SAE Aerospace
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AEROSPACE INFORMATION REPORT

SAE AIR1168/5 **REV. A**

Issued	1990-02
Reaffirmed	2006-03
Stabilized	2011-07

Superseding AIR1168/5

Aerothermodynamic Test Instrumentation and Measurement

RATIONALE

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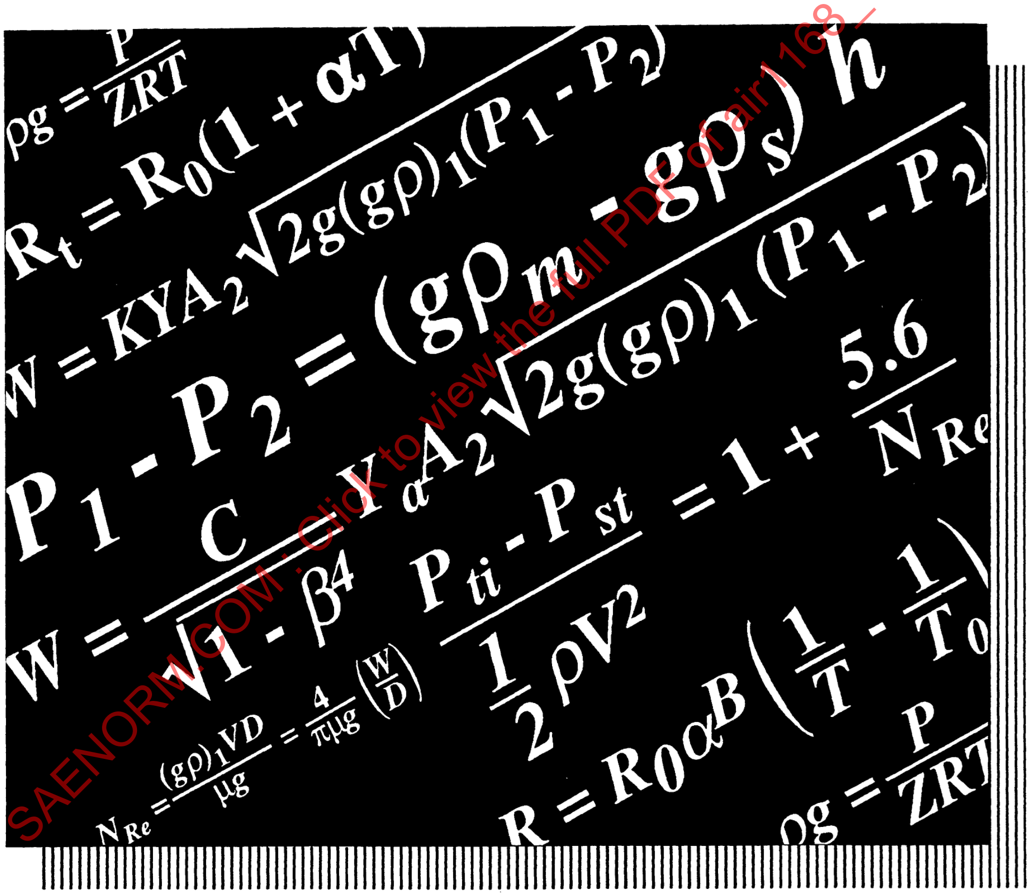
Aerothermodynamic Test Instrumentation and Measurement

AIR1168/5



SAE Aerospace Applied Thermodynamics Manual

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PREFACE

This document is one of 14 Aerospace Information Reports (AIR) of the Third Edition of the SAE Aerospace Applied Thermodynamics Manual. The manual provides a reference source for thermodynamics, aerodynamics, fluid dynamics, heat transfer, and properties of materials for the aerospace industry. Procedures and equations commonly used for aerospace applications of these technologies are included.

In the Third Edition, no attempt was made to update material from the Second Edition nor were SI units added. However, all identified errata were corrected and incorporated and original figure numbering was retained, insofar as possible.

The SAE AC-9B Subcommittee originally created the SAE Aerospace Applied Thermodynamics Manual and, for the Third Edition, used a new format consisting of AIR1168/1 through AIR1168/10. AIR1168/11 through AIR1168/14 were created by the SAE SC-9 Committee.

The AIRs comprising the Third Edition are shown below. Applicable sections of the Second Edition are shown parenthetically in the third column.

AIR1168/1	Thermodynamics of Incompressible and Compressible Fluid Flow	(1A,1B)
AIR1168/2	Heat and Mass Transfer and Air-Water Mixtures	(1C,1D,1E)
AIR1168/3	Aerothermodynamic Systems Engineering and Design	(3A,3B,3C,3D)
AIR1168/4	Ice, Rain, Fog, and Frost Protection	(3F)

AIR1168/5	Aerothermodynamic Test Instrumentation and Measurement	(3G)
AIR1168/6	Characteristics of Equipment Components, Equipment Cooling System Design, and Temperature Control System Design	(3H,3J,3K)
AIR1168/7	Aerospace Pressurization System Design	(3E)
AIR1168/8	Aircraft Fuel Weight Penalty Due to Air Conditioning	(3I)
AIR1168/9	Thermophysical Properties of the Natural Environment, Gases, Liquids, and Solids	(2A,2B,2C,2D)
AIR1168/10	Thermophysical Characteristics of Working Fluids and Heat Transfer Fluids	(2E,2F)
AIR1168/11	Spacecraft Boost and Entry Heat Transfer	(4A,4B)
AIR1168/12	Spacecraft Thermal Balance	(4C)
AIR1168/13	Spacecraft Equipment Environmental Control	(4D)
AIR1168/14	Spacecraft Life Support Systems	(4E)

F.R. Weiner, formerly of Rockwell International and past chairman of the SAE AC-9B Subcommittee, is commended for his dedication and effort in preparing the errata lists that were used in creating the Third Edition.

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1. INTRODUCTION

1.1 Scope

Like the technologies to which it contributes, the science of instrumentation seems to be expanding to unlimited proportions. In considering instrumentation techniques, primary emphasis was given in this section to the fundamentals of pressure, temperature, and flow measurement. Accent was placed on common measurement methods, such as manometers, thermocouples, and head meters, rather than on difficult and specialized techniques. Icing, humidity, velocity, and other special measurements were touched on briefly. Many of the references cited were survey articles or texts containing excellent bibliographies to assist a more detailed study where required.

1.2 Nomenclature

This list contains the general symbols used in equations, graphs, and tables in this AIR. Other symbols having single or limited usage are defined in the text sections where they are used.

A = Area, ft^2, $in.^2$
c_p = Specific heat at constant pressure, Btu/lb-°F
D,d = Diameter, in., ft
exp = Exponent
G = Weight velocity, lb/ft^2-sec
g = Gravitational acceleration, ft/sec^2
$g\rho$ = Specific weight (density), lb/ft^3
h = Surface heat transfer coefficient, $Btu/hr\text{-}ft^2$-°F
k = Thermal conductivity, Btu/hr-ft-°F
M = Freestream Mach No., dimensionless
N_{Re} = Reynolds No., dimensionless
P = Pressure (units defined in text)
P_t = Total pressure (units defined in text)
R = Universal Gas Constant, ft-lb/lb-°R
r = Ratio of static pressures, P_2/P_1
t = Temperature, °F
T = Temperature, °R
V = Velocity, ft/sec, ft/min
W = Weight flow rate, lb/sec, lb/min, lb/hr
Y = General adiabatic expansion term for head meters, dimensionless
Y_a = Adiabatic expansion term for nozzles and venturis, dimensionless
Y_1 = Adiabatic expansion term for orifices, dimensionless
α = Temperature coefficient of resistance, ohm/ohm-°F
β = Diameter ratio, dimensionless
γ = Ratio of specific heats, c_p/c_v, dimensionless
ε_w = Wire emissivity, dimensionless
μ = Absolute viscosity, lb/sec-ft, lb/hr-ft
ρ = Mass density, $lb\text{-}sec^2/ft^4$
ρg = Specific weight (density), lb/ft^3

σ = Stefan-Boltzmann constant, 0.171 × 10^{-8} Btu/hr-ft^2-°R^4
τ = Time constant (time required for 63 percent response to a step change), sec
ω = Specific humidity, lb-water/lb-dry gas

1.3 Common Abbrevations

abs	— Absolute
AGARD	— Advisory Group for Aerospace Research and Development
ASME	— American Society of Mechanical Engineers
ASME Trans.	— ASME Transactions
ASTM	— American Society for Testing and Materials
atm	— Atmosphere(s)
deg	— Degree
dia	— Diameter(s)
ed.	— Edition
emf	— Electromotive force
Eq./Eqs.	— Equation/Equations
exp	— Exponent
°F	— Degrees Fahrenheit
Fig./Figs.	— Figure/Figures
fpm	— Feet per minute (ft/min)
fps	— Feet per second (ft/sec)
ft	— Feet
ga., Ga.	— Gage
hr	— Hour
in.	— Inch
ISA	— Instrument Society of America
J.	— Journal
lb	— Pound
LWC	— Liquid - water content
max	— maximum
Mech. Eng.	— Mechanical Engineering (ASME)
min	— minimum
MIT	— Massachusetts Institute of Technology
NACA	— National Advisory Committee for Aeronautics
NAE	— National Aeronautical Establishment (Canada)
NATO	— North Atlantic Treaty Organization
NBS	— National Bureau of Standards
no.	— Number
%	— Percent
Par./Pars.	— Paragraph/Paragraphs
p./pp.	— Page/Pages

ppm — Parts per million
psf — Pounds per square foot
psi — Pounds per square inch
psia — Pounds per square inch absolute
psig — Pounds per square inch gage
°R — Degrees Rankine
Ref./Refs. — Reference/References
RH — Relative humidity
RM — Research Memorandum
rms — Root mean square
rpm — Revolutions per minute
TN — Technical Note
TR — Technical Report
SAE — Society of Automotive Engineers, Inc.
sec — Seconds
V — Volts
vol. — Volume
WADC — Wright Air Development Center

2. PRESSURE MEASUREMENT

Three forms of pressure can be measured:

1. Static pressure is the force per unit area exerted by a fluid on a boundary that is parallel to the fluid streamlines. At a given station in a duct where the streamlines are straight and parallel, the static pressure is the same everywhere except for pressure differences due to elevation. For gases, the effect of elevation usually is negligible.

   Static pressure in a gas represents the summation of the molecular collision forces on the boundary and is a function of molecular velocity (temperature dependent) and molecular concentration (density dependent). It is thus a property, the knowledge of which contributes to the definition of the state of the gas.

2. Dynamic pressure is the pressure rise resulting from a perfect conversion of fluid translational momentum into pressure. Ideally, this occurs on fluid impact with a stationary boundary normal to the fluid streamlines.

3. Total pressure is the sum of the dynamic and static pressures.

2.1 Static Pressure Measurement

2.1.1 Wall Static Tap

Measurement of static pressure in a fluid can be accomplished usually by a well-located, carefully made, wall static tap. To assure that the streamlines are parallel to the duct wall at the point of measurement requires about 5 dia of straight duct to the nearest upstream symmetrical disturbance; for example, a reducer. Downstream of a bend or other asymmetrical disturbance, 10 dia are required.

Unfortunately, in aircraft systems and components such ideal locations can not be realized. At stations where the flow is disturbed it may be desirable to locate more than one wall tap. A number of taps can be manifolded together in a "piezometer ring," which may introduce some consistency in the readings, but is not a true averaging device. A better technique is the individual reading of each tap.

Even so, the significance of an average static pressure in a region of disturbed flow is questionable. If the measurement is made with the aim of understanding the flow at that station, additional tools, such as visualization techniques, probes for determining the flow direction, and traversing hot wire anemometers, should be used.

On the other hand, if the measurement is made to establish the performance of a component, then adherence to an agreed code is wise. For example, in measuring the static pressure downstream of an axial flow fan, a significant difference can exist if the rotational energy is recovered with straightening vanes prior to the static pressure tap. Traditionally, the fan manufacturer is credited with this increment and, by code (in this case the National Association of Fan Manufacturers) the static tap measurement is made downstream of straighteners. The largest source of error in wall static measurements stems from tap fabrication irregularities (Fig. 3G-1).

The effect of both hole size and tap configuration was explored by Rayle (Ref. 1). Fig. 3G-2 illustrates that the smallest hole considered should be one that will not foul easily by dirt or other suspended solids in the system. For most cases, a 0.020 – 0.040 in. diameter hole is satisfactory; however, for gas streams containing combustion products, a 0.040 in. dia should be the minimum. Rayle suggests countersinking to 1/2D (negative error of 0.3%) to partially offset the positive error of hole size. Time response of the system depends upon the hole size.

