

Airflow Calibration of a Bellmouth Inlet for Measurement of Compressor Airflow in Turbine-Powered Propulsion Simulators

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SUMMARY

The development of turbine-powered propulsion simulators for high-speed wind tunnel models has led to a requirement for a bellmouth inlet which can accurately measure compressor-inlet airflow. A bellmouth inlet was instrumented with total pressure probes, static pressure probes, and thermocouples for airflow measurement. A calibration of this bellmouth flowmeter against a critical venturi flowmeter was conducted at the Colorado Engineering Experiment Station, Inc. (CEESI). The bellmouth was calibrated over a range of sea-level-referenced airflow, $\dot{m}/\theta/\delta$, from 0.27 to 0.73 kg/sec. The calibration was done at four inlet pressures ranging from 58 to 114 kPa (8.4 to 16.5 psia). The bellmouth discharge coefficient was found to vary as a function of bellmouth-throat Mach number. Over the range of Reynolds number and Mach number tested, Reynolds number was not a significant influence on the discharge coefficient. The experimental scatter in the data was approximately $\pm 0.25\%$. The overall accuracy (scatter plus bias) of the bellmouth inlet as a flowmeter was estimated to be $\pm 0.5\%$ of the flowmeter reading.

INTRODUCTION

NASA Ames Research Center is developing test techniques for high-speed wind tunnel models utilizing the Compact Multimission Aircraft Propulsion Simulator (CMAPS) (refs. 1 and 2). Airflow instrumentation within the propulsion simulator must be calibrated against an accurate flowmeter during static tests so that compressor airflow can be accurately determined during wind tunnel tests.

A bellmouth inlet was instrumented as a flowmeter to measure compressor airflow in the propulsion simulator during static tests. A calibration of this bellmouth flowmeter against a critical (sonic-throat) venturi flowmeter was conducted at the Colorado Engineering Experiment Station, Inc. (CEESI). This report describes the procedure and results of this bellmouth calibration.

SYMBOLS

A	area, m^2
C_D	discharge coefficient, $\frac{\dot{m}_{\text{actual}}}{\dot{m}_{\text{ideal}}}$
\dot{m}	mass flow rate, kg/sec
M	Mach number

- P_o ambient pressure, kPa
 P_s static pressure, kPa
 P_t total pressure, kPa
 R ideal gas constant, 287.1 J/kg K for air
 T_o ambient temperature, K
 T_t total temperature, K
 δ ratio of local ambient pressure to sea-level standard pressure, $\frac{P_o}{101.325}$
 θ ratio of local ambient temperature to sea-level standard temperature, $\frac{T_o}{288.05}$
 γ ratio of specific heats, 1.4 for air
 ψ angular location on bellmouth, deg from top centerline

MODEL DESCRIPTION

The bellmouth inlet was designed to have the same internal profile as an ASME long-radius nozzle with a diameter ratio of 0.5 (ref. 3). Figure 1 shows the geometry of the bellmouth inlet. The bellmouth throat diameter was 7.62 cm (3.00 in.) and the inlet diameter was 15.24 cm (6.00 in.). The axial length from the inlet plane to the tangent point of the elliptical contour with the cylindrical throat was 7.62 cm (3.00 in.). The overall axial length of the bellmouth was 18.16 cm (7.15 in.). The mounting flange was designed to fit the compressor face of the CMAPS. The leading-edge lip of the bellmouth was designed to be removable so that the bellmouth could be attached to a bulkhead or a plenum chamber.

Figure 2 shows the instrumentation installed in the bellmouth. Four wall-static pressure orifices, three total-pressure probes, and a total pressure rake were installed in a plane 3.81 cm (1.50 in.) downstream of the tangent point (figs. 2(a) and 2(b)). The total-pressure rake had six equal-area-weighted probes, located at the centerline and at radial locations of 1.88 cm, 2.45 cm, 2.90 cm, 3.29 cm, and 3.64 cm from the throat centerline (fig. 2(c)). The other three total-pressure probes were located 1.88 cm from the throat centerline (fig. 2(d)). To simplify data acquisition, the four total-pressure probes at the 1.88-cm radius were manifolded together to provide a single, averaged, total-pressure measurement. Similarly, the four static-pressure orifices were manifolded to provide a single, averaged, static-pressure measurement. Total and static pressures were measured with Paroscientific Digiquartz 0-158 kPa (0-23 psia) absolute pressure transducers. Appendix A provides information on these transducers. The five remaining total pressures from the rake were measured with a manometer board to survey the total-pressure distribution at the throat.

