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A REVIEW OF THE MASS-FLUX PROBE

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The mass-flux probe is used to measure the mass flow rate
per unit cross-sectional area of supersonic streams. The
probe consists of an aspirating tube with a supersonic inlet
which "swallows" the shock and ingests the stream flow tube.
The mass flow rate per unit area of the stream is determined
by measuring the flow rate of ingested gas through the probe
at a convenient downstream station, and then dividing by the
probe's inlet area. The instrument has been applied to studies
of supersonic boundary layers, and of high-enthalpy, high-
temperature gas flows, such as may occur in hypersonic flight.
This review presents a description of the instrument, a histor-
ical review of work reported in the literature, and a discus-
sion of the factors influencing performance. These factors in-
clude probe inlet geometry, angle of attack, and Reynolds and
Mach number effects.

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 supersonic streams, where ρ is density and V is linear velocity. This probe finds particular application in streams when it is difficult to measure temperature or static pressure independently, because for these cases, a measurement of one of these quantities, along with a measurement of mass flux and total pressure, allows determination of the other quantity. 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; that is, the linear velocity into the mouth will be the same as the linear velocity of the free stream. The mass flow rate through the probe is then determined at a mass-flow-rate measuring station, S. 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 total pressure is measured in a conventional manner.

Such a mass-flux probe has been applied to stream-profile surveys of arc jets[1,2,3,4,5,6,7] and to mass-flow-ratio determination in inlet tests;[8] it is also applicable to combustion studies in advanced turbojet and ramjet engines. 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.

A review of the early work involving mass-flux probes shows that most of the units were developed for a particular application, and attempts were made to evaluate them in the flow systems associated with this application. As a result, the accuracy of the probes and their usefulness as a reliable diagnostic tool was obscured by uncertainties in the flow conditions to which they were exposed. More recent work has involved studies of potential inaccuracies and also has indicated limits in applicability. This has led to more definitive experiments using well-defined flow fields and calibration standards to evaluate both components and overall systems.

FACTORS AFFECTING PROBE PERFORMANCE AND OPERATION

Flow Capture

Inlet Contraction Ratio

In the correct operation of the probe with adequate aspiration, the shock wave, that would otherwise exist in front of the probe with inadequate or no aspiration, is swallowed; consequently, the flow into the inlet is supersonic. For an ideal inlet, the probe is then capturing a stream tube of area, A_e, which is equal to A_g (Fig. 1). In this mode of operation, a normal shock wave will exist in the diffuser downstream of the inlet. The lowest value M_{min} of the stream Mach number at which swallowing will occur depends on the value of contraction ratio, which is the ratio of minimum area A_{th} inside the inlet to the geometric inlet area, A_g. Figure 2 shows the variation in minimum Mach number with contraction ratio, for isentropic flow. One study[9] treats the nonideal internal flow in the probe and shows that M_{min} increases with internal friction. For a high temperature gas, M_{min} would also increase if A_{th}/A_g were reduced by differential thermal expansion between the inlet lip and throat. On the other hand, M_{min} would be decreased by the cooling of the ingested gas which would increase its density in the throat.

Once flow is established in the probe, the stream Mach number can be decreased beyond the minimum Mach number for swallowing the supersonic flow, as shown by the shock expulsion curve of Fig. 2. This curve is based on the existence of sonic velocity at the minimum-area section inside the probe, which is the condition for shock expulsion.

This "hysteresis" effect is an advantage in surveying streams with Mach
number gradients, in that the probe can be used at lower Mach numbers
than that required for starting the supersonic flow.