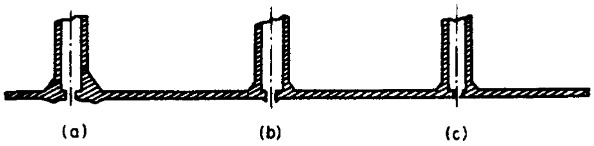

Figure 3G-1 - Common Static Tap Fabrication Errors with Estimates of Possible Error as a Percent of the Dynamic Pressure. (a) Wavy wall or well penetration, 50%; (b) Protruding burrs, 20%; (c) Flush burrs, 2%

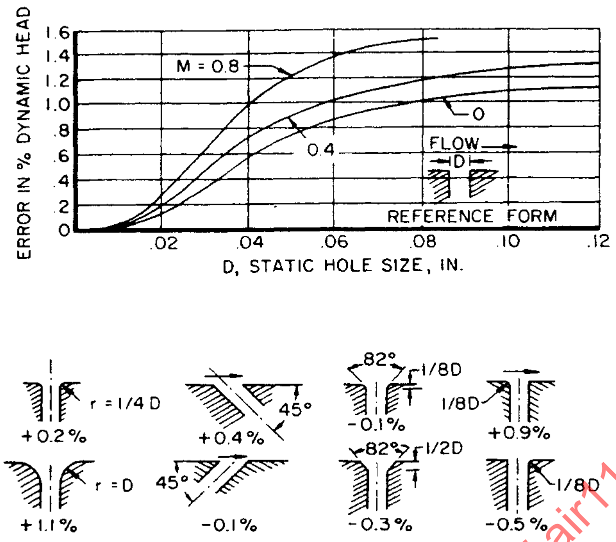

Figure 3G-2 - Effect of Hole Size and Configuration on Wall Static Tap Pressure Reading

2.1.2 The Static Probe

At times it is desired to explore the flow field with a static pressure probe of the type illustrated in Fig. 3G-6, with or without a total pressure hole. Caution is warranted because the static probe is very sensitive to yaw. At Mach numbers above 0.7, the static probe experiences serious errors caused by local shocks aft of the nose.

A special design (Ref. 2) using slender body theory was shown to be independent of Mach number up to Mach 2.0. The combination of static tube and total pressure pickup (the pitot-static tube) will be discussed in more detail in a later section. Use of the static tube in boundary layer measurements should be avoided because of probe-wall interaction. A wall static tap will usually suffice.

As a general rule, where it is reasonable to believe that either the wall static tap or the static tube will meet the requirements of the measurements, the wall static will give more accurate and consistent results.

2.1.3 Turbulence

In regions of high turbulence, turbulent velocity components normal to a surface containing a static hole cause readings that are higher than the freestream static. Turbulence levels of 10% (not uncommon in turbomachinery) will introduce a positive error of 1% of the dynamic head (Ref. 3), while 20% levels increase the error to 4%. The turbulence level (that is, the ratio of the root mean square value of the turbulent velocity to the average stream velocity) is determined usually with a highly responsive, hot-wire anemometer.

2.2 Total Pressure

2.2.1 Total Pressure Probe

The simplest type of total pressure probe is a bent tube (Fig. 3G-3), with the nose aligned to the flow velocity.

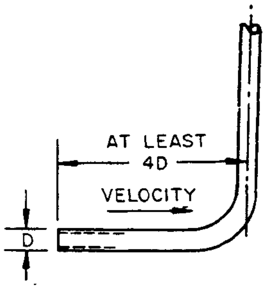

Figure 3G-3 - A Simple Total Pressure Probe

The details of the nose configuration determine the sensitivity of the probe to angle of yaw (Fig. 3G-4). Increases in Mach number affect the various probe shapes differently, but usually the range of yaw insensitivity is decreased. For example, using shielded probes with yaw insensitivity to 63 deg at Mach 0.26 results in serious errors at yaw angles above 40 deg at Mach 1.6.

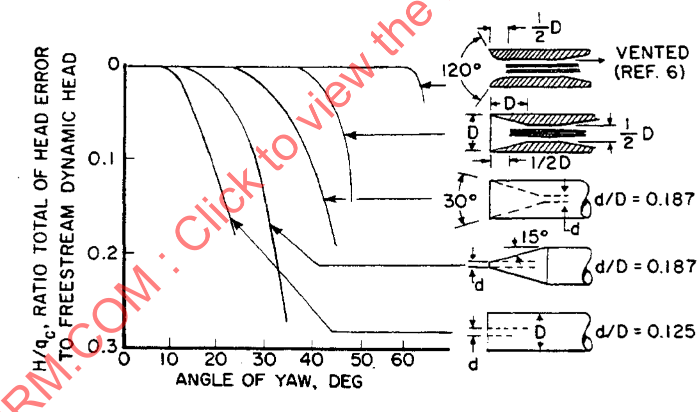

Figure 3G-4 - Typical Yaw Sensitivity of Total Pressure Probes with Different Nose Shapes, Mach Number = 0.26. (Source: Refs. 4-7)

2.2.1.1 Total Pressure Measurement in Supersonic Flow

If the total pressure probe is used in a region where the Mach number is above 1.0, a normal shock will exist at the nose of the probe. To obtain the freestream total pressure, P_{t1}, from the observed total pressure, P_{t2}, the Rayleigh equation must be applied:

$$\frac{P_{t1}}{P_{t2}}=\left[\frac{2\gamma}{\gamma+1}M^2-\frac{\gamma-1}{\gamma+1}\right]^{1/(\gamma-1)}\bullet\left[\frac{(\gamma-1)M^2+2}{(\gamma+1)M^2}\right]^{\gamma/(\gamma-1)} \qquad (3G\text{-}1)$$

where M is the freestream Mach number.

2.2.1.2 Effects of Viscosity and Low Gas Densities

When making total pressure measurements at low Reynolds numbers (based on the probe orifice radius), viscosity effects cause a deviation from the isentropic impact process. Such low Reynolds numbers ($N_{Re} < 30$) are encountered at very low gas densities or with small boundary layer probes at low velocities. The deviation is described approximately by the expression (Ref. 3):

$$\frac{P_{ti} - P_{st}}{\frac{1}{2}\rho V^2} = 1 + \frac{5.6}{N_{Re}} \qquad \text{(3G-2)}$$

where P_{ti} = indicated total pressure, lb/ft^2
P_{st} = static pressure, lb/ft^2

Measurement problems in the slip flow, transition flow, and free molecule flow regimes are discussed in Ref. 8.

2.2.1.3 Turbulence

In turbulent flow, the observed total pressure of an impact tube will be higher than the actual by an incremental dynamic pressure based on the root mean square (rms) of the axial component of turbulent velocity. The influence is the same as that described for the static hole (Par. 2.1.3).

2.2.1.4 Entrained Moisture

Measurements in airstreams containing entrained moisture create two problems:

1. The observed total pressure will be between the total pressure for the saturated air and the total pressure for a gas with a density equivalent to the saturated air plus entrained moisture.
2. The water catch by the probe may be sufficient to introduce hydrostatic head errors in the connecting lines.

If measurements under these circumstances cannot be avoided, an analysis of possible errors and the frequent clearing of lines is indicated. A special scavenging probe is proposed in Ref. 9 for measuring total pressure in moisture-laden gas.

2.2.2 Measurements in the Boundary Layer

Boundary layer surveys with a total pressure probe require considerable care because the boundary layer is unavoidably affected by introduction of the probe. Boundary layer probes are usually made of hypodermic tubing [Fig. 3G-5(a)]. Another probe is the Stanton probe [Fig. 3G-5(b)], which by analysis and calibration can be related to the boundary layer profile (Ref. 3).

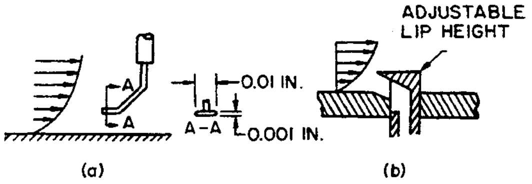

Figure 3G-5 - Boundary Layer Probes. (a) The flattened hypodermic; (b) The Stanton probe

2.3 Dynamic Pressure

2.3.1 The Pitot Static Probe

Where uniform flow conditions prevail, a wall static tap and an impact tube are sufficient to obtain a dynamic pressure profile. However, in cases where a static pressure variation through the flow field is suspected, it is desirable to use a pitot static probe. Pitot static probes are influenced by two conditions:

1. A tendency toward negative readings caused by local accelerations around the pitot nose.
2. A positive pressure propagation upstream from the stem.

The Prandtl probe [Fig. 3G-6(a)] is designed to balance these errors, resulting in a relatively short probe. The "improved form" [Fig. 3G-6(b)] allows enough length to eliminate nose and stem effects. The improved form is somewhat less sensitive to yaw (-1% error in dynamic head at 13 deg against +1% at 6 deg for the Prandtl form).

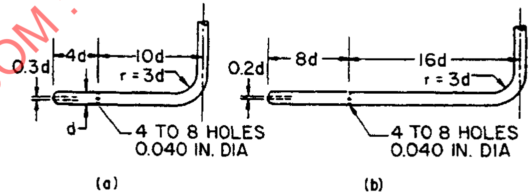

Figure 3G-6 - Pitot Static Probes (a) Prandtl; (b) Improved Form

2.4 Rakes

Static, pitot static, or total pressure probes may be arranged as rakes to obtain a survey where traversing is inconvenient (Fig. 3G-7).

Again, the problem is one of assessing the disturbance to the normal flow which the rake will introduce. In high velocity flow the possibility of shock reflections and local choking must be evaluated, either by analysis or by visual observations (for example, Schlieren) of the flow field.

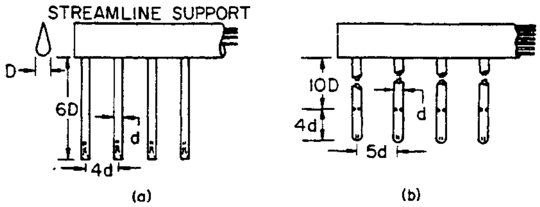

Figure 3G-7 - Geometry of Pressure Rakes. (a) Total pressure; (b) Static or pitot static

In general, the probes should not be manifolded, since (as in the case of the piezometer ring) a true average will not result.

2.5 Pressure Indicating Instruments

2.5.1 Manometers

The manometer (Fig. 3G-8) is the simplest, most reliable, and, in the range where it is applicable, the most common pressure indicating instrument.

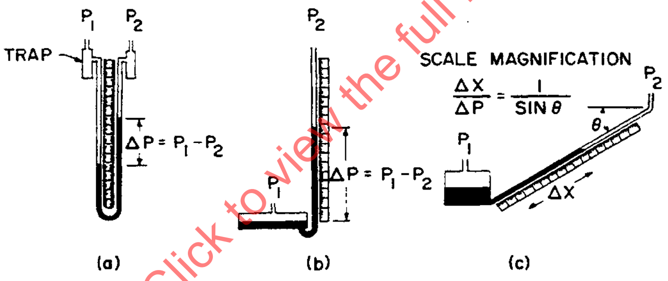

Figure 3G-8 - Three Basic Manometer Designs. (a) U-tube; (b) Well-type; (c) Inclined

Traps should be provided to prevent carryover of manometric fluid into a test system in the event of overpressuring. Even the best traps may not completely prevent carryover, so that extreme caution is warranted when attaching a mercury manometer to expensive test items such as valves and turbomachinery. Aluminum and brass are especially susceptible to amalgamation and subsequent disintegration.

Some of the common manometer fluids are listed in Table 3G-1.

Because the indicated head reflects a pressure that is a function of the observed column height and the fluid density, manometer readings should be corrected to a reference temperature. A common reference used in fluid meter work is 68°F, which is fairly close to average room temperature, and will minimize the correction. Corrections of water and mercury columns to 68°F can be made using Figs. 3G-9 and 3G-10.