Three Chromel-Constantan (type E) thermocouples were installed 3.0 cm upstream of the inlet plane on the lip of the bellmouth. The three thermocouples were wired in parallel to the reference junction to provide an average temperature measurement. The temperature was measured with a Kay Digistrip Recorder, which provided the reference junction compensation and converted the thermocouple output to degrees Fahrenheit. Appendix A provides information about the Kay Digistrip Recorder.

TEST SETUP

Figure 3 shows the installation of the bellmouth in the CEESI flow-conditioned plenum chamber. A porous plate and a honeycomb flow-straightener were installed in the plenum chamber to provide uniform inlet-flow conditions for the bellmouth. A 15.0-cm inside-diameter exhaust duct was connected to the downstream side of the plenum flange. To eliminate any flow curvature and static pressure distortion in the bellmouth throat caused by an abrupt area change, an extension tube was attached to the bellmouth exit. The cylindrical extension tube was 10.0 cm long with a 7.62-cm inside diameter.

The complete test setup is shown in figure 4. A critical-venturi flowmeter and a precision pressure-control valve were installed in the air-supply line upstream of the plenum. The critical-venturi flowmeters were supplied by CEESI. They were originally calibrated by the National Bureau of Standards (NBS) for use as calibration references. A manual plenum-pressure control valve was installed in the exhaust duct.

For test conditions which required plenum pressures above ambient pressure at the test site (approximately 82.7 kPa (12 psia) at 1520 m (5000 ft) above sea level), the exhaust duct discharged to atmosphere outside the lab. For test conditions which required pressures below atmospheric pressure, the exhaust duct was connected to a vacuum storage reservoir.

TEST CONDITIONS

The bellmouth was calibrated over a range of sea-level-referenced airflow, \dot{m}/\sqrt{A} , of 0.27 to 0.73 kg/sec. To cover ranges of both Reynolds number and Mach numbers independently, the calibration was done at four inlet plenum pressures. Data were taken at plenum pressures of 57.9 kPa (8.4 psia), 75.8 kPa (11.0 psia), 93.1 kPa (13.5 psia), and 113.8 kPa (16.5 psia). Table 1 gives the test matrix of airflows attained at the four pressures and four constant values of sea-level-referenced airflow.

Data were taken twice under each set of test conditions using different critical-venturi flowmeters as calibration standards. This was done to reduce any bias error from the reference flowmeters.

The Paroscientific pressure transducers were calibrated against a precision mercury barometer once each day. The thermocouples and the Kay Digistrip Recorder were calibrated against an ice bath at the beginning of the test.

RESULTS

For each data point, a discharge coefficient was calculated as the ratio of the actual airflow measured by the critical venturi to the ideal airflow calculated from measurements at the bellmouth. The ideal airflow was calculated using the continuity equation for one-dimensional isentropic flow of ideal gases (ref. 4). Appendix B shows the equations and sample calculations used in reducing the data.

Figure 5 shows computed discharge coefficients for all data versus bellmouth-throat Mach number. The data taken at inlet pressures of 75.8 kPa (11.0 psia), 93.1 kPa (13.5 psia), and 113.8 kPa (16.5 psia) show very little scatter, approximately $\pm 0.25\%$. The data taken at an inlet pressure of 57.9 kPa (8.4 psia) have significant scatter, approximately $\pm 1.5\%$. This was the result of inadequate vacuum storage at the CEESI facility for the desired test conditions. Test conditions could not be stabilized when the plenum pressure was below atmospheric pressure. As the vacuum reservoir filled up, the valve downstream of the bellmouth had to be opened manually, which caused variations in the total and static pressures measured at the bellmouth. Three high-airflow points at inlet pressures below ambient were unobtainable because of inadequate vacuum capacity.

