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SURFACE VEHICLE RECOMMENDED PRACTICE

An American National Standard

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(R) MEASUREMENT OF INTAKE AIR OR EXHAUST GAS FLOW OF DIESEL ENGINES

1. ***Scope***—This procedure establishes recommendations on the measurement of diesel engine intake air flow under steady-state test conditions. The measurement methods discussed have been limited to metering systems and associated equipment found in common usage in the industry, specifically, nozzles, laminar flow devices, and vortex shedding. The procedure establishes accuracy goals as well as explains proper usage of equipment. The recommendations concerning diesel engine exhaust mass flow measurements are minimal in scope.

1.1 **Purpose—**This SAE Recommended Practice is intended to provide guidance for the proper measurement of combustion air flow into diesel engines as utilized in engine test cell environments.

2. *References*

2.1 **Applicable Publications—**The following publications form a part of the specification to the extent specified herein. Unless otherwise indicated the lastest revision of SAE publications shall apply.

1. SAE J177—Measurement of Carbon Dioxide, Carbon Monoxide, and Oxides of Nitrogen in Diesel Exhaust.
2. ASME PTC 19.5:4-1959—"Flow Measurement."
3. "Fluid Meters, Their Theory and Application," ASME, Sixth Edition, New York, 1971.
4. ISA 1979, ISBN 87664-453-3, Tutorial, "Test Measurement Accuracy."
5. Voss, L. R., and Hollyer, R. N., "GMR True Radius Nozzles," General Motors Research Laboratories, Warren, MI, January 1961.
6. "Tables of Thermal Properties of Gases," National Bureau of Standards Circular 564, 1960.

3. Definitions—Symbols and Abbreviations

3.1 Abbreviations

abs—Absolute
cal—Calibration
exh—Exhaust
rpm—Revolutions per minute
vol—Volume
mo—Moist

3.2 Symbols—SI Units (English Units)

B—Barometric pressure, kPa (in Hg); abs
C—Coefficient of discharge
D—Upstream pipe diameter, mm (in)
E—Velocity of approach factor
Fa—Area thermal expansion factor
MW—Molecular weight, kg/kg-mole (lbm/lbm-mole)
N_H—Hodgson's number
N_R—Reynolds number
P—Pressure, kPa (in Hg)
Q—Volume flow rate, m^3/s (ft^3/s)
RU—Universal gas constant, 8314.4 J/kg-K (1545.3 ft-lb/lbm mole °R)
R—Gas constant, specific gas, J/kg-K (ft-lbf/lbm-°R)
SW—Swept volume, m^3 (ft^3)
T—Temperature, Kelvin (°Rankine)
U—Uncertainty
V—Velocity, m/s (ft/s)
Y—Expansion factor
Z—Compressibility factor
b—Bias error
d—Nozzle throat diameter, mm (in)
e—Vapor pressure, kPa (in Hg, abs)
f—Frequency, Hz
k—Ratio of specific heats
m—Mass flow per unit time, kg/s (lbm/s)
t—Ambient temperature, °Celsius (°Fahrenheit)
μ—Viscosity, absolute, centipoise
β—Ratio of nozzle throat diameters (throat or orifice to pipe diameter)
ρ—Density, kg/m^3 (lbm/ft^3)
σ—Precision error
Y—Ratio of specific heats, 1.40 for air
ΔP—Pressure differential, kPa (in H_2O)

3.3 Subscripts

A—absolute
d—Dry
dt—Dry at test conditions
t—Test
mo—Moist
(test)—Test conditions
(cal)—Calibration conditions
L—Leakage
v—Vapor
1—Location point at meter inlet
2—Location point at meter outlet

4. Principal Equipment

4.1 Component Description—Components necessary for measurements are as described as follows and as in Figure 1:

a. Filter — Only as required by flow meter.
b. Flow meter — As described in Section 5.
c. Nonpulsating blower — Optional, to restore pressure loss due to flow meter and temperature control.
d. Temperature control — Optional.
e. Restriction valve — To control engine inlet air pressure.
f. Plenum — See 4.2.
g. Engine.
h. Pressure sensors, P_1, P_2, P_3, and P_4.
i. Temperature sensors, T_1, T_2, T_3, and T_4.
j. Chamber to engine line may be flexible. Should be minimum length; diameter selected on basis of maximum velocity not to exceed 90 m/s.
k. Restriction valve — Optional, to control engine back pressure. Locate the valve at usual muffler position. However, if muffler location is unknown, it is recommended that the valve be located 20 diameters of exhaust pipe from the engine exhaust flange.