Table 3G-1 - Properties of Manometer Fluids[1]

Fluid	Specific Gravity @ 60°F	Color	Volumetric Coeff. of Thermal Expansion, 1/°F	Remarks
Water, H_2O	0.99913	Colorless	See Fig. 3G-9	Corrodes iron and steel
Mercury, Hg	13.57	Silver	See Fig. 3G-10	Poisonous, toxic; amalgamates with aluminum, copper, brass
Methyl Alcohol, CH_3OH	0.7928	Colorless	1.199×10^{-3}	Poisonous, toxic; corrodes iron and steel
Ethyl Alcohol, C_2H_5OH	0.7893	Colorless	1.12×10^{-3}	Poisonous, toxic; corrodes iron and steel
Acetylene Tetrabromide (Merriam No. 3)	2.96	Yellow (colored red for commercial use)	1.087×10^{-3}	Poisonous; corrodes iron and steel, weakens some plastics and rubbers
Merriam Red Oil (mineral oil)	0.827	Red	3.73×10^{-4}	Poisonous; noncorrosive
Merriam Unity Oil (mineral oil + Hollowax)	1.047	Red	3.875×10^{-4}	Poisonous; noncorrosive

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[1] Based on material from Ref. 3

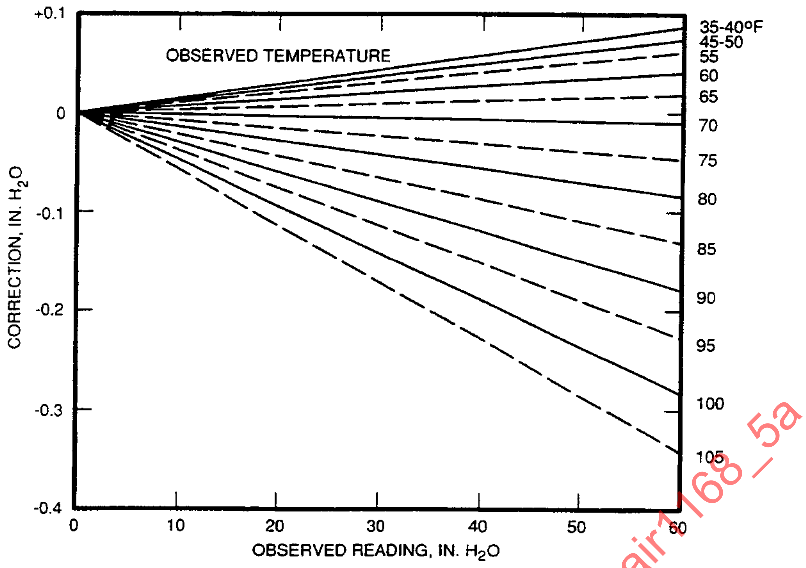

Figure 3G-9 - Corrections for Water Columns; Reference Temperature 68°F

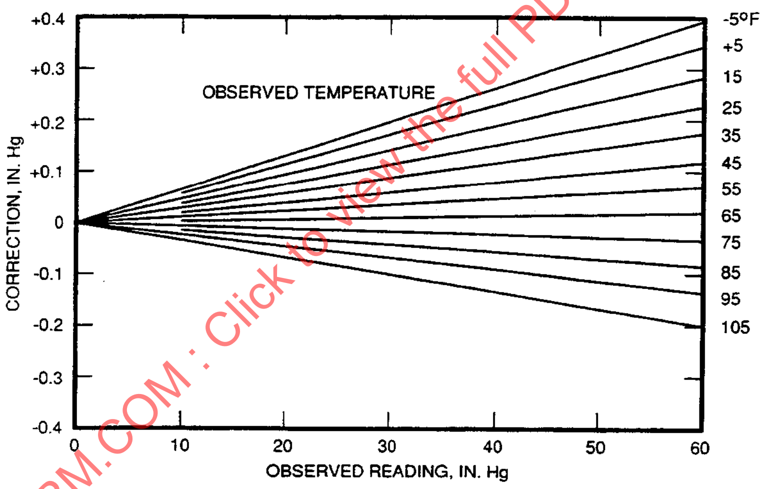

Figure 3G-10 - Corrections for Mercury Columns; Reference Temperature 68°F

When making manometric measurements on liquid systems, special attention must be paid to the manometer elevation, to correct for the leg of system fluid and to free the lines from vapor. Two common usages of manometers using liquid systems are illustrated in Fig. 3G-11. The correct expression for calculating pressure differences are as follows:

For Fig. 3G-11(a):

$$P_1 - P_2 = (g\rho_m - g\rho_s)h \tag{3G-3}$$

and for Fig. 3G-11(b),

$$P_1 - P_A = g\rho_m h_2 - g\rho_s h_1 \tag{3G-4}$$

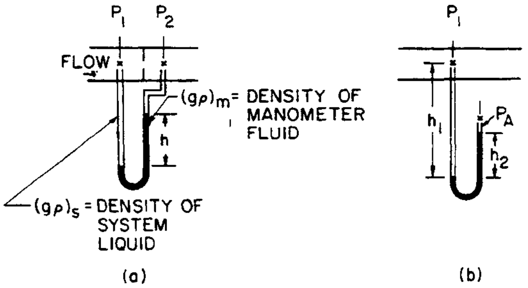

Figure 3G-11 - Manometers Used on Liquid Systems

The low density of air results in this type of correction being negligible when air is the working fluid. However, with heavier gases, it would be well to note the magnitude of the term $g\rho_s h$ (Fig. 3G-11(a)), and apply the correction if it is appreciable.

The major causes of errors when using manometers are:

1. Leaks in connecting tubing or lines: Pressure decay tests of the manometer and connecting lines are satisfactory and easy to devise.
2. Liquid or vapor in the connecting lines: Suitable traps and bleeds should be provided to assure that in liquid systems there is no vapor in the connecting lines, and in gas systems there is no liquid. Exceptional care must be taken where a change of state (evaporation or condensation) occurs in the connecting lines.
3. Meniscus capillary errors: The most frequent source of avoidable error in manometry is reading the meniscus level. Either the top or the bottom of the meniscus may be read if the practice is consistent in reading and zeroing.

Unfortunately, the meniscus is not always the same shape, introducing reading errors that can be minimized only by extremely clean fluid and large bores. Mercury should be cleaned frequently to eliminate mercury oxide. In an 8 mm bore, meniscus capillary errors result in an uncertainty interval of about 0.1 in. if water is the manometer fluid (Ref. 3).

Micromanometers are used in the range 0 – 6 in. of water to measure differential pressure to an accuracy of 0.001 in. of water or better. A good discussion of the features of many outstanding micromanometer designs, and some of the precautions necessary for extremely accurate measurements can be found in Ref. 3.

2.5.2 Pressure Gages

Commercial pressure gages are of the bourdon, bellows, or diaphragm type (Fig. 3G-12). In general, all can be purchased as (1) pressure, (2) vacuum, (3) compound, or (4) differential gages. Although these units are usually direct reading, all of the types can be supplied for remote reading. The bourdon gage, probably the most widely used, is the least expensive and the least sensitive. The bellows and diaphragm gages are usually more expensive and more sensitive; the diaphragm gage tends to be more temperature sensitive.

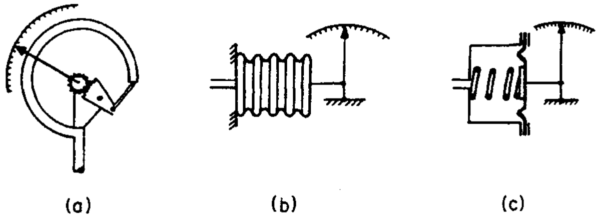

Figure 3G-12 - Pressure Gage Elements with Typical Ranges. (a) Bourdon: min range, 0 – 12 psig; max range, 0 – 100,000 psig; (b) Bellows: min range, 0 – 5 in. H_2O; max range, 0 – 800 psig; (c) Diaphragm: min range, 0 – 0.2 in. H_2O; max range, 0 – 400 psig

Pressure gages should be calibrated frequently with dead-weight testers. This is a method that is accurate and repeatable. Very few gages read the average of a pulsing pressure. Suitable pressure transducers should be used to explore unsteady pressures. Where sudden pressure shocks are expected, gages should be protected by snubbers (special restrictions).

An excellent discussion of gages and transducers is presented in Ref. 10.

2.5.3 Pressure Transducers

Current research on shock waves and combustion phenomena has provided impetus to the technology of transient pressure measurement. Principles being used are:

1. Use of bonded and unbonded strain gages for elements loaded by pistons, diaphragms, or bellows.
2. Using the change of electrical resistance in a pressure sensitive element, such as a carbon pile.
3. Measurement of change in inductance or reluctance in a magnetic circuit, caused by deflection of a pressure sensitive element.
4. Sensing of a capacitance change resulting from pressure induced deflection.
5. Measurement of the electric potential output of an elastically deformed, piezoelectrically active crystal.

Routine laboratory transducers, usually of the diaphragm strain gage type, are accurate to about 1% for pressure transients taking place over milliseconds. The more advanced techniques detect pressure changes taking place in a microsecond or less (Ref. 11).

The transducer output is usually put into a suitable oscillograph or stored on magnetic tape for later processing. In any dynamic pressure measuring system, the line sizes and transducer volumes must be carefully sized to assure adequate response (Ref. 12).

2.5.4 High Vacuum Gages

Vacuum measurement in the range of 1 to 1 × 10^{-16} mm Hg requires gages that do not sense pressure directly, but rather are sensitive to phenomena related to pressure. Most vacuum gages read parameters that vary proportionally with pressure and require frequent calibration to assure accuracy.

The most commonly used standard for calibration is the McLeod gage (Fig. 3G-13(a)). Mercury is raised into a trapped volume with a sample of the gas to be measured in it. This volume terminates in a closed, uniform capillary that is adjacent to an identical capillary open to the vacuum being measured. The trapped volume is measured. Then, after raising the mercury, the difference in height of the two columns of mercury enables the operator to compute the absolute pressure of the vacuum from Boyle's law.

There are two relatively inexpensive utility vacuum gages based on sensing the thermal conductivity of the gas sample. The thermocouple gage [Fig. 3G-13(b)] measures the temperature of a heated wire in the gas sample, while the Pirani gage [Fig. 3G-13(c)] compares the resistance of a heated wire in a near absolute vacuum with an identical wire in the gas sample.

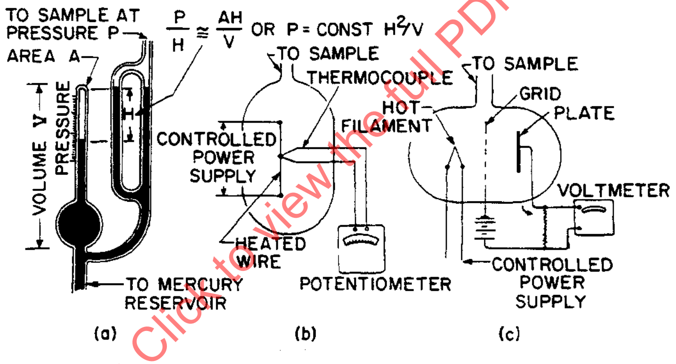

Figure 3G-13 - Several Common Types of Vacuum Gages. (a) McLeod gage: lower limit of application = 10^{-4}mm. (b) Thermocouple gage: lower limit of application approximately 10^{-3}mm. (c) Hot filament ionization gage: lower limit of application approximately 10^{-7}mm

Measurements of vacuum are frequently required in chambers where tests are performed or on very high altitude flight vehicles. The first measurement should be performed with a vacuum gage installed either in the chamber or connected to the chamber by a tube length that is as short as possible. The inside diameter of the connecting tube should not be less than 1/2 in. for pressures less than 10^{-3}mm of mercury.

The second measurement, when used on rockets, satellites, and other space vehicles, usually requires that the gage be protected from the atmosphere before it reaches the altitude where pressure readings can be taken. This may be accomplished by the breaking of a glass envelope or the opening of a valve. Table 3G-2 tabulates some of the common types of vacuum gages and their characteristics.

Table 3G-2 - Characteristics of Common Vacuum Gages

Name or Type	Range, Torr[1]	Principle of Operation	Application and Advantage
Bourdon	atm – 10^{-1}	Deflection of pressurized tube	Simple, reliable
Diaphragm	atm – 10^{-4}	Deflection of diaphragm causes capacitance change	Simple, reliable, rugged
Alphatron	atm – 10^{-4}	Radioactive source produces an ion current	Linear output
Thermocouple	$10 – 10^{-3}$	Change of heat transfer sensed by thermocouple	Inexpensive, small, easy to clean
Pirani	$500 – 10^{-4}$	Change in resistance of hot wire	Rugged
Triode	$10^{-3} – 10^{-8}$	Ion current caused by grid electron current	High range, pumping effect
Bayard Alpert (Inverted Triode)	$10^{-3} – 10^{-11}$	Same as preceding triode but X-ray current reduced by change	High range, pumping effect
Cold Cathode Magnetron	$10^{-3} – 10^{-13}$	Ion current caused by discharge of high voltage	High range, rugged
Mass Spectrometer	$10^{-4} – 10^{-16}$	Reads partial pressures of individual gases	Quantitative analysis
McLeod Gage	$10 – 10^{-6}$	Compresses gas and reads starting pressure by Boyle's law	Used as standard to calibrate other gages

---

[1] The unit "Torr" is defined, approximately, as 1 Torr = 1 mm of Hg abs.

2.5.5 Partial Pressure Measurement

Partial pressure measurement is of particular interest to the aerospace environmental engineer for determining the partial pressures of gaseous components found in ecological systems. The partial pressure of a component gas in a mixture of gases is defined as the pressure exerted by the component gas as if it alone were present in the same volume and at the same temperature as the mixture.

Major sources of gaseous components result from the supply gas, external leaks into the system, metabolic processes, outgassing of on-board materials, and physical and chemical changes in materials. Table 3G-3 tabulates some of the partial pressure measurement devices and their characteristics.

2.5.5.1 Selection of Partial Pressure Instrumentation

For aerospace and ground systems the following factors must be considered:

1. Range, accuracy, and response time required for each component gas.
2. Total system pressure.
3. Oxygen compatibility.
4. Desirability of continuous monitoring.
5. Interference effects of other components upon the measurement of interest.
6. Sampling pumps, if required, that may affect the sampling stream's composition.
7. Thermal vacuum exposure.
8. Availability and cost.

For aerospace systems, the factors are:

1. Minimum volume, weight, and power.
2. High reliability.
3. Sustained repeatable performance under all environmental and load conditions.
4. Shelf life.
5. In-flight calibration (not desirable).
6. Automatic operation.

2.5.5.2 Description of the Partial Pressure Devices

The devices listed in Table 3G-3 are discussed in the following paragraphs.

1. **Infrared:** The infrared type operates on the principle that a gas molecule will absorb radiant energy only at wavelengths characteristic of its molecular structure. The energy absorbed is a function of wavelength and the partial pressure of the gas.