A least-squares fit through the data using a third-order polynomial is shown in figure 5. Six of the data points taken at 57.9 kPa with greater than $\pm 1.0\%$ scatter were not included in the fit (denoted by solid symbols in fig. 5). The curve fit was subject to the additional constraint that the curve could not have a local maximum value over the range of Mach number tested.

Data were taken at four inlet pressures to vary the throat Reynolds number independently of throat Mach number. The data from all four inlet pressures fit a single curve within the experimental scatter of $\pm 0.25\%$. This pattern indicates that over the range of Mach number and Reynolds number tested, Mach number was the dominant influence on the bellmouth discharge coefficients whereas Reynolds number was not a significant influence on bellmouth-discharge coefficients.

The six-probe rake was used to survey the total pressure distribution in the bellmouth throat. Figure 6 shows a representative pressure distribution. The bellmouth-throat boundary layer was very thin because the rake did not have probes close enough to the wall to survey the boundary layer because the boundary layer was very thin.

ERROR ANALYSIS

The Paroscientific Digiquartz pressure transducers had a stated calibration accuracy of 0.015% of full scale (FS) and a combined precision (repeatability plus hysteresis) of 0.01% FS. The expected overall accuracy of the pressure transducers was therefore 0.025% FS. The transducers which were used had a range of 0-158 kPa (0-23 psia), so the pressure measurements were considered to be accurate to ± 0.040 kPa (0.006 psia). Thermocouple measurements were accurate to $\pm 1.00^\circ\text{C}$ (ref. 5).

Appendix B gives an example of how these uncertainties influence the ideal airflow calculation in the bellmouth. The maximum error in the ideal airflow caused

by instrumentation error was estimated to be $\pm 1.00\%$ of the reading. The experimental data showed $\pm 0.25\%$ scatter, which is considerably better precision than this analysis indicates.

The $\pm 0.25\%$ scatter exhibited in the calibration data is the measurement precision that is expected for this bellmouth. It does not reflect any error in the determination of the actual airflow from the reference flowmeters or any systematic error from other aspects of the facility. CEESI estimates the overall airflow accuracy of airflow calibrations in their facility to be $\pm 0.25\%$.

The overall accuracy of the bellmouth inlet as a flowmeter may be estimated by the combination of the measurement precision and the facility calibration accuracy. The accuracy is estimated to be $\pm 0.5\%$, based on the observed scatter in the calibration data. However, the absolute error based on the advertised precision of the transducers could be as high as $\pm 1.25\%$.

CONCLUSIONS

Within the range of bellmouth Mach number and Reynolds number tested, Mach number was the dominant influence on the discharge coefficient; there was no significant influence of Reynolds number on the discharge coefficient. The discharge coefficient varies from a value of 0.966 at a Mach number of 0.15 to a value of 0.972 at a Mach number of 0.45.

The overall accuracy of this bellmouth inlet as a flowmeter is estimated to be $\pm 0.5\%$ of reading, although the absolute error may be as large as $\pm 1.25\%$.

APPENDIX A

INSTRUMENT SPECIFICATIONS

Paroscientific, Inc. Digiquartz Absolute Pressure Transducer

Pressure range (full scale).....	0-23 psia (0.16 MPa)
Repeatability (average about midpoint).....	0.005% full scale
Hysteresis (average about midpoint).....	0.005% full scale
Acceleration sensitivity (under full scale pneumatic pressure load - 0.008% full scale/g worst axis).....	0.0038% full scale/g
Temperature null shift (average deviation over 100°F excursion about turnaround point).....	0.0004% full scale/°F (0.0007%/°C)
Temperature sensitivity shift.....	0.0026%/°F (0.0049%/°C)
Vibration sensitivity.....	Negligible
Supply voltage sensitivity.....	Negligible

Kaye Instruments, Inc. Digistrip II Digital Multipoint Recorder

Input type	Range	Conformity to NBS	Accuracy
Voltage	32 mV, 65 mV 650 mV, 6500 mV (6.5 V)		±(0.003% reading + 1 count + 3 μV)
Thermocouples			
Type E	-105°C to 857°C (-158°F to 1576°F)	0.06°C	±(0.003% reading + 0.3°C)
Type J	-108°C to 1130°C (-163°F to 2066°F)	0.06°C	±(0.003% reading + 0.3°C)
Type K	-105°C to 1369°C (-157°F to 2496°F)	0.06°C	±(0.003% reading + 0.3°C)

System accuracy includes all instrument errors including maximum conformity deviations, reference junction compensation with worst-case thermal scatter of input terminals, long-term drift, temperature coefficients, analog/digital (A/D) conversion errors, and scanner errors. System accuracy, 30 days 20°C to 30°C ambient.