Aspiration Requirements

Back pressure. The change in total-pressure level within the probe
with variation in aspiration is illustrated in Fig. 3. A schematic draw-
ing of the probe system is shown in the upper portion of the figure, with
a bow wave standing in front of the inlet (nonswallowed condition). The
lower portion shows the variation in total pressure p_{tn} upstream of the
measuring station as the aspiration is varied through the probe. With
the shut-off valve closed, p_{tn} equals the pressure p_{t2} behind the
normal shock in front of the inlet. As the valve opens, p_{tn} becomes
less than p_{t2} by the amount Δp_{tf} of the internal friction in the flow
passage between the inlet and the flow measuring station. As the valve
is further opened, p_{tn} will drop suddenly as the shock wave is swallowed.
Therefore, in order to swallow the shock, the maximum permissible value
of p_{tn} is $(p_{t2} - \Delta p_{tf})$. Calculations of Δp_{tf} for high-temperature
applications should include the effects of heat transfer and of any heat
exchangers within the flow passage.

If the flow measuring station uses a sonic nozzle, p_{tn} will drop
to some value and remain fixed regardless of how low the pressure down-
stream of the nozzle throat becomes as the valve continues to open.

Heat exchanger. In high-temperature flows, the captured gas must
be cooled to facilitate the flow rate measurement at the measuring sta-
tion. Since the main portion of the probe shell is normally cooled with

water flowing through concentric tubes, the simplest method is to pro-
vide sufficient probe length to insure adequate conditions at the meas-
uring station. Examples of this method are given in two studies.[2,7]
For cases imposing tubing-length restrictions, a heat exchanger can be
placed within the aspiration tube,[9] or at the end of the tube immediately
upstream of the measuring station.[6]

Probes designed for short-duration, high-temperature flows[8,10,11,12]
($\sim$ 10 ms) require a storage-type heat exchanger such as shown schematic-
ally in Fig. 4. The exchanger consists of a porous matrix of a material
which is initially at ambient temperature and causes a continued reduc-
tion in the temperature of the gas as it passes through. This type of
mass-flux probe has the inlet, heat exchanger, and measuring station in
a compact arrangement within the probe head.

Subsonic Capability

The mass-flux probe in its simplest form requires a supersonic
stream; it is advantageous for the Mach number to be high. The probe
has not been applied to a subsonic stream to date. To do so, a method
would be required to sense when the probe is capturing the stream tube
as the aspiration through the probe is adjusted. Possibly, the pres-
sure at an internal pressure tap near the inlet lip could be compared
with stream static pressure, and the aspiration adjusted accordingly.
Such increase in complexity of probe design and use limits the probe's
usefulness in subsonic flow.

Definition of Capture Area

Capture Area

Referring to Fig. 1, the stream mass flux ρV may be obtained by simply dividing the measured mass flow-rate of the probe $\dot{m}$ as obtained at the measuring station, by a suitable capture area. For the ideal case, using a slender, sharp-lipped inlet, this area would be the geometric capture area A_g. For a rounded lip A_g is taken as the area of the circle through the leading edge (stagnation line) of the lip. Because of the uncertainty in the location of the stagnation line at the lip of a practical inlet (i.e., one whose lip thickness is not negligibly small compared to the inlet diameter), an effective capture area A_e will yield a more accurate value of ρV. A_e is obtained by calibrating the mass flux probe in a supersonic stream of known ρV. The ratio A_e/A_g can be used as a figure-of merit for the inlet. A value of A_e/A_g greater than unity would indicate "super" capturing, and a value less than unity would indicate spillage at the entrance.

Shape, Size, and Bluntness

Both circular and rectangular openings have been used in mass-flux-probe inlets. The round opening has the advantage that it is simple to build. The rectangular opening, although more difficult to construct, gives a greater mass flow rate through the measuring station for a given height of the opening. Rectangular openings have been used in boundary layer surveys[13] with the minor dimension as small as 0.2 mm. Probes with round openings have varied in inlet diameter from 0.8 to 25 mm.

There are several reasons for making the opening of the probe large. First, if the frontal area associated with the lip thickness is small compared to the total area of the inlet opening, the uncertainty in capture area is reduced. Also, physical measurement of the dimensions of the opening becomes more accurate as the size increases. Finally, the accuracy in measuring the total flow rate at the measuring station normally gets better as the flow increases. On the other hand, the opening must be kept small enough to resolve the local distribution of ρV.