Table 3G-3 - Instrument Selection Guide for Partial Pressure Measurements of Gases and Vapors

Component	O_2	CO_2	H_2O (vapor)	N_2	CO	H_2	CH_4	NH_3	H_2S(8)	Halogens	Low M Hydrocarbons
Range of Interest, mm Hg,	100–300	1–30	0–50	0–650	0–0.05	0–10	0–4	0–0.05	0–0.05	0–2	0–0.1
ppm; (10)					0–65			0–65	0–65		
Instruments											
Infrared											
Dispersive	*	Q	Q	*	Q	*	(7); Q	B,Q	*	(7); Q	(7); Q
Accuracy⁺								± 2%			
Nondispersive	*	C	NR	*	NR	*	NR	NR	*	NR	NR
Accuracy⁺		±2%									
Gas Chromatograph Detectors											
Thermal Cond.	B,F; (1)	B,F;(2)	NR	B,F; (1)	B,F; (2)	B,F; (1)	NR	NR	NR	NR	NR
Accuracy⁺	±2%	±2%		±2%	±2%	±2%					
Flame Ionization	*	*	*	*	* (3)	*	B;(4);	*	*	NR	B; (4);
Accuracy⁺							±2%				±2%
Electron Capture	NR	NR	NR	NR	NR	NR	NR	NR	NR	B,F,Q; (6);	NR
Accuracy⁺										±2%	
Argon Ionization, Ultrapure Helium Carrier Gas	B,F; (4)	B,F; (4)	NR	B,F; (4)	B,F; (4)	B,F; (4)	NR	NR; (4) (5)	NR	NR	NR
Accuracy⁺	±2%	±2%		±2%	±2%	±2%					
Mass Spectrometer	B,F,Q	B,F,Q	Q; (7)	B,F,Q	Q; (7)	Q; (7)	Q; (7)	Q; (7)	Q; (7)	Q; (7)	Q; (7)
Accuracy⁺	±3%	±3%		±3%							
Electrochemical											
Oxygen Sensor	A	*	*	*	*	*	*	*	*	*	*
Accuracy⁺	±3%										
CO_2 Sensor	*	A	*	*	*	*	*	*	*	*	*
Accuracy⁺		±5%									
Paramagnetic	B; (9)	*	*	*	*	*	*	*	*	*	*
Accuracy⁺	±1%										
Dew Point	*	*	C	*	*	*	*	*	*	*	*
Accuracy			±1°F								

Key:
- * No response
- ⁺ ±% Full scale.
- NR Not recommended.

Suggested Application(s):
- A Aerospace systems only.
- B Ground systems only.
- C Aerospace and ground systems.
- Q Qualitative analysis.
- F Has aerospace potential.

Notes:
- (1) For detection of concentrations greater than 20 ppm (rough guide).
- (2) For detection of concentrations greater than 50 ppm (rough guide).
- (3) By converting carbon monoxide to methane; detection of less than 5 ppm is possible.
- (4) For detection of concentrations less than 1 ppm.
- (5) Carrier gas, argon.
- (6) Highly sensitive to halogenated compounds; less than 1 ppm.
- (7) Procedure of Par. 2.5.5.3 may be required.
- (8) For H_2S a chemical analysis is preferable.
- (9) Can detect less than 100 ppm.
- (10) To convert ppm to partial pressure, multiply ppm by 760 × 10^{-6}. (assumes 1 atm total pressure)

The measurement is obtained by the use of a dispersive or a nondispersive spectrometer. A dispersive spectrometer plots infrared absorbence versus wavelength and is used primarily as a tool for the qualitative and quantitative analysis of trace and major atmospheric components.

A nondispersive spectrometer monitors one gas in a mixture of gases at a selected wavelength range and gives a continuous readout corresponding to the partial pressure of the gas.

Advantages (nondispersive):

a. Extremely specific for certain gases.

b. High sensitivity.

c. Continuous output.

d. Good accuracy.

e. Fast response time.

Disadvantages (nondispersive):

a. Response is affected by variations in total pressure.

b. Normally requires temperature compensation.

c. No positive means of identification.

d. Cannot detect oxygen and nitrogen.

2. **Gas Chromatography:** A gas chromatography instrument operates by use of a packed column or a capillary column coated with a high boiling point liquid. A carrier gas passes continually through the column. The gas mixture to be analyzed is injected into the carrier gas stream at the head of the column. The relative affinities of the packing or coating material to the gas mixture components cause the components to separate.

As each component leaves the column, it passes into a detecting device, producing an electric signal that appears on a strip chart recorder as a peak. The retention time (the time between injection into the column and detection) identifies each component. The area under the recorded peak is a function of its partial pressure in the mixture.

Advantages:

a. Good accuracy.

b. Analyzes many components in one instrument.

c. High sensitivity.

d. Monitors a known gas mixture continually without the requirement of an operator.

Disadvantages:

a. Readout is not continuous for each component.

b. Requires a recording device.

c. Requires external carrier gas.

d. No positive means of identification. For a particular column the retention time of unknown components may be identical to the component of interest.

3. **Mass Spectrometer:** The mass spectrometer ionizes molecules of the gas sample and then separates the ions according to their mass. The spectrometer consists of three basic parts: an ion source, an analyzer or separation region, and a collector-detector system. The amplitude of the output signal for each detected mass is proportional to the partial pressure of gaseous components having that mass.

One type of mass analyzer is the pulsed time-of-flight spectrometer, in which ions are accelerated (pulsed) into a field-free drift tube. Since all ions enter the drift tube at the same energy, the velocity of the ions is a function of their mass. Ions of lighter mass will reach the collector ahead of heavier species. An appropriate detector system can successively collect each mass and scan the mass spectrum.

Advantages:

a. Good accuracy (if less than five or six constituents).

b. Highly specific for most gases.

c. High sensitivity.

d. Provides continuous analysis of several components when tuned to specified mass numbers.

e. Used for the qualitative and quantitative analysis of trace and major components in atmospheres.

Disadvantages:

a. Vacuum system required; ion source and analyzer system must operate at pressures at or below 10^{-4}mm Hg.

b. Fairly complex instrumentation.

c. Cannot measure trace quantities of carbon monoxide in the presence of nitrogen or carbon dioxide.

d. Requires heated filament for operation; filament subject to oxygen contamination.

e. Sensitive to pressure variations of the sample.

f. Cannot distinguish between gases of equal mass.

g. Sample gases may be cracked to molecular fragments.

h. Can be difficult to interpret when many gases are present.

4. **Electrochemical Oxygen Sensor:** The electrochemical oxygen sensor operates on the principle that oxygen is electrically reduced at the cathode by an applied potential. The reaction causes a current to flow between the electrodes that is directly proportional to the partial pressure of oxygen in the sample.

Advantages:

a. Small size and weight.

b. Low power consumption.

c. Good accuracy and linearity.

d. Rugged.

e. Continuous output.

Disadvantages:

a. Frequent maintenance required (once per week, normally).

b. Temperature dependent.

c. Requires calibration.

d. Cannot be exposed to vacuum and should be operated in an environment of 50% RH or higher.

5. **Electrochemical CO_2 Sensor:** This sensor measures the partial pressure of carbon dioxide by observing the change in pH of a small quantity of electrolyte when this electrolyte is subjected to a gas containing CO_2.

Advantages:

a. Small size and weight.

b. Rugged.

c. Continuous reading.

d. Pressure and flow insensitive.

Disadvantages:

a. Rather long response time.

b. Temperature dependent.

c. Requires calibration.

d. Cannot be exposed to vacuum and should be operated in an environment of 50% RH or higher.

6. **Paramagnetic Oxygen Sensor:** The paramagnetic oxygen sensor operates on the principle that the magnetic susceptibility of oxygen is extremely large compared to that of other gases normally found in atmospheres. This property provides an excellent method for the accurate measurement of oxygen in complex gas mixtures.

Advantages:

a. Good accuracy.

b. Highly specific to oxygen.

c. Simple instrumentation.

d. No electronics (for laboratory version).

e. Requires little calibration (for constant temperature).

Disadvantages:

a. Extremely fragile.

b. Vibration and shock sensitive.

c. Temperature dependent (cannot be easily temperature compensated).

2.5.5.3 Practical Method for Qualitive and Quantitative Analysis

Dispersive infrared analyzers and mass spectrometers are ideal qualitative tools for the analysis of a pure or nearly pure gas component. Note: If the spectra of a multicomponent mixture are superimposed, the multiplicity of overlapping patterns may defy qualitative analysis.

Gas chromatographs are efficient for separating quantitatively multicomponent mixtures, but are not ideally suited for component identification.

Qualitative and quantitative analysis of a gas mixture is achieved as shown in Fig. 3G-14.

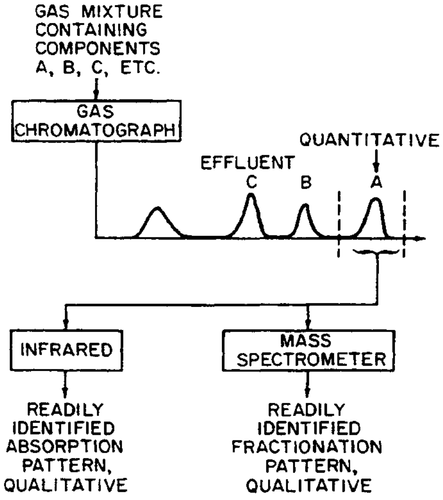

Figure 3G-14 - Methods of Gas Analysis

3. TEMPERATURE MEASUREMENT

3.1 Thermocouples

Two wires of dissimilar metals joined in a loop will generate an electromotive force (emf) if the junctions are at different temperatures. This phenomenon, known as the Seebeck effect, produces an emf that is dependent upon the metals used and the difference in temperature between the junctions. The application of this principle in the form of a thermocouple results in one of the most accurate and convenient ways of measuring temperature.

An intermediate metal may be used without error only if the junctions are at the same temperature; that is, in Fig. 3G-15, point A must be at exactly the same temperature as point B, and point C must be the same as point D. However, A and C need not be at the same temperature.

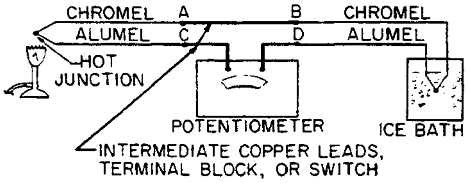

Figure 3G-15 - A Simple Thermocouple Circuit With An Intermediate Metal

It is obvious that if a new junction, such as the chromel-copper junction at A, is introduced, it must be compensated by an equal and opposite junction at B that is at the same temperature.

Because of the difficulty in maintaining uniformity of temperature in the area of terminals and switches, good design practice suggests eliminating all unnecessary intermediate junctions. This problem can also be solved, at considerable cost, by making all switches and terminal blocks out of appropriate thermocouple materials to eliminate intermediate metal junctions. It should be recognized that lot-to-lot differences in apparently similar materials may occur. When highly accurate measurements are required, it may be necessary to treat all material connections as if they were intermediate metal junctions.

A temperature gradient in a homogeneous metal wire will not generate an emf. Thermocouple wires are sometimes tested for homogeneity using this principle because spurious emf's indicate a lack of desired uniformity in the wire. All terminals should be kept clean and dry to avoid electrolytic potentials between dissimilar metals that will introduce serious errors.

3.1.1 Thermocouple Materials

The characteristics of common thermocouple materials are presented in Table 3G-4, and the millivolt outputs of these thermocouples are shown in Fig. 3G-16.

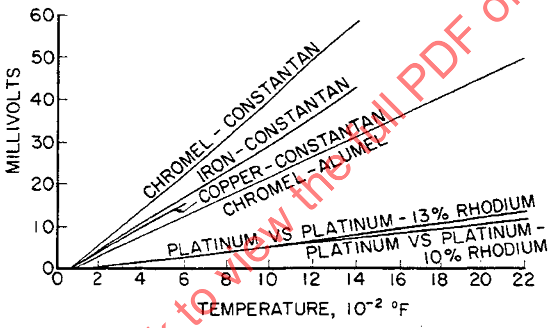

Figure 3G-16 - Temperature-millivolt Curves for Common Thermocouples With 32°F Reference Junction

In summary, copper-constantan is the most satisfactory thermocouple material in the -300 to 600°F range. Because of the purity with which these materials can be produced, copper-constantan wire can be used with a lower limit of error than other materials. Iron-constantan offers, at somewhat less precision, a greater range of 0 – 1400°F, but is susceptible to rust and corrosion. Chromel-alumel thermocouples find wide application in the range 500 – 2100°F, but are of limited accuracy and unsuitable for reducing atmospheres.

Platinum thermocouples, while expensive and therefore not used for routine applications, have a high degree of repeatibility. Once calibrated, they can be used as a reference standard in the range 1000 – 2700°F. There are no important differences between the platinum-platinum/10% rhodium and the platinum-platinum/13% rhodium, although the latter has a slightly higher output and is usually supplied with a lower limit of error.