4.2 Plenum Chamber Volume—Due to the nature of diesel engines, pressure pulsations in the air measurement system may be present. In general, pulsations in the systems have adverse effects on most air flow metering devices and must be controlled for proper air flow measurements. A plenum chamber between the meter and the engine air intake can help isolate the meter by attenuating the pulsations.

4.2.1 The minimum recommended plenum chamber volume should conform to Equation 1:

$$vol = \frac{K \times SW}{rpm \times \sqrt{Stroke/Rev}} \quad \text{(Eq. 1)}$$

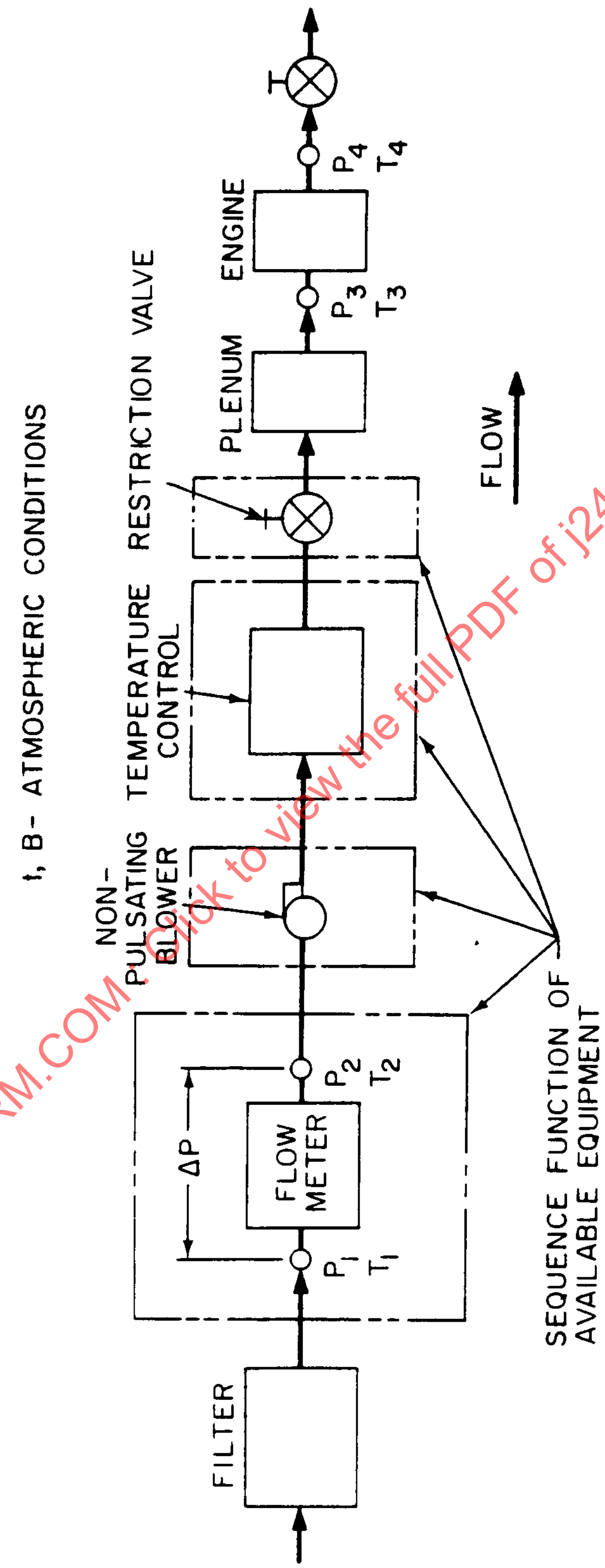


FIGURE 1—COMPONENT FIGURATION

where:

vol	=	Volume of plenum chamber	m^3	in^3
SW	=	Swept volume of one cylinder	L	in^3
rpm	=	Lowest engine speed at which air flow measurements are to be made	rpm	rpm
Stroke/Rev	=	Number of intake strokes per engine revolution		
K	=	Dimensionless constant.		
		Suggested values are:		
		Naturally aspirated diesel w/nozzle	180	180 000
		Naturally aspirated diesel w/o nozzle	90	90 000
		Other meters and engines	90	90 000

4.2.2 The plenum may be excluded if test data show that the engine and flow meter are insensitive to the plenum chamber volume. The check, as follows, may help determine the effect of the pressure pulsations.