Since the lip of the inlet cannot be made perfectly sharp, the shock wave will be detached from the front of the lip by a small distance and the swallowed portion will become oblique around the lip. The detachment distance depends on the lip radius. Subsonic flow will exist behind the detached shock wave, along with a region of viscous flow. A recent paper[14] discusses the effects of the detached shock and of viscous flow on the location of the stagnation streamline, and concludes that a double-bevel inlet such as that shown in Fig. 5(a) produces the least uncertainty in stagnation-streamline location, because of the symmetrical flow pattern around such an inlet. One series of tests[8] on typical inlet shapes such as those shown in Fig. 5 showed that double-bevel inlets gave capture-area ratios closer to unity than the other designs.

In flows producing high stagnation-line heat transfer rates, blunting of the lip may be required to prevent leading-edge temperatures from becoming excessive. Studies[15] have been made on the effect of blunting a 7 mm diameter inlet of the type shown in Fig. 5(b). As the lip radius

was successively increased from 0.02 mm (sharp) to 0.28 mm, the capture

area ratio, A_e/A_g, stayed within the range of 1.01 to 1.04.

The heat transfer at the inlet lip for supersonic flow can be esti-

mated from the following approximation of an equation[16] for stagnation

point heat transfer

$$q_0 \cong \frac{4500 \sqrt{\rho_\infty} \; V_\infty^3}{\sqrt{R_0}}$$

where q_0 is the heat input at the stagnation line in watts/cm^2, ρ_∞ is

the gas density in gm/cm^3, V_∞ is free-stream gas velocity in km/sec,

and R_0 is lip radius in cm. (In this approximation, total enthalpy of

the gas stream is considered large compared to the enthalpy of the gas

at the temperature of the lip.) This equation can be used to estimate

the amount of blunting required in a particular high temperature appli-

cation. A calculation of this type has been made[15] for a hypersonic-

engine flight application.

Effects of Low Reynolds Number

For a sharp-lipped inlet, with shock attached to the leading edge,

the effective capture area would be equal to the geometric capture area.

However, for small inlets operating at low Re (Reynolds number), the

shock no longer is attached to the probe lip and the layer of gas be-

tween shock and lip could divert the stream flow, particularly for an

inlet lip that does not have equal internal- and external-bevel angles.

Several tests[8,13,17] have been performed on mass-flux probes with

flows at low Reynolds numbers. One result[8] showed that the effective

capture area was within ± 5 percent of the geometric capture area for

Re/m > 4×10^6.

In two other independent investigations[13,17] probes were operated over a range of Reynolds numbers; results showed that the ratio A_e/A_g was constant within 2 percent for $Re/m > 5 \times 10^6$ and decreased at lower values of Re/m.

Low Reynolds number may arise from low gas density rather than from high viscosity. Studies in rarefied gases may involve such a situation. Since we are dealing with flow about the inlet lip, it may be more appropriate to use lip thickness rather than inlet passage dimensions for the dimensional unit used to define probe Reynolds number. Many of the small probes reported in the literature have lip thicknesses of about 0.025 mm. Using this as a nominal value, then for a stream of 4×10^6 Re/m, the probe Reynolds number will be about 100. The previously cited test[8] where the effective capture area was within ± 5 percent of the geometric capture area, was performed in the slip flow region, and other applications[18] were made in free molecule flow with satisfactory results.

Angle of Attack Effects

A recent study[19] investigated the angle-of-attack effects of the inlet of Fig. 5(a) using a double bevel with a $15°$ half angle. The results are reproduced in Fig. 6. The ordinate of Fig. 6 is the ratio of mass-flux-probe indication at nonzero angle of attack to the indication at zero angle. The experimental data are compared to the expected cosine variation based on the change in projected geometric capture area, which becomes elliptical, with change in angle of attack α. When the

cosine correction is first made for the projected geometric capture area, the probe requires no further empirical correction at flow angles up to approximately 20°. It is doubtful that the swallowed shock has been expelled even at $\alpha > 20^{\circ}$ because, if expulsion did occur, a step would be expected in the graph.