APPENDIX B

Airflow is referenced to sea-level standard conditions by the ratios of existing ambient pressure and temperature to the standard conditions:

$$\frac{\dot{m}/\theta}{\delta} = \frac{\dot{m} \sqrt{T_o/288.15}}{P_o/101.325}$$

The mass flow rate of a compressible gas in a duct is given by the one-dimensional, isentropic, continuity equation:

$$\dot{m}_{ideal} = P_t A \sqrt{\frac{\gamma}{RT_t}} M \left[1 + \frac{\gamma-1}{2} M^2 \right]^{(\gamma+1)/2(1-\gamma)}$$

where

$$M = \sqrt{\frac{2}{\gamma-1} \left[\left(\frac{P_t}{P_s} \right)^{(\gamma-1)/\gamma} - 1 \right]}$$

The discharge coefficient is defined as the ratio of the actual airflow through the flowmeter to the ideal airflow computed from the installed instrumentation.

$$C_D = \frac{\dot{m}_{actual}}{\dot{m}_{ideal}}$$

The maximum measurement error possible in determining ideal airflow was found by choosing a set of nominal values for each measured quantity, and applying the maximum error to each quantity. Care must be taken to apply positive or negative errors as appropriate to determine the maximum accumulated error.

Choosing the nominal values of

$$P_t = 113.00 \text{ kPa}$$

$$P_s = 108.20 \text{ kPa}$$

$$T_t = 289.0 \text{ K}$$

results in a computed airflow per unit area

$$\dot{m}/A = 0.111 \text{ kg/sec/m}^2$$

Adding the maximum measurement error to each value results in

$$P_t = 113.00 + 0.04 = 113.04 \text{ kPa}$$

$$P_s = 108.20 - 0.04 = 108.16 \text{ kPa}$$

$$T_t = 289.0 - 1.0 = 288.0 \text{ K}$$

These values result in a computed airflow per unit area

$$\dot{m}/A = 0.112 \text{ kg/sec/m}^2$$

The error in the computed airflow is therefore

$$(0.112 - 0.111)/0.111 = 0.01$$

or approximately 1.0%.

REFERENCES

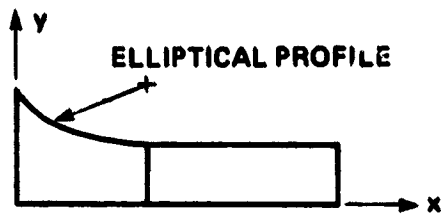
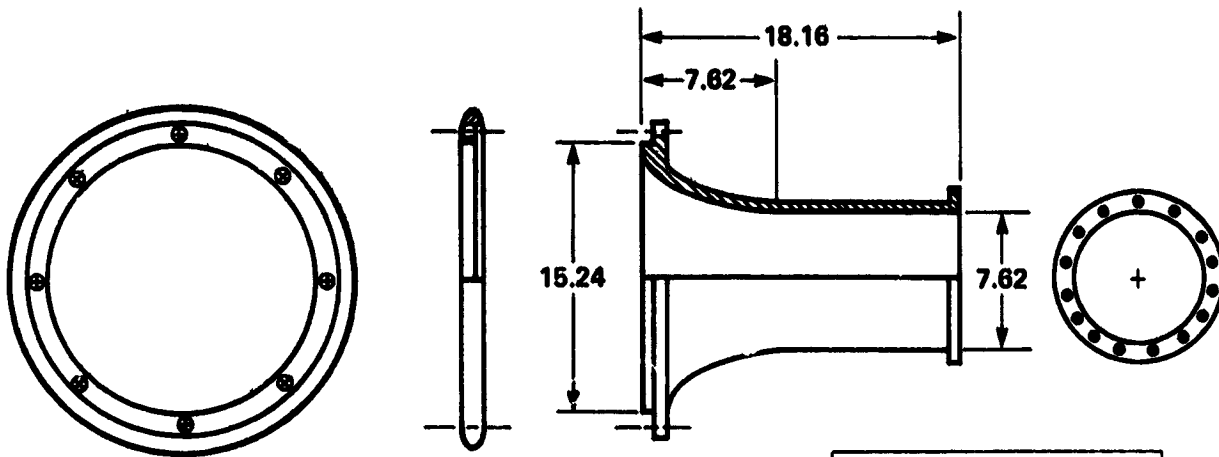
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TABLE 1.- CALIBRATION TEST MATRIX OF MASS FLOWS:
 \dot{m} , kg/sec