Table 3G-4 - Characteristics of Common Thermocouple Materials (with ISA designation)

Character	Copper-Constantan, (T)	Iron-Constantan (J, Y)	Chromel-Alumel (K)	Platinum, 10% Pt-Rh (S)	Platinum, 13% Pt-Rh (R)
Approximate Composition					
Positive metal	100% Cu	100% Fe	90% Ni, 10% Cr	90% Pt, 10% Rh	87% Pt, 13% Rh
Negative metal	55% Cu, 44% Ni, 1% Fe-Mn	55% Cu, 44% Ni, 1% Fe-Mn	94.5% Ni, 2.5% Mn, 2% Al, 1% Si	100% Pt	100% Pt
Recommended Temperature Range (large wires), °F					
Continuous	−300 to +600	0–1400	0–2100	0–2800	0–2800
Intermittent	−300 to +600	0–1800	0–2400	0–2900	0–2900
Preferred Atmosphere	Oxidizing or reducing	Reducing or neutral	Oxidizing	Requires ceramic protection tube	Requires ceramic protection tube
Limits of Error,[1] temp °F					
−150 to 75	±2%	. . .	. . .	. . .	. . .
−75 to 0	±1.5%	±4%	±4%	±5%	±2.5%
0–200	±1.5%	±4%	±4%	±5%	±2.5%
200–530	±0.75%	±0.75%	±0.75%	±5%	±2.5%
530–700	±0.75%	±0.75%	±0.75%	±5%	±2.5%
700–1000	. . .	±0.75%	±0.75%	±5%	±2.5%
1000–1500	. . .	±0.75%	±0.75%	±0.5%	±0.25%
1500–2300	. . .	. . .	±0.75%	±0.5%	±0.25%
2300–2700	. . .	. . .	. . .	±0.5%	±0.25%
Recommended Working Limits Max Temp,[2] °F Loop Resistance,[3] ohm/ft					
Wire No.					
8	600 0.0186	1200 0.0215	2000 0.0367		
16	600 0.1187	900 0.138	1800 0.234		
20	500 0.300	800 0.349	1800 0.593	2700 0.182	2700 0.188
24	400 0.785	700 0.881	1600 0.149	2700 0.459	2700 0.474
28	400 1.914	650 2.225	1400 3.781	2600 1.160	2600 1.196
30	400 3.032	600 3.525	1200 5.970	2400 1.836	2400 1.805
40	400 30.93	500 36.06			

---

[1] Limits of error given for standard grade thermocouple wire as normally supplied (errors of connection and instrumentation not included). Special grade wire may be obtained with approximately one-half error indicated for the standard grade.

[2] The recommended working temperature limits for bare wire (except platinum, which requires ceramic tube protection), given in temperature °F.

[3] Loop resistance at ohms per foot, taken at 70 °F for various B & S wire sizes.

Thermocouple reference tables are available from wire manufacturers or from the Government Printing Office (Ref. 13).

The search for improved thermocouple materials and combinations of materials continues. For many years, chromel-constantan has been suggested as a universal couple for the entire range of -300 to 1800°F, offering greater range, higher potential output, and good corrosion resistance. As yet, however, lack of the desired repeatability and stability has deterred wide acceptance of the combination.

The very high temperature range, up to 5000°F, presents a formidable challenge (Ref. 14). In this region, a host of combinations has been advanced, usually with tungsten as one leg of the combination (Ref. 15). Some of the most interesting are tungsten-rhenium, tungsten-molybdenum/1% iron, and various iridium-rhodium combinations. However, all known extreme-temperature couples have serious drawbacks such as drift, oxidation, and fragility. A superior thermocouple for use above the melting point of platinum, from 2700 to 5000°F, is not currently available. Methods of extending the useful range of measurement for thermocouples by the cooled gas pyrometer, the pneumatic probe, and other innovations are discussed in Ref. 14.

Thermocouple insulations, as illustrated in Table 3G-5, must be compatible with the application requirements. In general, the higher the temperature requirement, the more susceptible the insulation is to the hazards of routine handling and use. If a short circuit develops through the insulation, the thermocouple will read the temperature of the junction made at the point of shorting.

Table 3G-5 - Properties of Thermocouple Insulations

Material	Resistance Capabilities			Max Temp Continuous Use, °F
	Moisture	Oil	Abrasion	
Polyvinyl	Excellent	Excellent	Good	220
Nylon	Excellent	Excellent	Good	225
Teflon	Excellent	Excellent	Fair	550
Fiberglas Braid	Fair[1]	Fair[1]	Fair[1]	700
Asbestos	Poor	Poor	Good	1100
Refrasil Braid	Poor	Poor	Poor	2000
Ceramic (SiO_2)	Excellent	Excellent	Brittle	3000

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[1] If coated with silicone varnish (max temp 350 °F).

3.1.2 Thermocouple Construction and Installation

Thermocouple junctions may be formed by welding, brazing, silver soldering, or soft soldering. Routine laboratory couples usually have silver-soldered, twisted-wire junctions. (See Fig. 3G-17). Where gas temperatures are being measured, butt-welded junctions are superior, since the recovery and radiation characteristics are better defined. Various detailed problems of thermocouple fabrication and installation are discussed in Ref. 16.

Figure 3G-17 - Thermocouple Junctions

Installation of accurate surface thermocouples requires that the leads have approximately the same temperature as the junction for at least 50 wire diameters [Fig. 3G-18(a), (b), (c), (d)]. When the leads are not cemented [Fig. 3G-18(d)], unless near isothermal conditions prevail, the results will be sufficiently erroneous to be meaningless.

In some cases, to avoid any protrusion from a metallic surface, it may be desirable to mill a slot in the surface to house the leads. The slot then should be filled with a thermally conductive cement, such as Technical B copper cement, available in dental supply houses.

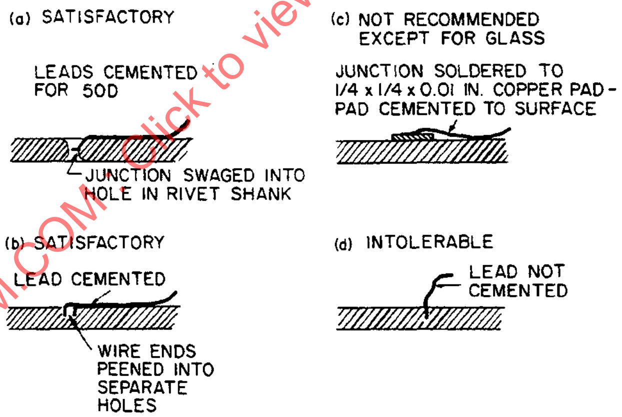


Figure 3G-18 - Several Surface Thermocouple Installations

3.1.3 Thermocouple Errors in Gas Stream Measurement

Principal sources of error in gas stream measurement are: heat conduction away from the junction, radiation heat loss, time lag, and gas velocity.

3.1.3.1 Radiation and Conduction Errors

A thermocouple indicates the temperature of its junction. Whether the junction indicates the gas temperature is dependent on the rather complicated heat transfer process that occurs at the junction. As can be seen in Fig. 3G-19, the junction commonly is involved in the three basic modes of heat exchange: conduction, convection, and radiation. For steady state, all these terms must add up to zero. To approximate a solution for this situation (Ref. 17), the following equation applies, where the emissivity of the gas is negligible:

$$T_g = T_w + T_r \varepsilon_w \left[1 - \left(\frac{T_D}{T_w} \right)^4 \right] + \frac{\psi_m}{1 - \psi_m} [T_w - T_B] \qquad \text{(3G-5)}$$

(A) (B) (C)

where (A) = Indicated temperature
(B) = Radiation error
(C) = Conduction error

in which $\psi_m = \sec h\,\sqrt{hL^2/k_w D}$

$T_r = \sigma T_w^4 / h$, radiation error

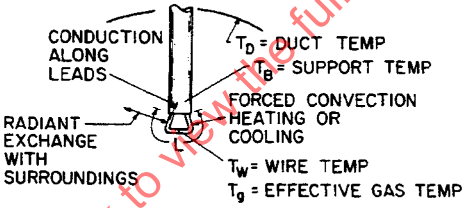


Figure 3G-19 - Junction Heat Exchange

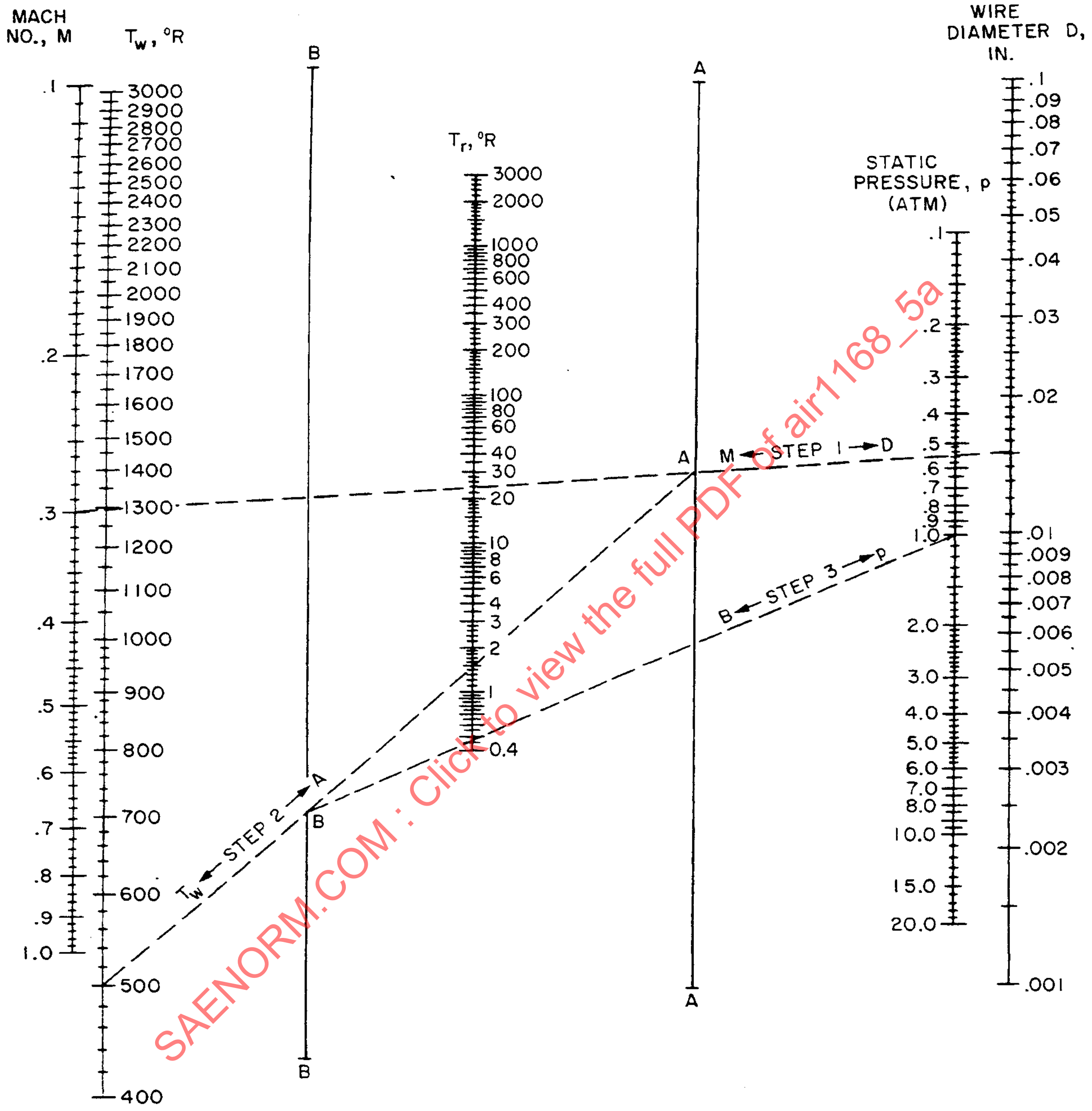
If *L/D* is greater than 30, the conduction error is insignificant. Totally enclosed wells should be analyzed with the fin equation; the nomogram for the computation of T_r is presented in Fig. 3G-20. Because the emissivity of the wire is seldom known with accuracy (typically about 0.8 for chromel-alumel), the preceding method should be considered as indicative of the maximum error likely in the reading, rather than as a necessary correction. Shielded and aspirated probes should be used where the radiation error may be significant (Refs. 18 and 19). However, shielding will tend to increase the time constant and may introduce conduction errors.

3.1.3.2 Thermocouple Response

Response times for bare wire thermocouples can be estimated using the following equation from Ref. 20:

$$\tau = \left[\frac{3.5 \times 10^3 \rho g c_p D^{1.25}}{T} \right] G \exp\left(\frac{-15.8}{\sqrt{T}} \right) \qquad \text{(3G-6)}$$

Eq. 3G-6 is valid only for cross flow. Typical response times for various gages of chromel-alumel at 1000°R are shown in Fig. 3G-21.



GIVEN: T_w = 500 °R
p = 1 ATM
M = 0.3
D = 0.015 IN.

PROCEDURE: CONNECT M TO D AND FIND INTERSECTION A.
CONNECT A TO T_w AND FIND INTERSECTION B.
CONNECT B TO p AND FIND ANSWER T_r.

ANSWER: T_r = 0.46 °R

Figure 3G-20 - Nomograph for Determining Radiation Error

An improvement in response can be realized by tubular junctions (Ref. 21). For shielded junctions, response times must be determined experimentally (Refs. 18 and 19).

