is expelled.

During the testing at zero angle of attack, the probe inlet was fixed and located along the axial centerline of the test section. For tests at nonzero angle of attack, the probe was rotated in such a manner that the center of the inlet remained in the same position when the angle of attack was varied up to 30°.

Platinum mass-flux probe. - The stainless-steel mass-flux probe was actually a prototype of a mass-flux probe which, mounted along with other survey sensors, was to be used in a high-temperature application. Because of the intended Mach 3, 1600 K application, this assembly (fig. 6) used platinum and platinum - 13-percent rhodium for the probe and sensors, and tantalum for the supporting struts.

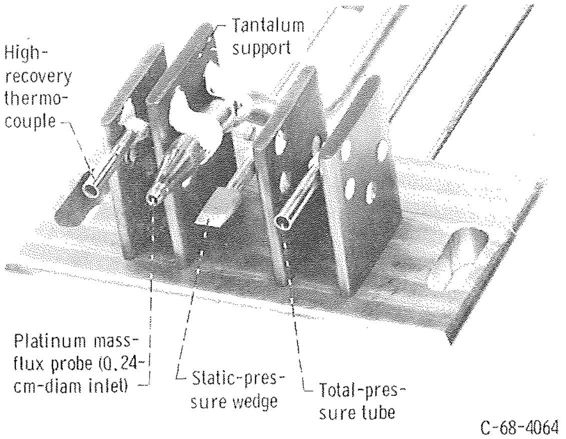


Figure 6. - Platinum mass-flux probe and associated survey sensors.

The internal geometry of the platinum mass-flux probe is the same as that of the stainless-steel probe with two exceptions. There is a small difference in inlet diameter (fig. 5(c)). And the 10° half-angle diffuser expands to a slightly smaller (0.53 cm) inside-diameter tube, because of the nominal tube size available.

The static-pressure wedge dimensions are the same as those of the stainless-steel survey sensor set previously described. The total-pressure tube and shielded thermocouple were physically larger than the equivalent sensors of the survey set, since size requirements were not so demanding for the high-temperature application.

Each probe of the platinum assembly was, in turn, fixed in the center of the test section for individual runs. The indications of the thermocouple and the pressure sensors provided a comparison of centerline flow conditions with those determined by the survey set previously used to calibrate the tunnel.

ACCURACY

Comparison of the mass flow rates per unit area as obtained from the mass-flux-probe system to those calculated from stream parameters is the primary evaluation criterion in the experiment. Mass flow rate per unit area can be arrived at by three methods. Two of these methods involve stream parameters. First, the mass flow rate per unit area may be calculated from plenum pressure, plenum temperature, and stream total-pressure-tube indication. Second, it can also be calculated from total-pressure-tube indication, static-pressure-wedge indication, and total-temperature-probe indication. Finally, the mass flux can be calculated from the mass-flux-probe system parameters. These parameters are the critical-flow-nozzle upstream pressure and temperature, the nozzle discharge coefficient, and the mass-flux-probe inlet area. The performance of the mass-flux probe is based on the comparison of the mass flow rate per unit area as calculated from mass-flux-probe system parameters with those calculated from the two methods using stream parameters.

The following is an estimation of the limit of error of measurements associated with the experiments, in percent of the measured value. The equations used in this error

Measurement	Error, percent
Stream parameters:	
Plenum pressure	0.24
Plenum temperature	.05
Total-pressure-tube indication	.24
Static-pressure-wedge indication	.31
Total-temperature-probe indication	.05
Mass-flux probe system parameters:	
Critical-flow nozzle upstream pressure	.16
Critical-flow nozzle upstream temperature	.05
Critical-flow nozzle discharge coefficient	.30
Mass-flux-probe inlet area	.85
Thermodynamic relations:	
Uncertainty in ρV because of uncertainty in thermodynamic relations	.20

analysis are not presented since they generally were not in closed form, and the scope of this report does not warrant detail of the computer program used.

Using these values in the root-sum squares formula, the fractional error expressed as a percentage error for the three methods of determining the mass flux are as follows:

(1) From plenum pressure, plenum temperature, and total-pressure-tube indication, 0.33

(2) From total-pressure-tube indication, static-pressure-wedge indication, and total-temperature-probe indication, 0.28

(3) From mass-flux-probe system parameters, 0.92

From the listings of the various errors, it can be seen that the primary source of error is in the uncertainty of the mass-flux-probe geometric inlet area. The uncertainty in the measurement of inlet diameter is primarily due to the mechanical imperfection of the inlet lip. For the probe sizes shown in figure 5, an uncertainty of 0.001 cm in inlet diameter creates an uncertainty of 0.85 percent in inlet area.