a. The frequency of the pulsations should be determined at a point between the flow meter and the plenum chamber.
b. Low-pressure transducers or microphones can be used to sense the pulsations with their output fed into a narrow-band frequency analyzer or FFT (Fast Fourier Transform analyzer).
c. Determine the effect of the pulsations by Equation 2:

$$N_H = \frac{Vol \cdot f \cdot \Delta P \cdot K_H}{Q \cdot P_A} \qquad \text{(Eq. 2)}$$

where:

			Metric	English
N_H	=	Hodgson Number	m^3	ft^3
Vol	=	Volume of the flow system (piping between the pulsation source and the meter)		
f	=	Frequency of the pulsations	H_Z	H_Z
Q	=	Average volume rate of flow	m^3/s	ft^3/min
ΔP	=	Average pressure drop in the system from pulsation sources to the meter		
P_A	=	Average absolute pressure at the meter	kPa	in Hg
K_H	=	Units conversion	1.0	4.42

d. The Hodgson Number(N_H should be larger than 2 to minimize the errors due to pulsations. For air flow measurement systems the effects of pulsations must be minimized by isolating the meter from the source, since there is no known correction factor.
e. With vortex-shedding meters it is important that the pulsation frequencies near the meter shedding frequencies be minimized in amplitude.

5. ***Measurement Systems***—Whenever possible, a flow measuring system per 4.1 should be used. The flow meter, nonpulsating blower, plenum, temperature control, and restriction valve may be combined in a single unit.

5.1 Flow Nozzle—The smooth approach nozzle is one of the most commonly used meters for diesel-engine air flow measurements. Classed as a head-type meter, it has a converging inlet section which blends smoothly into a reduced cylindrical cross-section or throat. The purpose of the convergent inlet is to direct the air to the throat in a well-defined, uniform manner. The reduced cross-section appreciably accelerates the flowing air and produces a differential pressure between the entrance and the throat. The convergent section can be of several forms. The ASME long and short radius nozzle, as well as the true-radius nozzle (see Appendix A), are examples of some of these forms. Each of these types of nozzles has similar but slightly different flow characteristics that are accounted for in their coefficient of discharge factors. Otherwise the flow calculations for each type of nozzle are the same. It is assumed for this document that the meters will be used to measure diesel-engine air flow at or near normal room temperatures and pressures. If temperature or pressure extremes are anticipated, it is recommended that a fluid metering handbook be consulted. Common installations are shown in Figures 2 to 4.

5.1.1 NOZZLE SELECTION—Commercial nozzles are available to cover most testing needs. Selection of several nozzles of different throat diameters will usually be needed to cover the flow range of most engines.

5.1.2 CALIBRATION—Each nozzle and its adjacent sections should be calibrated over its entire flow range. Systems that conform to Figure 2 can delete the pipe sections; and, if standard ASME nozzles are used, calibration can be substituted with discharge coefficient equations presented in 7.2.2. The accuracy of the air flow measurement depends directly on the accuracy of the calibration (see 7.2 for sources of error). The accuracy goal should be dictated by the uses of the data. Diesel engine inlet air flow is used in several basic engine performance calculations and can be required to be within 2% of reading.

There is more than one acceptable method used to calibrate nozzle flow meters. The volumetric tank system described in Appendix B is the preferred method. An alternate method is to place the nozzle flow meter to be calibrated in series with a previously calibrated flow meter and record related data throughout their mutual range. The data to be recorded are described in Section 7.

Recalibration and leak checking of the system are recommended whenever any changes are made to adjacent pipe sections or when any wear or contamination occurs to the nozzle in its approaching section or in the throat. With care in use and cleaning, a nozzle flow meter should not need periodic recalibration.

5.2 Laminar Flow Meter—The metering element consists of a large number of narrow flow passages arranged in parallel (Figure 5). The structure must be sufficiently rigid to assure fixed geometry in normal handling between calibration tests. The meter size must be selected such that the flow through the metering element is laminar in nature under all test conditions. When the flow is laminar, the pressure drop across the meter is directly proportional to the gas velocity through the meter and the time average pressure drop is directly proportional to the time average volumetric flow rate. The meter can be used to measure slightly pulsating flows when the peak flow rates are well within the laminar range, and a true time average pressure drop can be read. In principle, for the same accuracy, a laminar flow meter can be used over a broader flow range than head-type meters, since the flow is directly proportional to the pressure drop rather than the square root of the pressure drop. Although the laminar flow meter has some desirable features, it requires cleaning and frequent periodic recalibration to maintain its accuracy.