$\dot{m}/\sqrt{\rho}$, kg/sec	P_t , kPa			
	57.9	75.8	93.1	113.8
0.273	0.156	0.205	0.250	0.306
.432	.247	.350	.397	.485
.568	.325	--	.522	.638
.727	--	--	.668	.814

REMOVABLE LIP

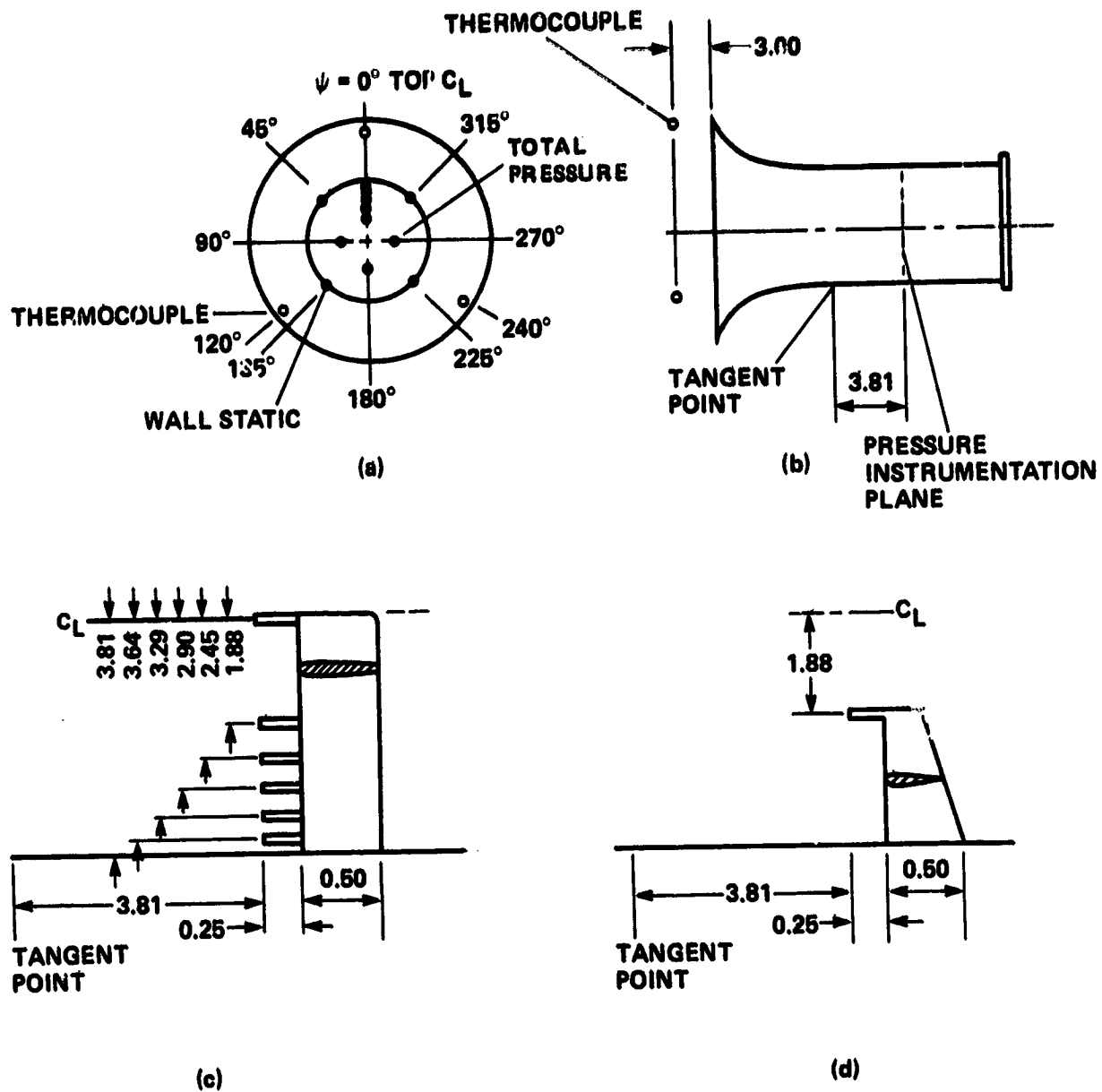
BELLMOUTH INLET



ALL DIMENSIONS IN centimeters

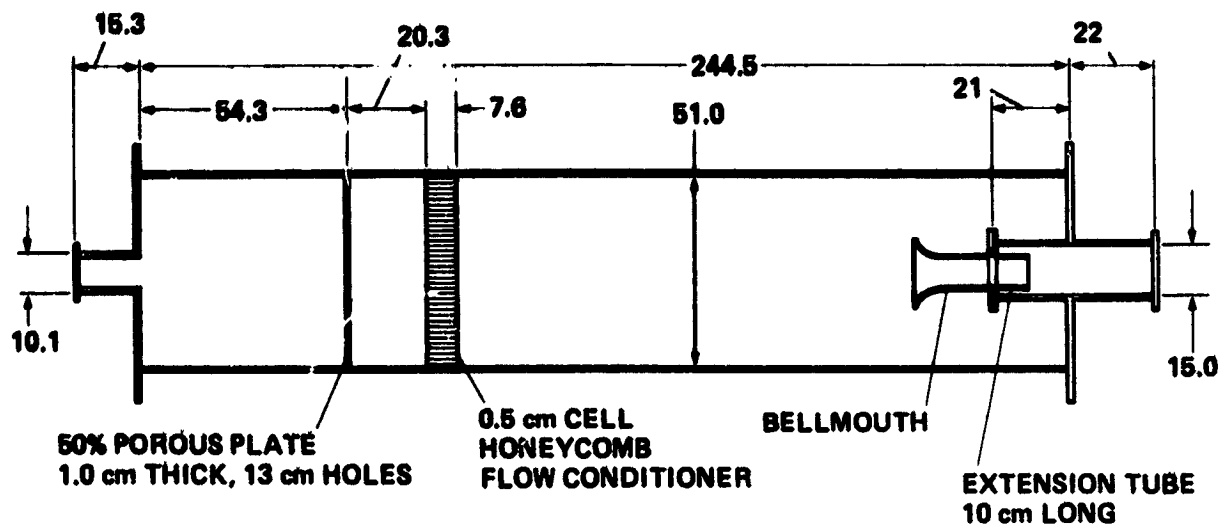
BELLMOUTH PROFILE COORDINATES		
STA.	x	y
0	0	7.620
1	0.127	6.927
2	0.317	6.533
3	0.635	6.092
4	1.270	5.514
5	1.905	5.100
6	2.540	4.780
7	3.810	4.320
8	5.715	3.932
9	7.620	3.810
10	18.160	3.810

Figure 1.- Bellmouth geometry.



ALL DIMENSIONS IN centimeters

Figure 2.- Instrumentation. a) Probe location; b) probe location (axial); c) total pressure rake, $\psi = 0^\circ$; d) total pressure probe, $\psi = 90^\circ, 180^\circ, 270^\circ$.



ALL DIMENSIONS IN centimeters

Figure 3.- Bellmouth installation in CEESI plenum chamber.