It should be pointed out that the second of the two stream methods of calculating mass flow rate per unit area is not completely independent of the first. The first method was used in determining the recovery factor of the test-section temperature probe. The total temperature behind the normal shock wave in front of the thermocouple can then be calculated from the thermocouple indication and its recovery factor.

RESULTS AND DISCUSSION

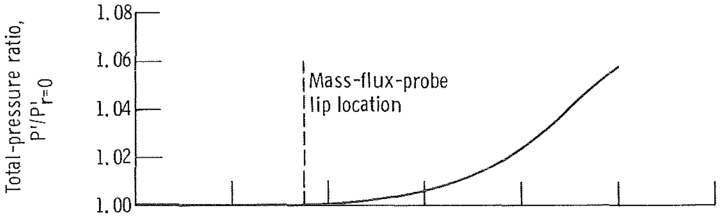
Test-Section Flow Conditions

The nozzle used to generate the supersonic free jet was designed for an exit Mach number of 3.00. The Mach number calculated from the measured plenum temperature and the ratio of test-section-centerline indicated total pressure to plenum pressure was 3.01, which is within 0.3 percent of the design valve. This agrees closely with a 0.2 percent limit of error for the calculated Mach number using the errors previously quoted for stream parameters.

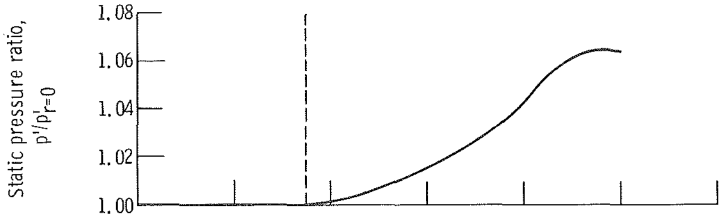
It should be noted that the calculation relating pressure ratio to Mach number is a favorable one, in that, at a Mach number of 3, a 1 percent change in the pressure ratio results in only a 0.4 percent change in Mach number.

In order to verify that the Mach 3 nozzle generated a suitable flat profile for probe testing, pressure and temperature surveys were performed with the test-section survey probes.

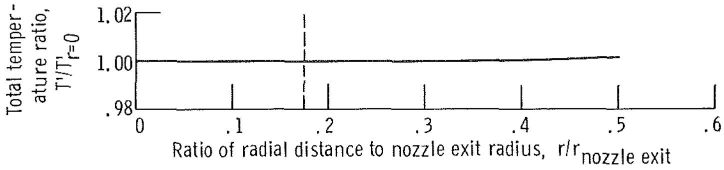
The pressure and temperature profiles in the test section at the exit of the Mach 3 nozzle are shown in figure 7. In figure 7(a), it is seen that the ratio of indicated total



(a) Total pressure.



(b) Static pressure.



(c) Total temperature.

Figure 7. - Pressure and temperature profiles at Mach 3 nozzle exit. Plenum pressure, 63×10^5 N/m^2; plenum temperature, 270 K. Ordinate scales are ratios of indicated values to centerline values.

pressure P' to the centerline value $P'_{r=0}$ is constant over the portion of the test section used by the mass-flux probe. The same result is true for the indicated static pressure p' (fig. 7(b)) and the indicated total temperature T' (fig. 7(c)). Since the inlet of the mass-flux probe remained within a radius ratio $r/r_{nozzle\ exit}$ of less than 0.2 for all of the tests, the probe was exposed to a region of constant mass flow rate per unit area. The mass flow rate per unit area for the stream could then be calculated without the necessity of integrating profiles.

Mass-Flux-Probe Performance

Table I shows the ratio of the measured mass flow rate of the probe $\dot{m}'$ as obtained at the measuring station, to the calculated mass flow rate based on the stream measure ments ρV and geometric capture area A_g. This ratio is also the capture-area ratio; that is, the ratio of effective capture area A_e to measured or geometric capture area:

$$\frac{\dot{m}'}{\rho V A_g} = \frac{\dot{m}'}{\dot{m}_g} = \frac{A_e}{A_g} \qquad (1)$$

TABLE I. - TEST RESULTS SHOWING RATIO OF MEASURED

TO CALCULATED MASS FLOW RATES

[Pressure range, 42×10^5 to 63×10^5 N/m^2, Reynolds number range, 4×10^8 to 6×10^8, per meter.]

Mass-flux probe	Geometric capture diameter, D_g, cm	Mass-flow-rate ratio, $\dot{m}'/\dot{m}_g$
Stainless steel	[a]0.233_7	[a,b]1.01_2
Platinum	[a]$.236_7$	[a,c]1.01_1

[a] Subscript digit indicates uncertainty as a significant digit.