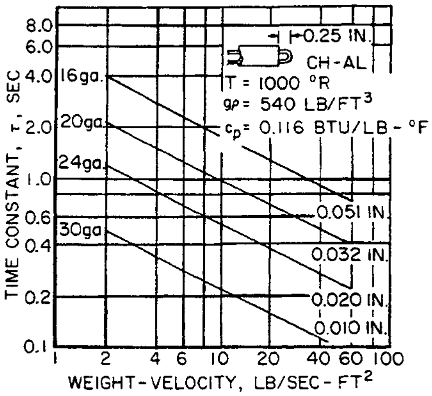


Figure 3G-21 - Dependence of Time Constant On Wire Diameter and Weight Velocity

3.1.3.3 Velocity Error

Imperfect energy recovery during impact deceleration will result in a thermocouple indicating a temperature that is lower than the true total temperature. This deviation from the ideal is commonly described by a number of redundant terms, such as

$$\text{Recovery ratio:} \quad R = \frac{T_g}{T_t} \qquad \text{(3G-7)}$$

$$\text{Recovery factor:} \quad r = \frac{T_g - T_{st}}{T_t - T_{st}} \qquad \text{(3G-8)}$$

$$\text{Recovery correction factor:} \quad \Delta = \frac{T_t - T_g}{T_t} = 1 - R \qquad \text{(3G-9)}$$

where T_g = Temperature of gas surrounding junction, °R

T_{st} = Static temperature, °R

T_t = Total temperature, °R

In applying the deviations of temperature from the ideal, the recovery correction factors (Δ) are perhaps the easiest to use. They are a function of pressure, temperature, probe size, and Mach number. Values of recovery correction factors at a reference condition, Δ_0, for a variety of probes are shown in Fig. 3G-22. As can be noted, all probes except for probes 3 and 6 show a decrease in the recovery correction factor as the pressure decreases; that is:

For probes 1, 2, 4, 5, 7, 8, 9:

$$\frac{\Delta}{\Delta_0} \approx 0.7 \text{ to } 1.0 \quad \text{at } 0.2 \text{ atm}$$

For probes 3 and 6:

$$\frac{\Delta}{\Delta_0} \approx 2 \text{ to } 4 \quad \text{at } 0.2 \text{ atm}$$

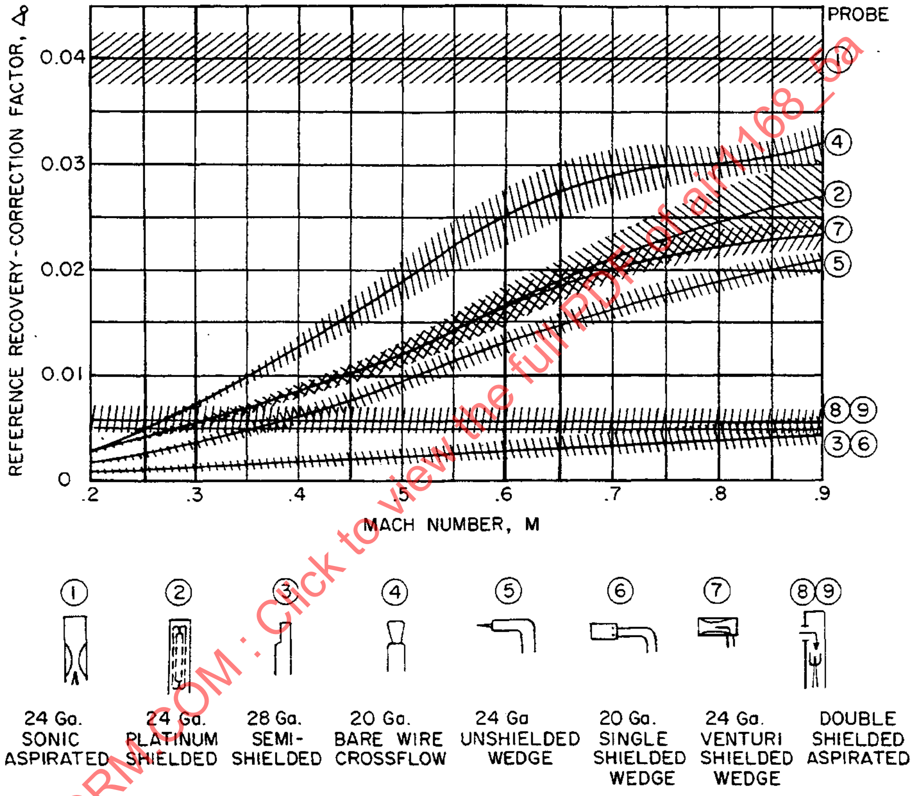


Figure 3G-22 - Variation of Reference Recovery-correction Factor Δ With Mach Number, at Reference Conditions (Total pressure, 1 atm; room temperature. Crosshatch represents spread in data for several probes.)

For butt-welded, bare-wire probes, this behavior has been correlated empirically using the following equation from Ref. 18

$$\frac{\Delta}{\Delta_0} = \left(\frac{P}{P_0}\right)^{1/5} \left(\frac{T_0}{T_t}\right)^{1/4} \left(\frac{d}{d_0}\right)^{1/5} \qquad \text{(3G-10)}$$

where subscript 0 indicates the reference condition.

3.1.4 Thermocouple Potentiometers

Most of the indicating instruments and potentiometers used with thermocouples are null-balancing bridge instruments, thus making the lead resistance unimportant. However, excessively high loop resistance (see Table 3G-4) will make the instrument sluggish. Manufacturers recommendations provided with the instrument should be adhered to. Table 3G-6 presents the performance to be expected of typical commercial instruments of various classes.

Table 3G-6 - Characteristics of Typical Commercial Potentiometers

Instrument Type	Calibrated Accuracy as % Scale Span or μv[1] (whichever is larger)	Sensitivity (larger of values)
Strip Chart Recorder	1/5% or 20 μv	1/32% or 4 μv
Indicator: Circular or Vertical Scales	1/4% or 30 μv	1/32% or 4 μv
Precision Indicator (Brown, Rubicon)	1/50% or 3 μv	1 μv
Portable Potentiometer (E. G., L & N 8662)	10 μv to 50 μv (depending on range)	
Laboratory High Precision Potentiometer (E. G., L & N K-3)	0.015% or 0.5 μv (0 – 16 mv) 0.015% or 2 μv (0 – 160 mv)	0.1 μv (0 – 16 mv) 1 μv (0 – 160 mv)

[1] Note: 10 μv is approximately 0.3°F with iron-constantan couple.

3.2 Resistance Thermometers

Underlying one important branch of thermometry is the fact that the electrical resistance of a wire is a function of its temperature. For most cases, the resistance at a given temperature, R_t, is approximated by

$$R_t = R_0(1 + \alpha T) \tag{3G-11}$$

where R_t = Resistance at a given temperature, ohm

R_0 = Resistance at reference temperature, ohm

α = Temperature coefficient of resistance, ohm/ohm-°F

Since the resistance-temperature curve is not always linear, a calibration should be made through the range of application. Platinum, copper, and nickel (Table 3G-7) are among the wires used. Typical resistance elements are shown in Fig. 3G-23.

Table 3G-7 - Characteristics of Resistance Wires[1]

Wire	Useful Temp Range, °F	α, Temp Coeff (Ref 32°F) for 32 to 212°F, ohm/ohm-°F	Accuracy	Cost
Platinum	−430 to 1650	0.00218	Excellent	High
Nickel	−240 to 570	0.0036	Good	Moderate
Copper	−330 to 250	0.00236	Good	Low

[1] Based on material in Ref. 10

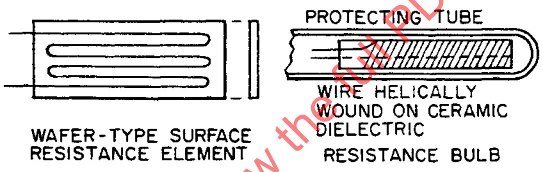


Figure 3G-23 - Resistance Thermometer Elements

3.3 Thermistors

Certain semiconducting materials, such as the oxides of manganese, nickel, zinc, and cobalt, have high negative coefficients of resistivity. These oxides may be used in the form of discs, beads, or rods, to manufacture thermistors (Fig. 3G-24) for measuring or controlling temperature.

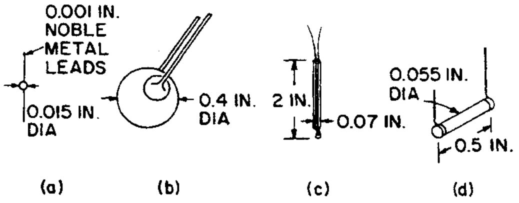


Figure 3G-24 - Typical Thermistor Elements. (a) Glass Coated Bead; (b) Disc; (c) Bead On Glass Probe; (d) Rod

The resistance change of thermistors is described approximately by

$$R = R_0\, \alpha^{B\left(\frac{1}{T}-\frac{1}{T_0}\right)} \qquad \text{(3G-12)}$$

where R = Resistance at temperature T, °R
R_0 = Resistance at temperature T_0, °R
α = Temperature coefficient of resistance, ohm/ohm-°F
B = Constant for limited temperature ranges $\approx -\alpha T_0^2$

Various proprietary combinations of semiconducting materials, with specific resistance in the range 100 – 10,000 ohm-cm are used in the manufacture of thermistors. Permutations of materials and geometries result in elements with resistances, R_0, from 1 to 10^8 ohms. Table 3G-8 presents data that are specific to the elements depicted in Fig. 3G-24 only, but suggest the general performance to be expected.

Table 3G-8 - Characteristics of Several Representative Thermistor Elements[1]

Description Fig. 3G-24	α, Temp Coeff at 77°F ohm/ohm-°F	Resistance, R_0, at 77°F ohm	Max Continuous Ambient Temp °F	Time Constant in Still Air sec
Bead (a)	−0.019	2000 ± 25%	300	1
Disk (b)	−0.021	100 ± 10%	260	160
Probe (c)	−0.021	2000 ± 20%	570	25
Rod (d)	−0.024	100,000 ± 10%	250	20

[1] Based on material from Ref. 10.

While thermistors have a greater sensitivity than resistance thermometers because of the large value of α, they exhibit some lack of stability and reproducibility, especially at higher temperatures. The drift is usually caused by diffusion of lead material into the semiconductor or by a change in chemical composition. Glass coatings can be used to reduce chemical degradation or decomposition.

Because of the high sensitivity, thermistors are well suited to narrow band temperature control applications, such as cabin and duct temperature sensors or heated window control sensors. The high resistance, R_0, of thermistors also lessens the problems of resistance effects in the leads to the sensors.

3.4 Radiation and Optical Pyrometers

Advances in general technological levels are related historically to achievement of higher and higher temperatures. Research on phenomena taking place near the melting point of refractory solids places emphasis on instruments that do not require contact with the material under study. The optical and radiation pyrometers (Fig. 3G-25) are of this type.

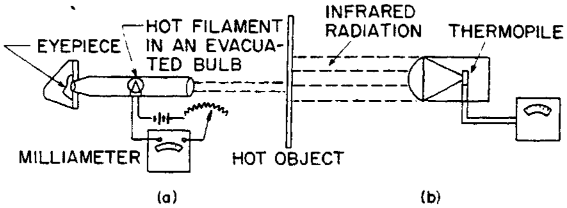


Figure 3G-25 - Optical and Radiation Pyrometers. (a) Simple Optical Pyrometer of Disappearing Filament Type; (b) Radiation Pyrometer

In the disappearing filament type of optical pyrometers, the temperature of a tungsten filament is adjusted by varying the current flow through it until it disappears against the background of the target. Normal limits of application lie between 1400 and 5200°F, but can be extended to 10,000°F with special absorbing screens (Ref. 10). Accuracies of ±2°F at 2000°F are claimed for quality instruments.

The radiation pyrometer depends upon focusing of the radiated energy upon the detecting element, such as a photocell, bolometer, thermocouple, or thermopile. This instrument is more flexible than an optical pyrometer, and can be used in the range from room temperature up to any conceivable temperature (Ref. 10). Many types, offering various specialized capabilities, are manufactured commercially.

3.5 Heat Meters

The heat meter is a device embodying the thermopile principle and consisting of junctions in series on each side of a thermal resistance layer, such as a thin sheet of bakelite. The millivolt output of the heat meter is proportional to the temperature difference across the thermal resistance layer and, therefore, to the heat flow. Commercial heat meters are usually made of plastic and have outputs in the range 2 – 700 μV/(Btu/hr-ft^2). Other methods of construction are discussed in Ref. 22. Reliable high temperature meters have not yet been developed.

Great care and experimental ability are required in applying heat meters. Constant monitoring of the calibration and the analysis of the disturbing effect of the meter on the heat flow are among the precautions required to avoid the pitfalls of this type of measurement. Repeatability to ±1/2% has been achieved under ideal laboratory conditions, but ±10% is more typical for routine applications.

Heat transfer rates often can be inferred from the transient temperature behavior of surfaces. Aerodynamic heating and shock tube studies often utilize this technique and, of the many discussions of the method, Refs. 23 and 24 are representative.

4. FLUID FLOW MEASUREMENT

Although fluid meters based on many physical principles have been developed, the fluid accelerators or head meters have gained the widest usage because of inherent simplicity and accuracy. Primary emphasis in this section will be given to the three basic head meters: nozzle, venturi tube, and orifice. Rotameters, magnetic meters, volume meters, sonic meters, and other special techniques may offer distinct advantages in certain applications. These meters and special features of each will be discussed briefly.