5.2.1 METER SELECTION—Commercial meters are available that are designed to optimum proportions to assure laminar flow, if the manufacturer's installation recommendations are followed. Flow straighteners and viscous dampers in the pressure taps should be used when recommended by the manufacturers.

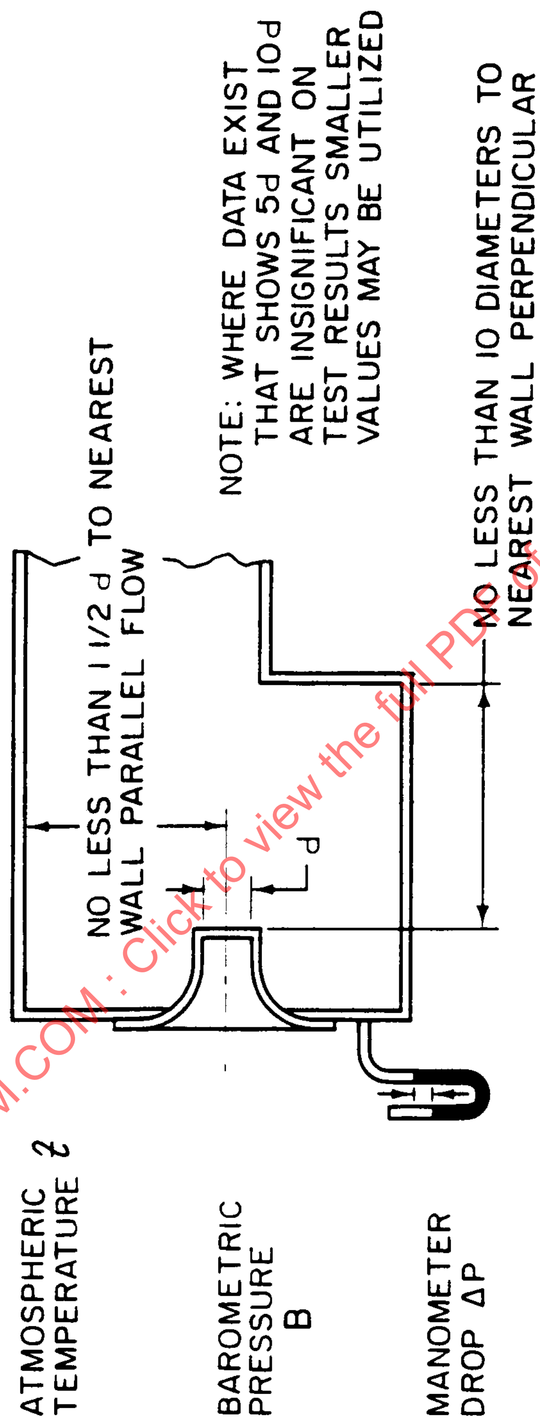


FIGURE 2—NOZZLE DISCHARGING FROM ATMOSPHERE INTO A VESSEL

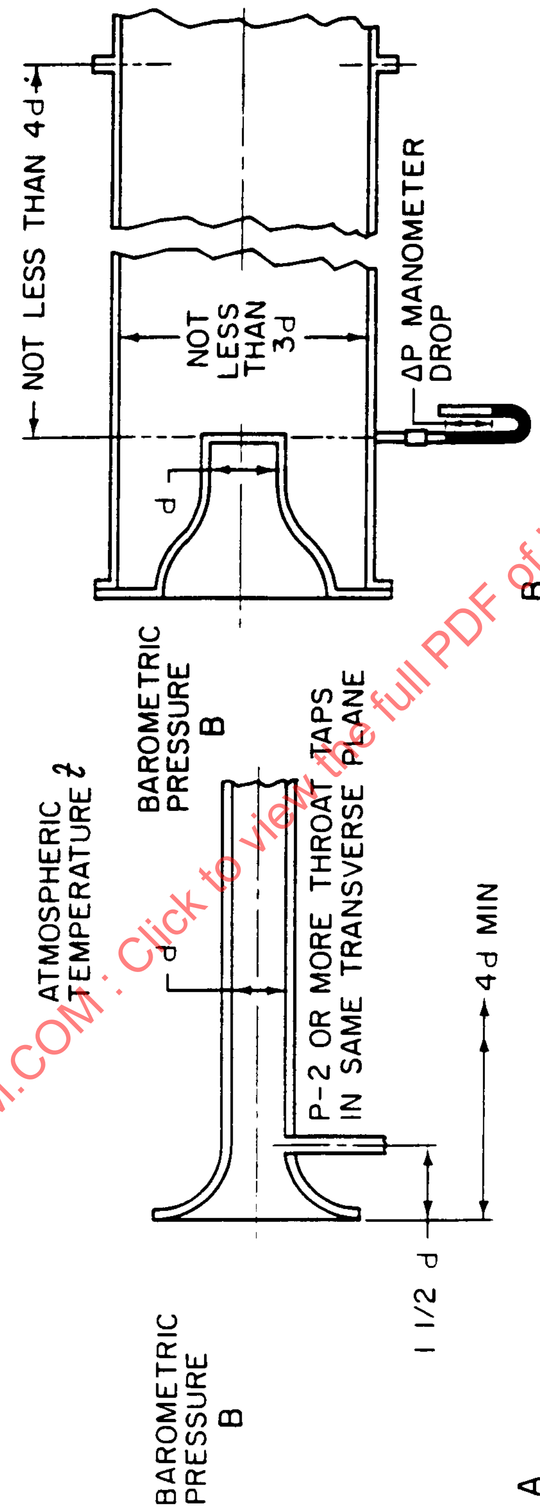