[b] Average of seven data points ranging from 1.00_1 to 1.02_1.

[c] Average of six data points ranging from 1.00_7 to 1.01_5.

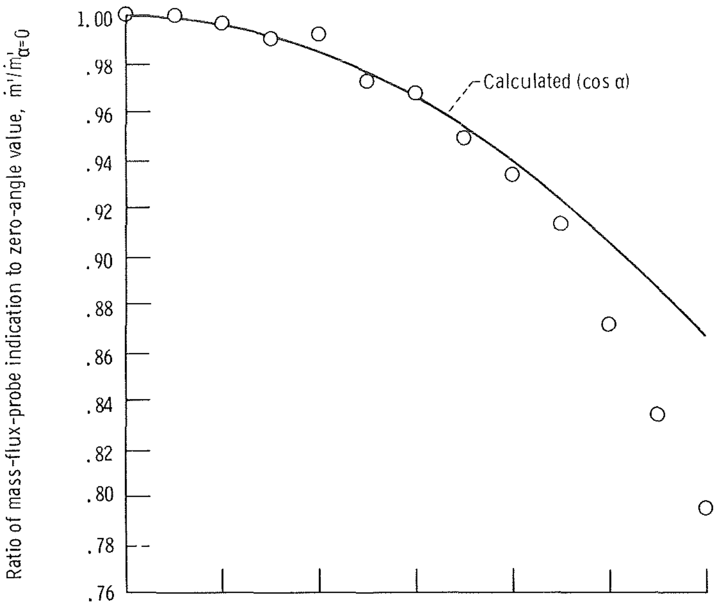
A value greater than 1 would indicate "super" capturing, and a value less than 1 would indicate spillage at the entrance. Both probes tested had a ratio of 1.01. This agreement between measured and predicted mass flux is about the same as the limit of error of the experiment. As stated previously, the major part of the 1 percent error is due to uncertainty in the geometric inlet area.

At the lower stream Reynolds number (4×10^8 per meter), the Reynolds number based on inlet diameter was 9×10^5, and was 1.5×10^4 based on lip thickness. These Reynolds numbers should be high enough for viscous effects to be negligible. Reference 1 reports viscous effects influencing the mass-flux-probe indication at Reynolds numbers based on probe height (ref. 1 probe has a rectangular inlet) below 1.5×10^3.

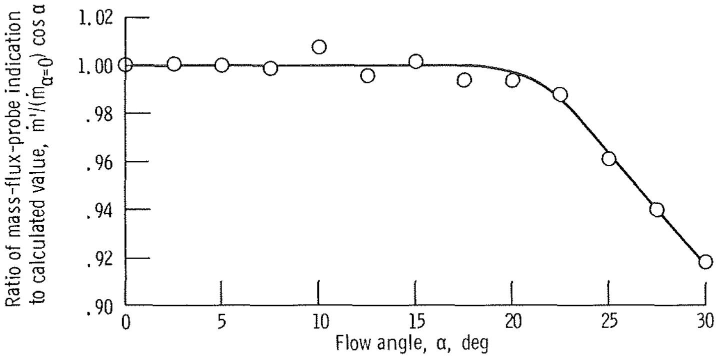
Figure 8(a) shows the effect of angle of attack on the performance of the stainless-steel mass-flux probe. The ordinate is the ratio of mass-flux-probe indication at angle of attack to the indication at zero angle. The experimental data are compared to the expected variation based on the change in projected geometric capture area with change in angle of attack α. If $\cos\alpha$ is included in the entrance-area calculation, the curve shown in figure 8(b) results. Here it is seen that when the changing projected geometric capture area is considered, the probe is insensitive to flow angle up to approximately 20°. Beyond 20°, the ratio decreases monotonically to about 0.92 at an angle of 30°. It is doubtful that the swallowed shock has been expelled even for the large angles because, if expulsion did occur, a step would be expected in the figure 8(b) curve.

One of the reasons for the favorable angle characteristics of the probe may be the fact that the projected capture area decreases as the flow angle increases. This decrease in projected capture area decreases the contraction ratio (inlet to throat area), which is a favorable condition for the shock to remain swallowed.

From figure 8(b), it is interesting to note that the mass-flux ratio begins to de-



(a) Comparison of measured and calculated values.



(b) Deviation of measured values from calculated values.

Figure 8. - Variation in mass-flux-probe indication with flow angle.

crease at an angle which is slightly larger than the 15° internal-bevel angle. If this flow-direction-angle characteristic is related to the internal-bevel angle, then, for applications where flow is incident at a nonzero angle, a probe design utilizing an internal bevel, rather than a straight inlet, would be advantageous. However, when this internal bevel is considered, a compromise must be made between flow-angle insensitivity and the lower Mach number limit which is a function of the probe contraction ratio.