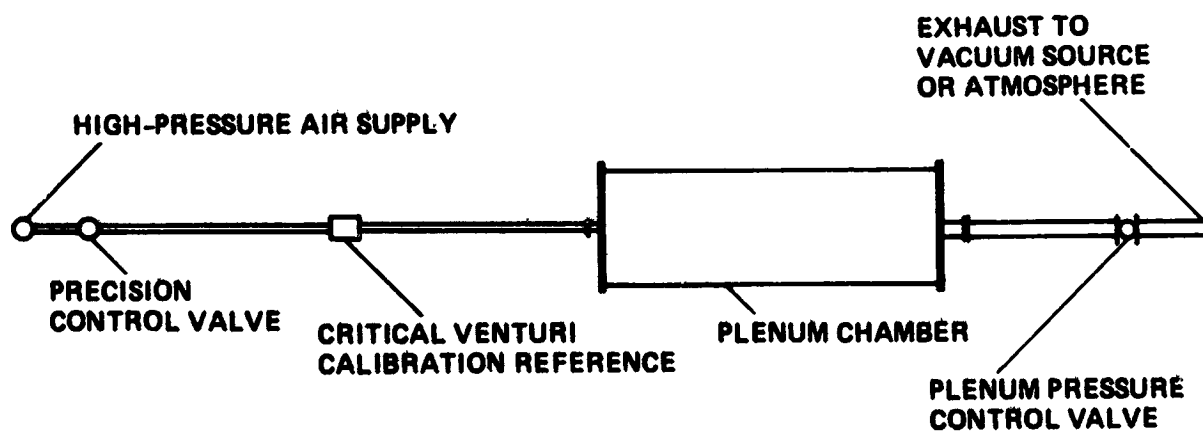


Figure 4.- Bellmouth calibration setup.