Where the operation of a fluid meter depends on pressure and temperature measurements, the necessary corrections to such observations should be made as indicated in previous sections.

Ref. 25 is a particularly authoritative compilation of fluid meter data. As nearly as possible, the nomenclature of this section is consistent with that work.

4.1 Characteristics of Head Meters

4.1.1 Selection of the Proper Head Meter

Each of the principal head meters has particular attributes that influence their suitability for a particular application.

Advantages:

1. **Orifice:** Most versatile, least expensive, and probably the most accurate of the head meters for general laboratory application; unsuitable for dirty fluid or slurries; fairly high unrecoverable pressure loss.
2. **Nozzle:** More accurate than an orifice for supercritical pressure ratios; handles dirty fluids and slurries better than an orifice; more expensive than an orifice to machine; unrecoverable pressure loss about the same as an orifice.
3. **Venturi Tube:** Characteristics similar to a nozzle except for the very low pressure loss, making it particularly suitable for applications where savings in pumping power are important.
4. **Pitot-Static Tube:** Offers negligible line restriction; possible to traverse where skewed velocity profile might invalidate another type of head meter, but traversing is cumbersome and time consuming; cannot be used where velocity pressure is low.
5. **System Line Loss:** A test technique for flow measurement without introducing meter disturbance; limited accuracy; requires calibration which may be very sensitive to variable upstream system geometry, for example, valve position.

Disadvantages:

1. Limited flow range for a given metering arrangement. For example, an orifice plate producing a 30 in. H_2O differential on a U-tube manometer at full flow can be utilized only to 20 to 30% of full flow with reasonable accuracy.
2. The usual application requires a flow computation, making the setting of a desired flow more difficult than with a direct indicating meter. Totaling varying flows over a time interval is difficult.
3. Behavior of head meters with pulsating flow is uncertain and the subject of continuing research (Ref. 25).

4.1.2 Basic Equation

The equations used for computing flow through nozzles, venturi tubes, and orifices usually are simplified forms of the basic nozzle equation, with empirical coefficients and corrections as required. Intelligent use of these simplified forms requires an examination of this equation, which can be derived from the general energy equation, the adiabatic relationship, and the continuity equation. For fluid meter applications, the equation is usually arranged as

$$\underset{\text{(A)}}{W = \frac{C}{\sqrt{1-\beta^4}}} \underset{\text{(B)}}{\left[\frac{\gamma}{\gamma-1} \frac{(1-\beta^4)\,(1-r^{(\gamma-1)/\gamma})\,r^{2/\gamma}}{(1-\beta^4 r^{2/\gamma})\,(1-r)} \right]} \underset{\text{(C)}}{A_2} \underset{\text{(D)}}{\sqrt{2g\,(\rho g)_1\,(P_1-P_2)}} \qquad \text{(3G-13)}$$

where the labeled expressions

(A) = Flow coefficient K
corrected for velocity of approach, dimensionless
(B) = Adiabatic expansion term Y_a, dimensionless
(C) = Nozzle area, ft^2
(D) = Flow velocity term, $(lb/sec)/ft^2$

and P_1 and P_2 are measured at stations 1 and 2 shown in Fig. 3G-26.

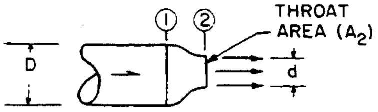


Figure 3G-26 - Measurement Stations

It will be noted that the flow velocity term is incompressible in form and contains the upstream density, which is more readily measurable. Actually, the weight flow is proportional to the product of the throat velocity and the throat density. Thus the Y_a term may be thought of as a correction factor applied to the incompressible flow velocity term to account for these effects. It also follows that for incompressible fluids, $Y_a=1$. The discharge coefficient C results from the fact that in a real fluid the boundary layer buildup along the nozzle walls prevents full utilization of the entire throat area at the predicted velocity.

For an orifice, the point of minimum flow area occurs downstream at the vena contracta. Because the vena contracta diameter and area ratio are indeterminate, the actual orifice dimensions are used and the flow coefficient K and expansion term (designated Y_1' for orifices) are empirical.

4.1.2.1 Specific Forms of the Basic Equation

Assignment of units, as indicated in Table 3G-9, to the basic flow equation

$$W = KYA_2\sqrt{2g(g\rho)_1(P_1 - P_2)} \tag{3G-14}$$

results in the equations of Table 3G-9, where $(g\rho)$ is always in lb/ft^3.

Table 3G-9 - Forms of Basic Equation

Equation	Units W	Units P	Units A or d
$W = 8.022KYA_2\sqrt{(g\rho)_1(P_1 - P_2)}$	lb/sec	psf	ft^2
$W = 96.26KYA_2\sqrt{(g\rho)_1(P_1 - P_2)}$	lb/sec	psi	ft^2
$W = 40.11KYA_2\sqrt{(g\rho)_1(P_1 - P_2)}$	lb/min	psi	in.^{2}
$W = 28.06KYA_2\sqrt{(g\rho)_1(P_1 - P_2)}$	lb/min	in. Hg[1]	in.^{2}
$W = 7.617KYA_2\sqrt{(g\rho)_1(P_1 - P_2)}$	lb/min	in. H_2O[1]	in.^{2}
$W = 5.982KYd^2\sqrt{(g\rho)_1(P_1 - P_2)}$	lb/min	in. H_2O[1]	in.

[1] At 68 °F

4.1.3 Corrections Common to All Head Meters

While the individual types of meters have characteristics that will be treated in detail in later subsections, there are certain corrections basic to all head meters.

4.1.3.1 Thermal Expansion

The area A_2 used in Eq. 3G-13 must be the true area at operating conditions. Since the diameter of the element is usually measured at room temperature, a correction factor should be applied to determine the area at elevated temperatures. From Fig. 3G-27:

$$(A_2)_{t_E} = F_a(A_2)_{70^\circ F}$$

4.1.3.2 Density Corrections for Compressibility and Humidity

The perfect gas law, commonly used to compute density, adequately describes real gas behavior only in a limited region. For example, with air at pressures from 0 to 200 psia and temperatures above 60°F, the perfect gas law is within 0.5%. Deviations from perfect gas behavior can be accounted for by using the compressibility factor Z, such that

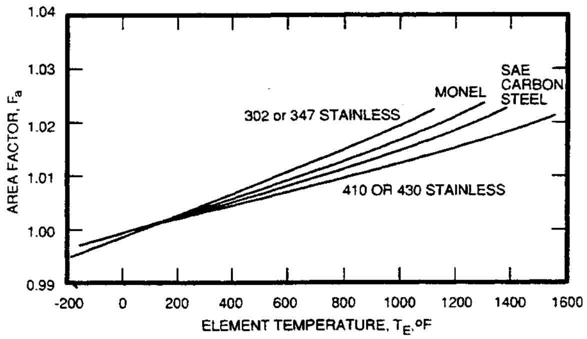


Figure 3G-27 - Correction Factor for Expansion of Metering Element

$$\rho g = \frac{P}{ZRT} \tag{3G-15}$$

For air, the trend in variation of Z is shown in Fig. 3G-28. Compressibility factors for the common gases can be found in Refs. 26 and 27. In some applications, a choice of meter locations will permit elimination of this correlation.

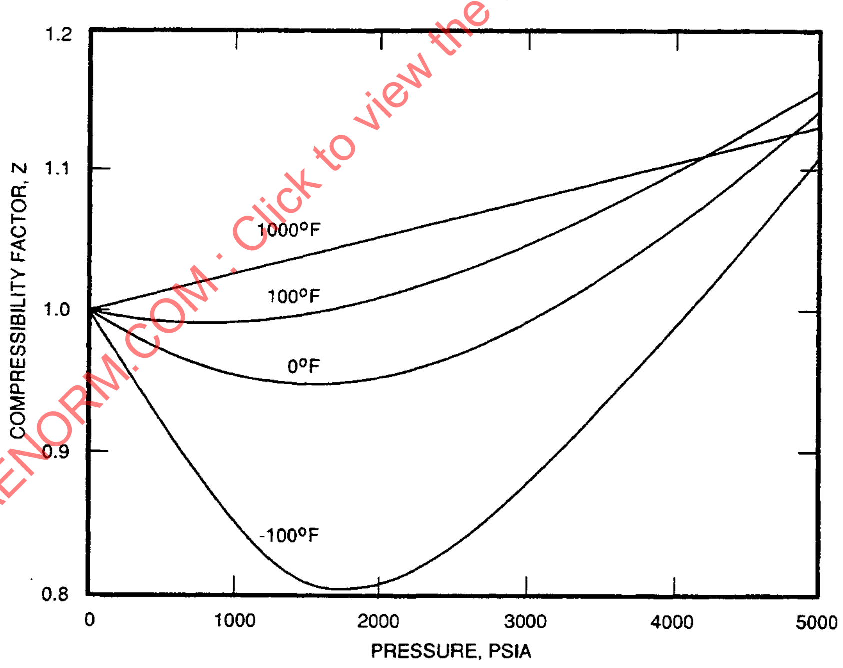


Figure 3G-28 - Compressibility Factor for Dry Air. (Based on data from Ref. 27)

Where the gas being metered contains water vapor, a correction is necessary to the density, computed on a dry gas basis. The corrected wet gas density may be obtained as follows:

$$(\rho g)_{\text{wet gas}} = (\rho g)_{\text{dry gas}} \left[\frac{1+\omega}{1+(M\omega/18.01)} \right] \qquad \text{(3G-16)}$$

and for air,

$$(\rho g)_{\text{wet air}} = (\rho g)_{\text{dry air}} \left[\frac{1+\omega}{1+1.608\omega} \right] \qquad \text{(3G-17)}$$

where M = Molecular weight of dry gas

Humidity effects on other terms in the flow equation are generally negligible (Ref. 3).

4.1.4 Proper Meter Installation

The head meters are seriously influenced by disturbing upstream and downstream conditions. While data exist (Ref. 28) for the requisite straight lengths preceding and following the meter for various kinds of disturbances, the conservative rules in Table 3G-10, with reference to Fig. 3G-29 (lengths a and b), should be adequate.

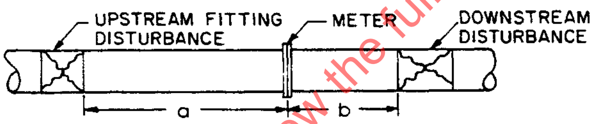


Figure 3G-29 - Illustration for Lengths a and b in Table 3G-10

Table 3G-10 - Disturbances Affecting Meter Installation

	Minimum Straight Lengths, dia	
Disturbance Type	a	b
All types (except two or more upstream bends in different planes):		
$\beta = 0.10 - 0.5$	10	3
$\beta = 0.60 - 0.70$	18	4
For upstream bends in different planes:		
$\beta = 0.10 - 0.4$	18	3

For all β (diameter ratios) above 0.70, and for β ratios above 0.4 when preceded by bends in different planes, it becomes desirable to use a flow straightener. In fact, any general purpose laboratory metering section should be so equipped. Two accepted designs for flow straighteners are shown in Fig. 3G-30.

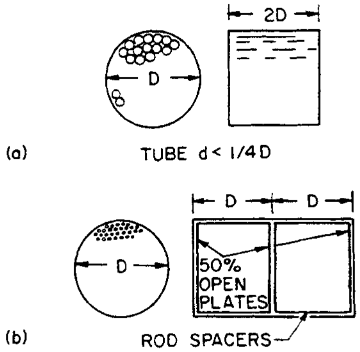


Figure 3G-30 - Accepted Designs for Flow Straighteners

Although it introduces a higher pressure loss (about 10 times the duct velocity pressure), the perforated plate straightener has been shown to be superior to either the packed tube or the egg crate type of flow straightener (Ref. 29). The straightener should be installed 10 dia upstream of the meter and should be preceded by an additional 2 dia of straight pipe.

4.2 The Flow Nozzle

4.2.1 Nozzle Geometry and Discharge Coefficients

The three most common nozzle designs are illustrated in Fig. 3G-31. The ASME nozzles usually are used with pipe-wall taps. The ISA nozzle with corner taps is used extensively in Europe. The ASME nozzles with pipe-wall taps are preferable, since an upstream corner tap tends to pick up some impact pressure, whereas the expansion factor Y_a is based on static pressures.

The ASME long radius nozzle discharge coefficients have been verified by a great number of experiments (Fig. 3G-32). Also, a reasonably accurate theoretical development of the discharge coefficient for this type of nozzle has been made using boundary layer theory (Ref. 30).

4.2.2 Calculation Procedure

Because the discharge coefficient is a function of Reynolds number, and thus of the flow, a small amount of iteration is involved in the computation. Using Eq. 3G-13,

$$W = \frac{C}{\sqrt{1-\beta^4}} Y_a A_2 \sqrt{2g(g\rho)_1 (P_1 - P_2)} \qquad \text{(3G-18)}$$

proceed as follows:

1. First make a reasonable guess at the nozzle flow and compute the Reynolds number from

$$N_{Re} = \frac{(g\rho)_1 VD}{\mu g} = \frac{4}{\pi \mu g}\left(\frac{W}{D}\right) \qquad \text{(3G-19)}$$

For air, use Fig. 3G-33 as an aid. Obtain C from Fig. 3G-32.