In some applications, the mass-flux probe is also used as a total-pressure tube by shutting off the aspiration through the probe. Figure 9 shows the angle characteristics of the stainless-steel mass-flux probe when used as a total-pressure tube. The ordinate is the indicated total-pressure error due to flow angle $(P' - P'_{\alpha=0})$, expressed in terms

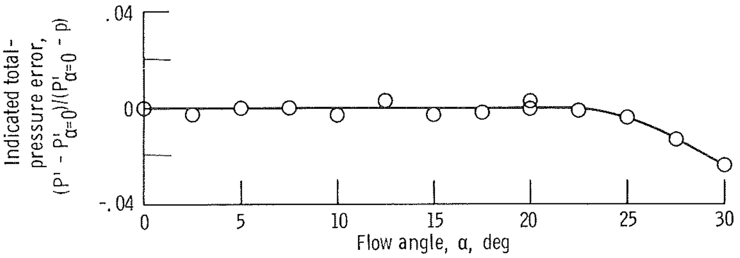


Figure 9. - Variation in indicated total-pressure error with flow angle for mass-flux probe with aspiration shut off.

of indicated impact pressure $(P'_{\alpha=0} - p)$. The figure shows an error of 1 percent at a flow angle of 27°. This compares favorably with a value of 29° for a similar geometry reported in reference 10.

It is interesting to note that, while obtaining the angle-of-attack data, the flow through the probe was stopped and started without difficulty while the probe was at each of the angle-of-attack settings, thus showing restart capability under angle-of-attack conditions.

CONCLUSIONS

This report has presented some characteristics of two 0.23-cm-diameter-inlet mass-flux probes in a Mach 3 gas stream with a nominal Reynolds number per meter of 5×10^{8}. The important findings are as follows:

1. Both probes tested agreed with the calculated mass flux of the gas stream to within the limit of error of the experiment (about 1 percent).

2. The major source of error in mass-flux determination for the probe size used was the uncertainty of geometric inlet area.

3. The mass-flux probe reported herein is insensitive to angle of attack up to about 20° if the capture area is based on the projected frontal area of the probe. Beyond 20°, the mass-flux ratio decreases monotonically to about 0.9 at an angle of 30°.

4. When used as a total-pressure tube (aspiration off), the probe is insensitive to angle of attack up to about 25°.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, September 18, 1969,
720-03.

REFERENCES

1. Coles, Donald: Measurements in the Boundary Layer on a Smooth Flat Plate in Supersonic Flow. II. Instrumentation and Experimental Techniques at the Jet Propulsion Laboratory. Rep. No. 20-70, Jet Propulsion Lab., California Inst. Tech., June 1, 1953.
2. Liccini, L. L.: N.O.L. Hypersonic Tunnel No. 4 Results VIII: Development and Calibration of Mass Flow Probes in Hypersonic Flow. NAVORD Rep. 4078, Naval Ordnance Lab., Nov. 1, 1955.
3. Stalker, R. J.: A Mass Flow Probe for Use in Short Duration Hypersonic Flows. The High Temperature Aspects of Hypersonic Flow. W. C. Nelson, ed., AGARDograph-68, Macmillan Co., 1964, pp. 271-280.
4. Van Camp, W. M., et al.: Study of Arc-Jet Propulsion Devices. Rep. No. E368, McDonnell Aircraft Corp. (NASA CR-54691), Mar. 1966.
5. Kroutil, Joseph C.: Mass Flux and Impact Pressure Probes for Use in Arcjet Exhausts. AIAA J., vol. 5, no. 8, Aug. 1967, pp. 1503-1504.
6. Huber, Franz J. A.: Probes for Measuring Mass Flux, Stagnation Point Heating, and Total Enthalpy of High Temperature Hypersonic Gas Flows. Paper No. 66-750, AIAA, Sept. 1966.
7. Anderson, Lewis A.; and Sheldahl, Robert E.: Flow-Swallowing Enthalpy Probes in Low-Density Plasma Streams. Paper 68-390, AIAA, Apr. 1968.
8. Crites, Roger C.; and Czysz, Paul: Inlet and Test Section Diagnostics Using a Miniature Mass Flow Probe in a Hypersonic Impulse Tunnel. Paper 68-389, AIAA, Apr. 1968.
9. Krause, Lloyd N.; and Glawe, George E.: Preliminary Tests with Mass Flux Probe in Supersonic Stream. NASA TM X-1524, 1968.
10. Gracey, William; Coletti, Donald E.; and Russell, Walter R.: Wind-Tunnel Investigation of a Number of Total-Pressure Tubes at High Angles of Attack. NACA TN 2261, 1951.

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