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 increases the effective contraction ratio, which is a favorable condition for the shock to remain swallowed.

It is interesting to note that the mass-flux ratio begins to decrease 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.

It was also noted[19] that, while obtaining the angle-of-attack data, the flow through the probe was stopped and started without difficulty while the probe was at nonzero angle of attack, thus showing restart capability under nonzero angle-of-attack conditions.

It's concievable that the angle-of-attack characteristics of the probe can be used to start the inlet at a lower Mach number than the

minimum Mach number for zero angle. If this is true, the useful Mach
number range of the probe can be increased by designing the probe with
a marginal contraction ratio, and then assuring the start of internal
supersonic flow by yawing the probe.

Internal Mass Flow Rate Measurement

The flow captured by the probe inlet is metered downstream at a
convenient measuring station. The metered flows of reported[3,19] appli-
cations have ranged from $1x10^{-7}$ to $1x10^{-2}$ kg/sec. These flow rates
were small because the area of interest was high-altitude supersonic
flight, where gas density was low. The measurement of such small mass
flow rates constitutes one of the major sources of error of the probe.
The accuracy of ρV measurement is directly proportional to the accu-
racy of flow rate measurement at the measuring station.

Several methods have been used to meter the flow rate. These
are

Sharp-edged orifice[15]

Venturi[6]

Sonic-flow nozzle[4,8,10,11,12,13,19]

Drag-body meter[3,20]

Pressure rise in known volume[13,17]

Only the last method is an absolute one; the other devices, for these
small flow rates, are usually calibrated by a technique such as the pres-
sure rise method. Each of these mass flow rate measuring methods has
shortcomings in the range of interest. The pressure-rise technique is
cumbersome and time consuming. It is not applicable when many flow rate

measurements are required such as in surveying a mass-flux gradient. The orifice, venturi, and sonic-flow nozzle may be operating at Reynolds number values in the hundreds, and, consequently, the discharge coefficient will be changing appreciably with flow rate. The pressure difference developed by the orifice or venturi may be very low (on the order of 100 N/m^2). The pressure loss associated with the sonic-flow nozzle increases the aspiration requirements. Because of the problems associated with measuring the low flow rates encountered when using the mass flux probe, a measurement with an error of less than 1 percent would be considered a very good measurement.

Of course, in any application at higher densities, several of the previously mentioned shortcomings would become less troublesome.

Total-Pressure Measurement

The primary function of a mass-flux probe is, of course, to determine the quantity ρV. However, by shutting off the flow through the probe, it can be used alternately as a total-head tube which, in a supersonic stream, measures the pressure behind a normal shock wave standing in front of the probe entrance. This indicated total pressure measurement is related to ρV^2. Thus, by obtaining a measurement of both ρV and ρV^2, the separate quantities ρ and V can be obtained.

The relationship between $p_{t,ind}/(\rho V^2)$ and free-stream Mach number is shown in Fig. 7. The calculations include real-gas effects; it can be seen that in the high Mach number range the value of ρV^2 is essentially constant and is very insensitive to real-gas effects. In application then, Mach number, pressure, temperature, and specific heat

ratios need not be known accurately to obtain a value of ρV^2, lying within the correlation band, to an uncertainty of 1 percent.

A mass-flux probe[19] was tested in nonaligned flow while operating as a total-head tube to determine its sensitivity to flow direction. This probe was found to measure p_{t2} accurately up to an angle of attack of about 20°, and had an error of 1 percent of indicated impact pressure at a flow angle of 27°. The results compared favorably with previous publications[21] describing total-pressure tube characteristics.

In some applications, an additional bonus can be gained from the probe in that it can be used to determine stream total enthalpy. Total enthalpy is equal to static enthalpy plus $V^2/2$. For the case of a high-Mach-number, high-enthalpy stream, the static enthalpy is small compared to total enthalpy. Therefore, total enthalpy can be determined reasonably well from V^2 without precise knowledge of the stream static enthalpy.