$$C_D = 0.239397 M^3 - 0.322058 M^2 + 0.144420 M + 0.951053$$

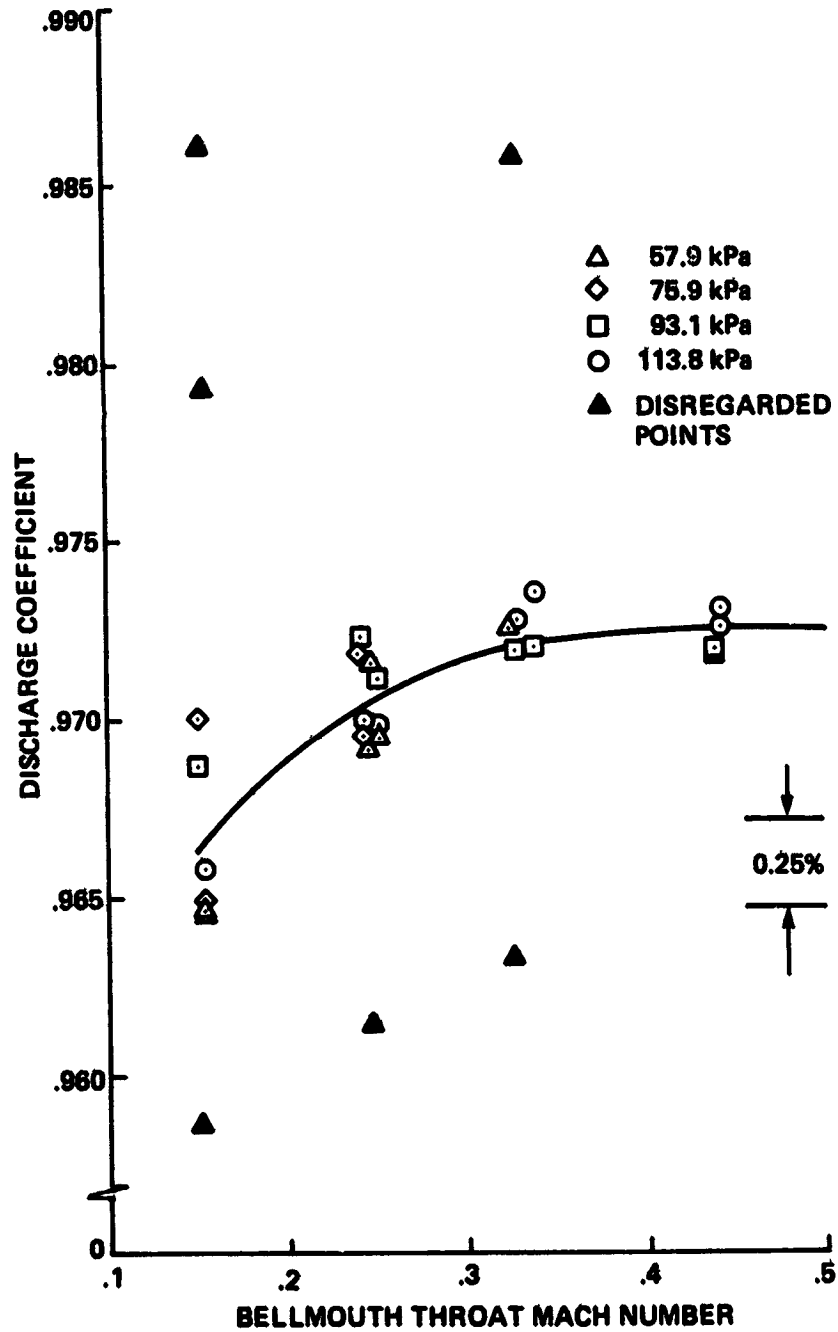


Figure 5.- Bellmouth discharge coefficient vs Bellmouth throat Mach number.

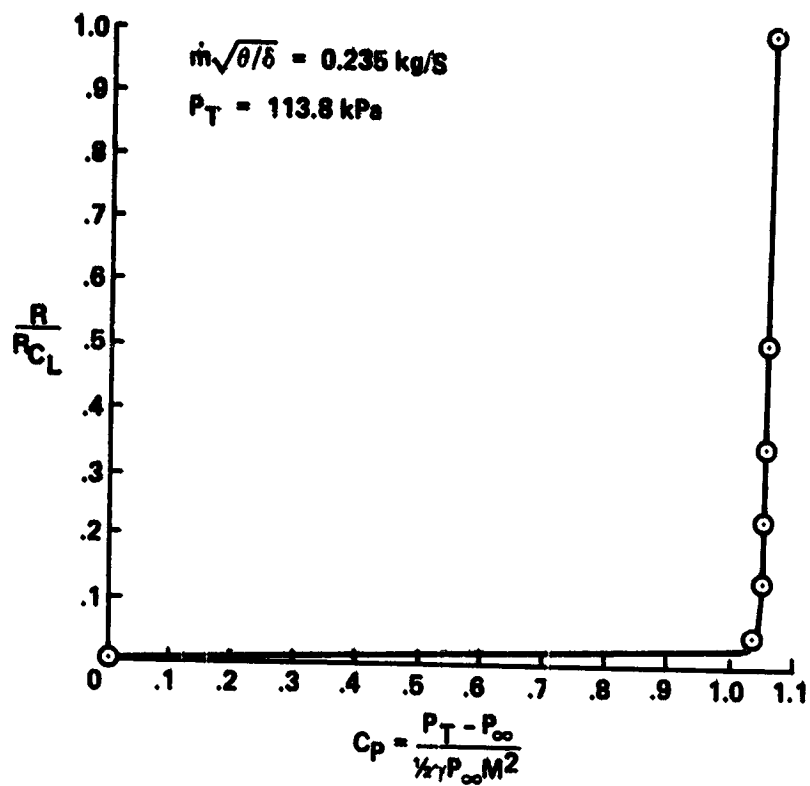


Figure 6.- Bellmouth throat total pressure distribution.

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16. Abstract <p>The development of turbine-powered propulsion simulators for high-speed wind tunnel models has led to a requirement for a bellmouth inlet which can accurately measure compressor-inlet airflow. A bellmouth inlet was instrumented with total pressure probes, static pressure probes, and thermocouples for airflow measurement. A calibration of this bellmouth flowmeter against a critical venturi flowmeter was conducted at the Colorado Engineering Experiment Station, Inc. (CEESI). The bellmouth was calibrated over a range of sea-level-referenced airflow, $\dot{m}\sqrt{\theta}/\delta$, from 0.27 to 0.73 kg/sec. The calibration was done at four inlet pressures ranging from 58 to 114 kPa (8.4 to 16.5 psia). The bellmouth discharge coefficient was found to vary as a function of bellmouth-throat Mach number. Over the range of Reynolds number and Mach number tested. Reynolds number was not a significant influence on the discharge coefficient. The experimental scatter in the data was approximately $\pm 0.25\%$. The overall accuracy (scatter plus bias) of the bellmouth inlet as a flowmeter was estimated to be $\pm 0.5\%$ of the flowmeter reading.</p>					
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