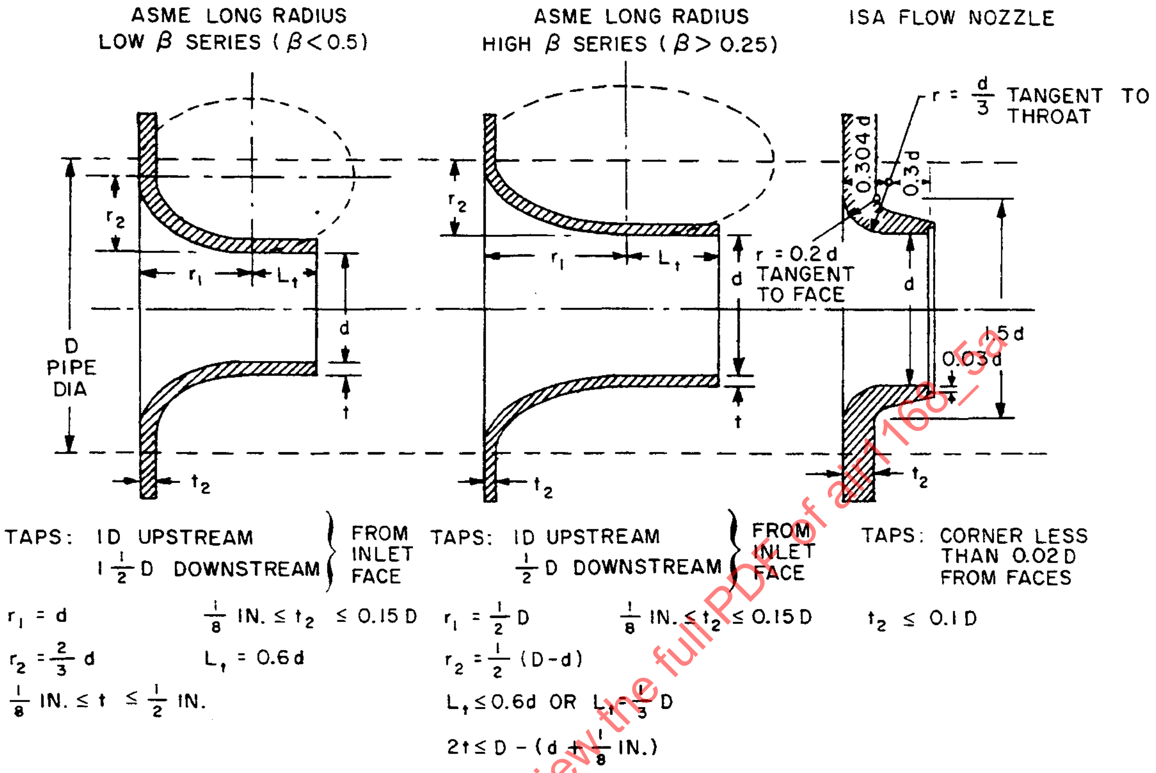


Figure 3G-31 - Geometry of Three Common Metering Nozzles

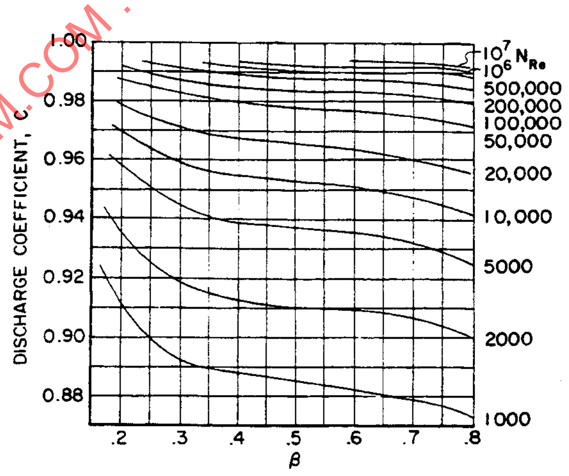


Figure 3G-32 - Discharge Coefficients of ASME Long Radius Nozzles With Pipe Wall Tap

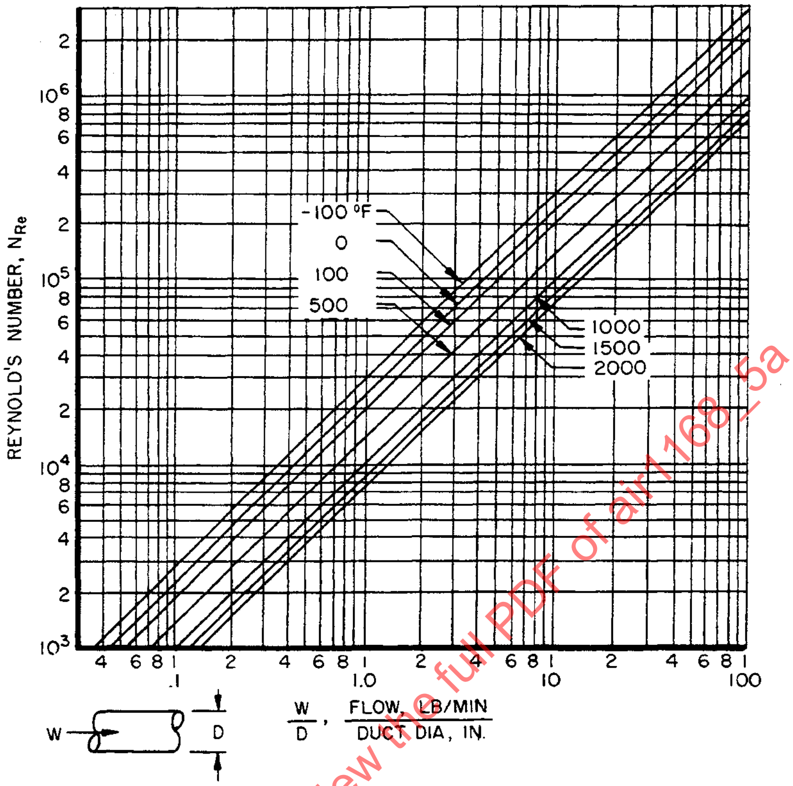


Figure 3G-33 - Reynolds Number As A Function of Flow Per Inch of Duct Diameter For Air

2. Compute the density from the upstream static pressure and temperature. For some liquids, it may be desirable to make an experimental density determination with a hydrometer or other suitable instrument. Make humidity and compressibility corrections.

3. If flow is compressible, using the β ratio and the nozzle pressures, determine Y_a from Fig. 3G-34 (for $\gamma = 1.4$) as

$$Y_a = \left[\left(\frac{P_1}{P_2}\right)^{2/\gamma} \left(\frac{\gamma}{\gamma - 1}\right) \left(\frac{1 - (P_2/P_1) \exp\left[\frac{\gamma - 1}{\gamma}\right]}{1 - (P_2/P_1)}\right) \left(\frac{1 - \beta}{1 - \beta^4 (P_2/P_1)^{2/\gamma}}\right)\right]^{1/2} \qquad (3G\text{-}20)$$

Curves for other specific heat ratios are available in Ref. 1. Also see Fig. 3G-35, where for flange taps, plotted for $\gamma = 1.4$,

$$Y_1 = 1 - (0.41 + 0.35\beta^4)\frac{P_1 - P_2}{P_1 \gamma} \qquad (3G\text{-}21)$$

4. Substituting in Eq. 3G-18, compute the flow. Recalculate the Reynolds number and obtain an improved value for the discharge coefficient. Improve the flow by the ratio of the new discharge coefficient to the original. Even when striving for high accuracy, it is usually not necessary to repeat this process more than once.

Since *C* does not vary more than a few percent in the working range, in some cases it may be permissible to use a single value for *C* and neglect the Reynolds number effects. However, it is wise to examine carefully the impact of all terms in Eq. 3G-18, in view of each specific application, before deciding that any can be assumed constant.

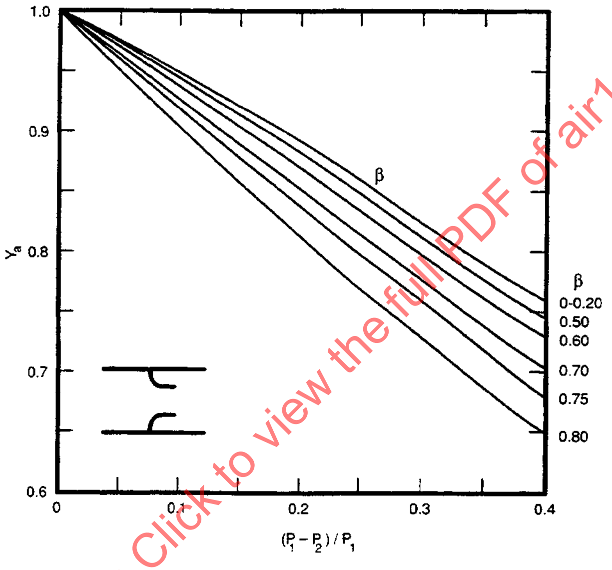


Figure 3G-34 - Expansion Factor for Nozzles and Venturi Tubes

4.2.3 The Choked Nozzle

As the Mach number in the nozzle throat approaches 1, Eq. 3G-13 tends to conceal the important variables, since it is purposely formulated as an incompressible flow equation with corrections for compressible flow. The equation may be rearranged as

$$\frac{W\sqrt{T_1}}{P_1A_2} = C\,\frac{\left[\frac{2g}{R}\left(\frac{\gamma}{\gamma-1}\right)\right]^{1/2}\left[r^{2/\gamma}\left(1-r^{(\gamma-1)/\gamma}\right)\right]^{1/2}}{\sqrt{1-\beta^4\,r^{2/\gamma}}} \tag{3G-22}$$

As the velocity at the throat approaches the acoustic velocity, the ratio of the throat static pressure to upstream static pressure becomes constant at a value of 0.528 for air, or greater, depending on the diameter ratio β. Beyond this point the throat pressure and the downstream pressure begin to diverge, but the flow is still governed by the fixed upstream-to-throat pressure ratio. Fig. 3G-36 depicts this behavior for nozzles and venturies. Fig. 3G-37 plots the data for orifices.

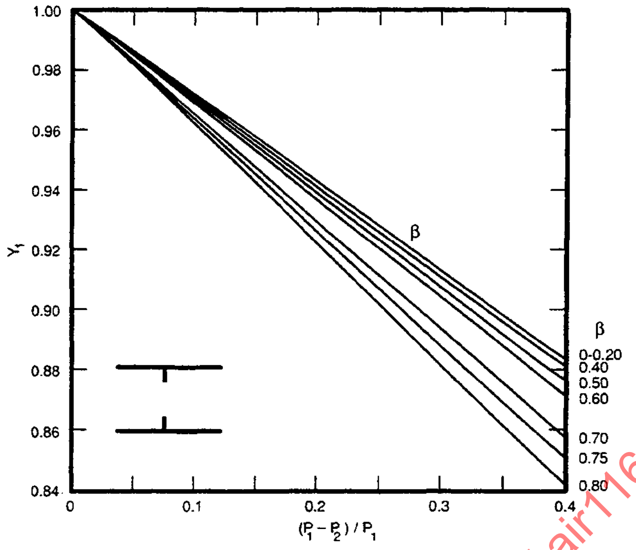


Figure 3G-35 - Expansion Factor for Sharp Edged Orifices

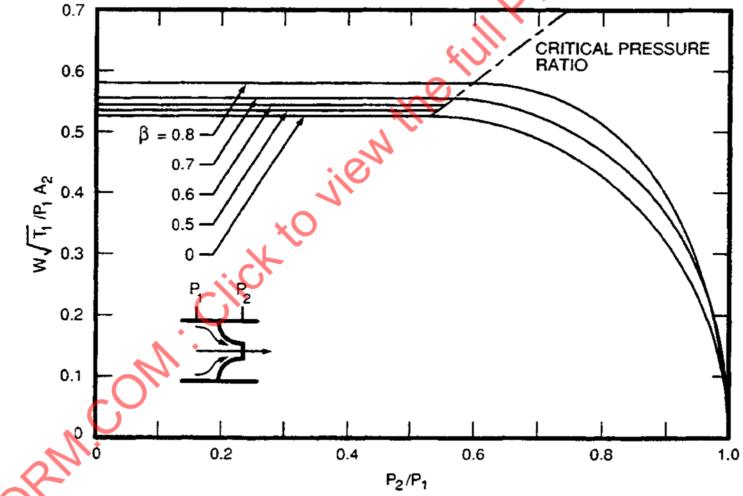


Figure 3G-36 - Flow Factors for Nozzles and Venturis (W = lb/sec, T_1 = °R, P_1 = psia, A_2 = nozzle or venturi throat area, in.^{2}. For air from Eq. 3G-22, $C_{assumed}$=0.985, γ = 1.4)

4.3 Venturi Tubes

4.3.1 Venturi Tube Design and Discharge Coefficients

The classical venturi design is widely used, although there are a number of variants (Fig. 3G-38). Perhaps the most interesting of these is the Dall tube, a highly individualistic form of the venturi with truncated approach and discharge sections (Ref. 31). The Dall tube has, for reasons yet unexplained, the lowest unrecoverable pressure loss of any of the acceleration type head meters.