<div align="center">Response Rate</div>

There are two types of applications in which the time response of the mass-flux probe must be considered. One is the short-duration facility, such as a shock tunnel, in which the response time of a fixed probe must be very short (a few ms); and the other is the surveying application in which the response is important in determining maximum permissible probe traversing speed when surveying gradients.

One short-duration study[10] treated the problem analytically and also obtained experimental data with a probe such as that of Fig. 4. Two ways of reducing the response time are to make the probe smaller

(decreasing internal volume and flow nozzle throat area), and to increase the inlet area. If a thermocouple is incorporated in the measuring station, to be used along with the pressure gauge,[11,12] the thermocouple should have a time constant no greater than the pneumatic time constant of the probe.

The factors influencing the response of a system such as that of Fig. 1 are the same as above except that the internal volume is usually greater, and, consequently, the probe is slower in responding. In one application where surveys were made[3] the probe was moved at a constant traversing speed of 1.3 cm/sec in the main core of the flow, where the flow gradient was small; but the probe was advanced in discrete increments and then held stationary at each step in order to measure the steep gradient of the boundary layer.

ACCURACY

Two factors enter into the establishment of the accuracy of the mass-flux probe. The main factor is the uncertainty in the effective inlet area, and the other is the uncertainty in the mass flow rate measurement at the measuring station. The measuring station accuracy can be handled simply by calibrating the flow rate device against a primary standard such as the method of pressure rise in a known volume. Preferably, the calibration will cover the Reynolds number range of use. By such methods, the flow rate at the measuring station can be established to within a fractional part of one percent.

The most accurate means of determining the effective inlet area is to calibrate the assembly in a supersonic stream of known ρV. This is

usually a wind tunnel in which the ρV is determined from a measurement of: plenum pressure, plenum temperature, and total-pressure-tube indication; or total-pressure-tube indication, static-pressure-wedge indication, and total-temperature-probe indication. Such a calibration can also usually be made to within a fractional part of one percent. One investigation[19] presented values of typical errors associated with the above parameters.

Another, less accurate way of arriving at the effective inlet area has been used in arc jet studies. In this case the probe is moved across the test section and the mass-flux profile is integrated to obtain total flow rate. This measurement is compared with the total flow rate through the arc obtained by metering the incoming supply gases.[2,4,18] Such a comparison is accurate to only about 5 percent because of uncertainties associated with the flow rate gradients in the boundary layer of the facility.

In situations where a calibration of effective inlet area is impractical, the only recourse is to rely on a physical measurement of the geometric area and to assume a capture area ratio of unity. An uncertainty in diameter measurement of only 0.02 mm would give an uncertainty in geometric area of 1 percent for a sharp-lipped inlet of 4 mm diameter. If the inlet were 1 mm diameter, the uncertainty would increase to 5 percent.

The errors of the mass-flux probes reported in the references have ranged from 0 to 30 percent, the larger errors usually being

associated with the more indirect methods of establishing the density and velocity of the test gas.

HISTORICAL REVIEW

One of the earliest uses of the mass-flux probe was in the studies of boundary layers of supersonic flows, carried on by Coles[13] 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. To prove the feasability of the idea, initial tests were made with a probe having a sharp-lipped, circular cross-section inlet (1.5 mm diam). Measurements with the probe in a uniform Mach 2.2 stream agreed with predicted values to within one percent. The probes finally developed for the boundary layer measurements were much smaller in size and with rectangular inlet shapes (0.2x1.3 mm). Some of these probes used pieces of household razor blades to form double-bevel (14°) sharp-lipped, inlet walls. The results encouraged Liccini,[17] 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[13,17] indicated that the ratio of effective capture area to geometric capture area decreased with decreasing Reynolds number. Coles[13] 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.

Hill, et al[22] in 1956 undertook a study of measurements for high-speed wind tunnels and considered the combined use of the mass-flux probe along with either a total-head tube or a plenum pressure measurement to determine free-stream Mach number. He concluded, however, that for his application other methods of measuring Mach number were more desirable.

In 1962, Stalker[10] 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. For this short-duration flow application, Stalker had to develop a probe, and its related measuring system, with a very short response time. This was one of the earliest reported applications of the probe in a high-energy stream where the heat loads on the sharp-lipped inlet and on the inside walls had to be considered. In 1964, Chevallier[11] and Brown[12] built fast-response mass flux probes similar to that of Stalker. Brown reported that by using the mass-flux probe alternately as a pitot tube, he derived a velocity which agreed to within 10 percent of the velocity as calculated from plenum conditions.

Christensen, et al[1,2] used a single probe design to obtain both mass-flux and total enthalpy. These two measurements were combined to determine the heat transfer rate in a high-enthalpy arc jet. A calibration of the mass-flux probe made by comparing the integrated mass-flux survey with the input mass-flow of the arc jet showed agreement within 5 percent.

Parobek[3] in his report on arc jet instrumentation described a sharp-lipped, single-beveled mass-flux probe. Young[20] developed and patented a drag-body flow measuring system for the probe and application described by Parobek. A mass-flow-rate system using a volume-pressure rise method was used to calibrate the drag-body flow measuring system. Final utilization of this mass-flux probe and flow measuring system yielded an integrated mass flux with average agreement within 7 percent of the measurements obtained by the facility mass-flow measurement.

Huber[14] 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.

Van Camp et al[4] and Kroutil[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 facility. The effective probe capture area deduced from this comparison is uncertain since arc-jet nozzle area was not clearly defined because of boundary-layer effects.

Patrick and Schneiderman[18] used a probe to alternately measure both mass flux and pitot pressure in a low-density arc jet. The probe

had a circular opening, a sharp-lipped inlet with an external bevel, and a divergent internal passage. Determination of probe accuracy involved consideration of free molecule flow theory.

In 1967, Loth[9] presented an analysis of mass-flux probe considerations including flow and heat transfer at the inlet, response time, mass flow metering, and internal losses. He also presented a design for a combination probe to measure mass-flux and thrust of a supersonic stream and, from these measurements, to yield stream density and velocity.

Krause and Glawe[15] investigated the accuracy of a mass-flux probe using two inlet designs (7.0 mm diam) 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 area, while the double-beveled sharp-lipped inlet gave perfect agreement between effective and geometric areas within the accuracy of the experiment (1/2 percent). In a second investigation, Krause and Glawe[19] studied a mass-flux probe system with a double-beveled, sharp-lipped inlet which used an inlet opening size (2.3 mm diam) more suitable for current propulsion experiments. The absolute accuracy in a well-defined, Mach 3 gas stream is presented for both aligned flow and for angles of attack up to 30°. In aligned flow the mass flux measured by the probe agreed with tunnel mass flux to within 1 percent.

Anderson and Sheldahl[6] used a mass-flux probe having a 25 mm 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[8] in 1968 reported on several miniature mass flux probes (1.5 and 3.9 mm-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. Calibration of a probe rake in a stream operating down to a value of 4×10^6 Re/m yielded probe mass-flux measurement which agreed with stream mass flux to within 5 percent.

In 1969, Folck and Smith[7] used a probe to take mass-flux and pitot-pressure surveys in a 50 MW arc jet facility, along with measurements of stagnation-point heat transfer rate. These measurements allowed calculation of enthalpy profiles. The resultant value of the integrated enthalpy profile agreed with bulk enthalpy calculated from the facility heat balance to within 10 percent.

CONCLUDING REMARKS

This review has shown that the mass-flux probe is a useful diagnostic tool, especially in high Mach number, high enthalpy flows. It is simple to use and, essentially, has no real-gas effects. When used in

conjunction with, or alternately as a total-head tube, the stream density and velocity may be determined.

The two major sources of error arise from the uncertainty in the effective capture area of the inlet, and the uncertainty in the flow rate measurement downstream from the inlet. With care, the probe is capable of measuring the stream mass flux per unit area to within 1 percent.

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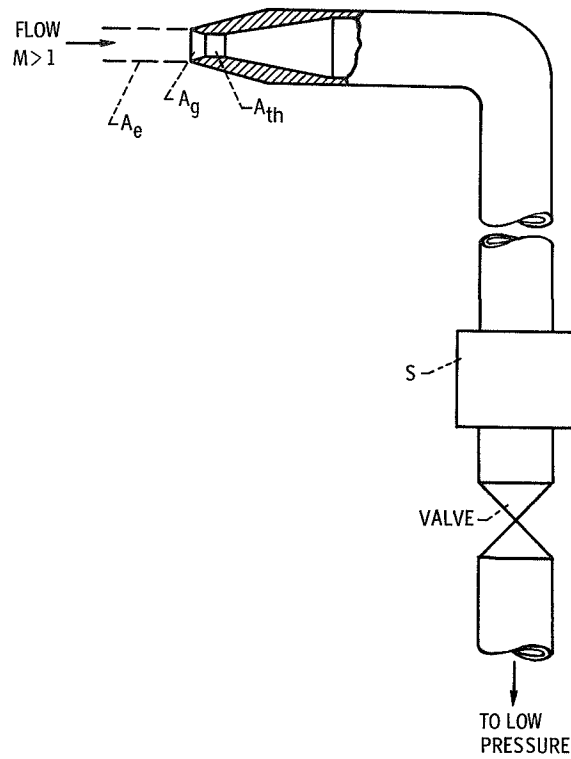
Figure 1. - Mass-flux-probe system. A_e - effective capture area of stream tube; A_g - geometric capture area; A_{th} - geometric throat area; S - mass-flow-rate measuring station.
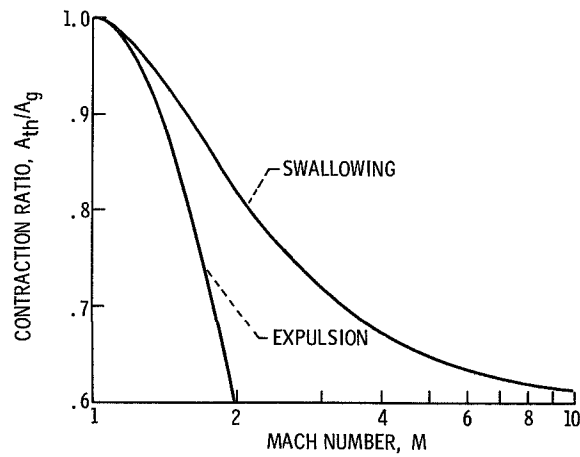
Figure 2. - Contraction ratio for a range of Mach numbers. Ratio of specific heats = 1.4.
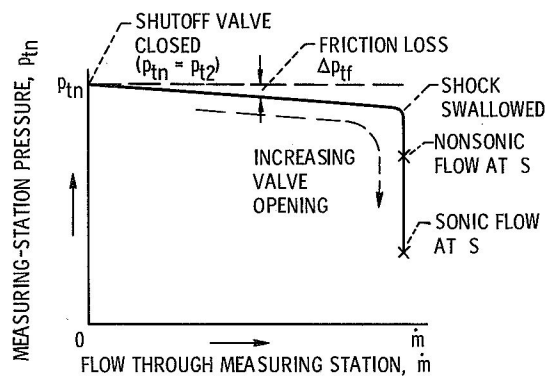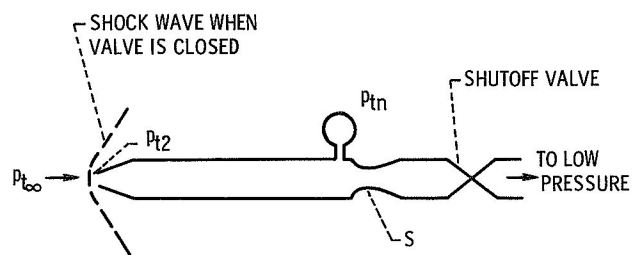
Figure 3. - Variation in measuring-station total pressure with flow rate through probe. Total pressures: $p_{t\infty}$, free stream; p_{t2}, downstream of normal shock; p_{tn}, at measuring station.
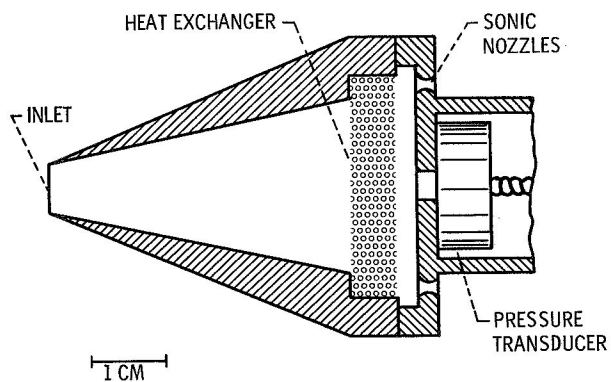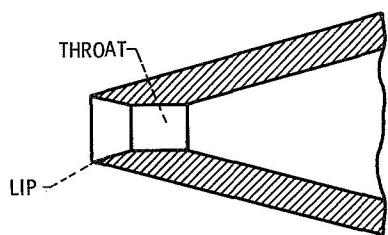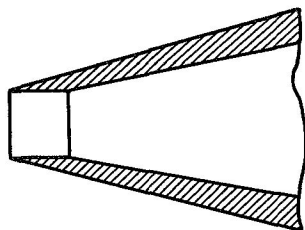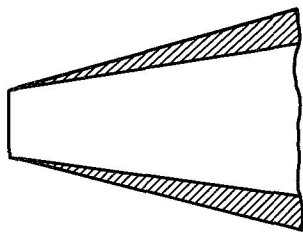

Figure 4. - Fast-response mass-flux probe[10].

(A) DOUBLE BEVEL.

(B) SINGLE BEVEL.
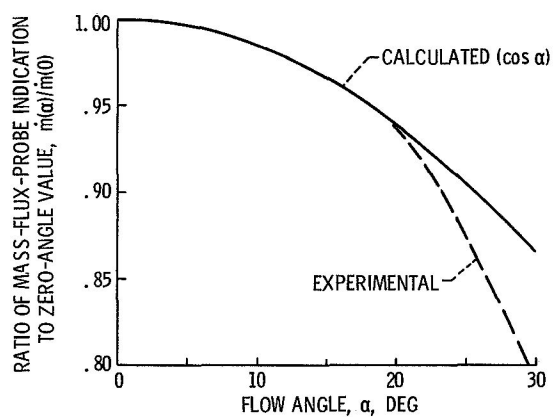
(C) DIVERGENT.

Figure 5. - Forms of inlet geometry.

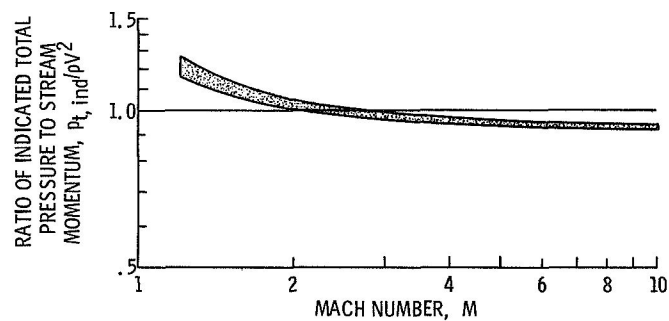Figure 6. - Variation in mass-flux-probe indication with flow angle.

Figure 7. - Variation in total-pressure indication for air. Total-pressure range $(0.1 - 100) \times 10^5$ N/m^2. Total-temperature range 300 - 2800 K.