FIGURE 3—NOZZLE DISCHARGING FROM ATMOSPHERE INTO A PIPE

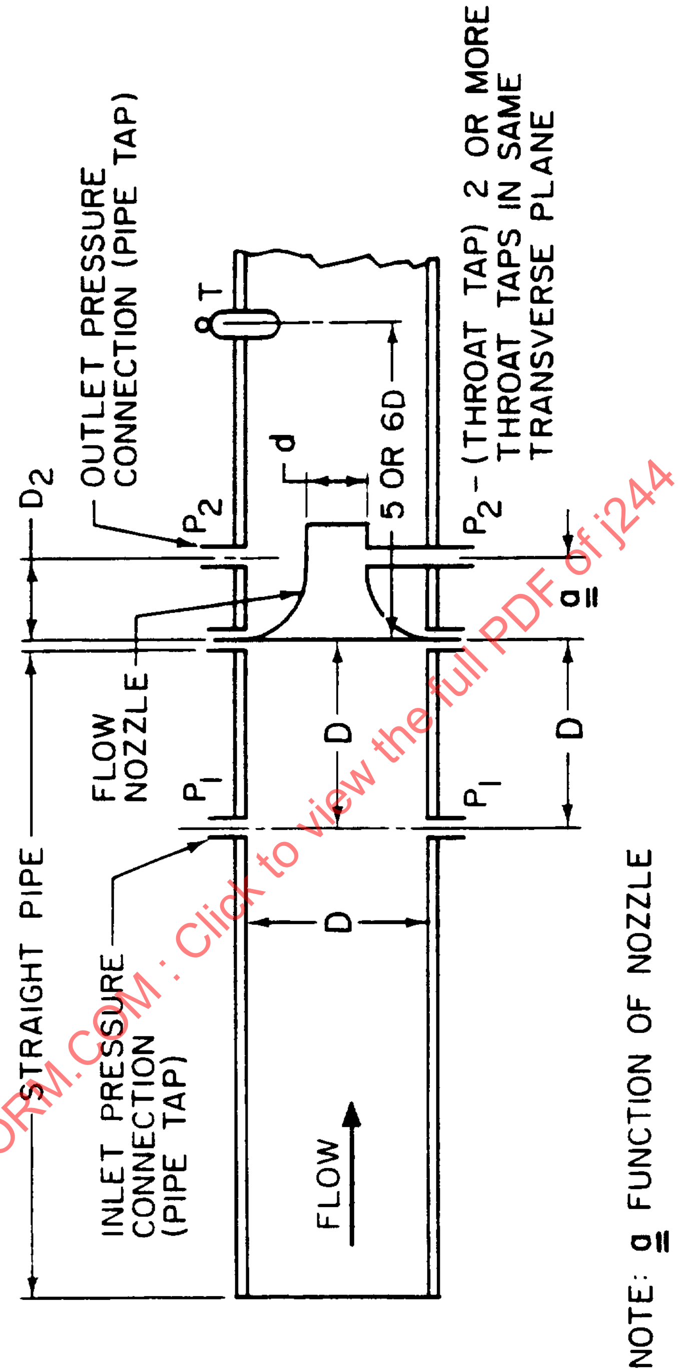


FIGURE 4—NOZZLE IN A PIPE

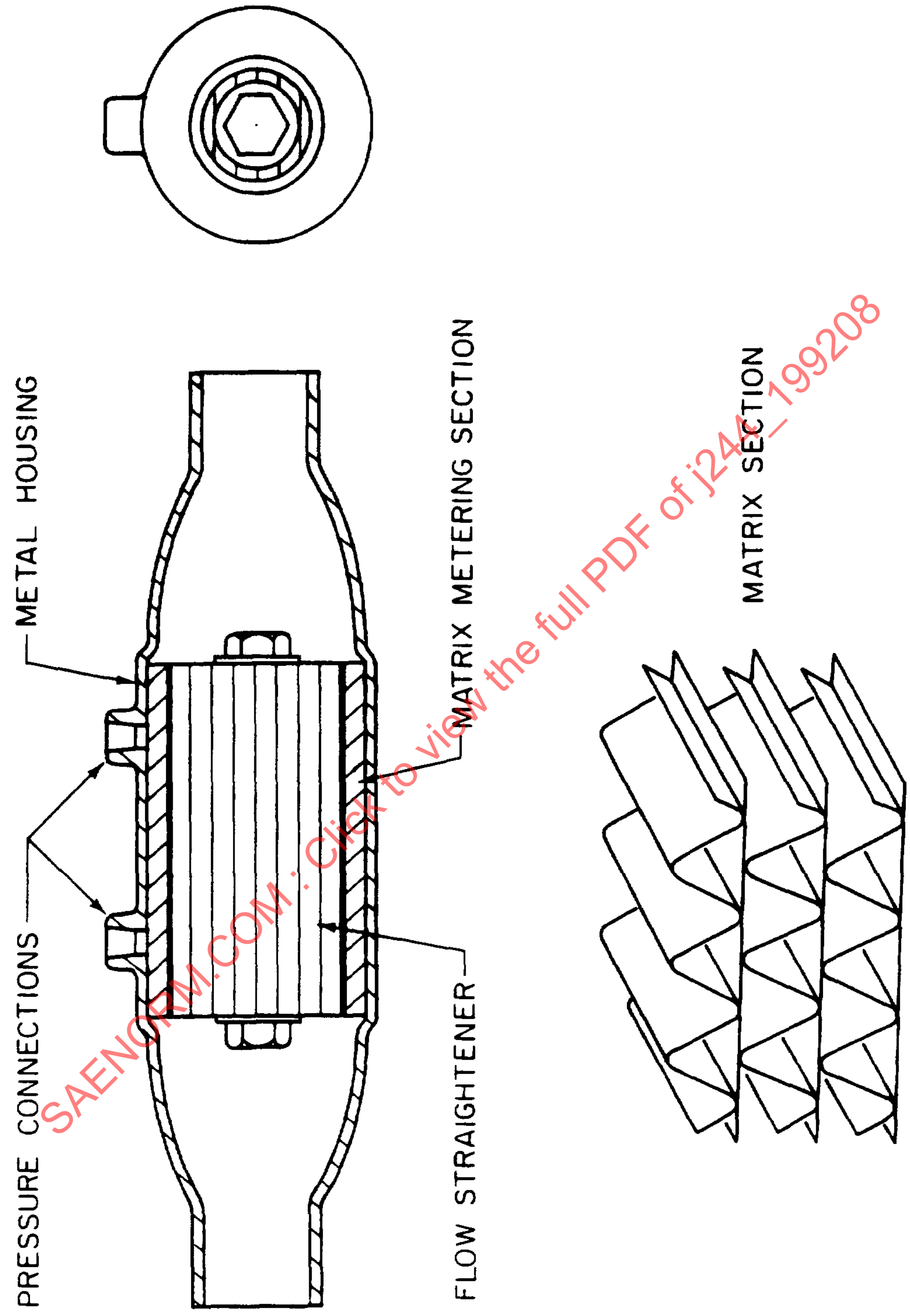


FIGURE 5—GENERAL CONSTRUCTION OF LAMINAR FLOW ELEMENT

5.2.2 CALIBRATION—Each flow meter should be calibrated over its entire flow range. If the installation deviates from that recommended by the flow meter manufacturer, the flow meter should be calibrated with its adjacent piping. The accuracy of the air flow measurement is dependent directly on the accuracy of the calibration. The accuracy goal should be determined by the uses of the data. Diesel engine inlet air flow is used in several basic engine performance calculations and can be required to be within 2% of reading.

There is more than one acceptable method used to calibrate laminar flow meters. The volumetric tank system described in Appendix B is the preferred method. An alternate method is to place the flow meter to be calibrated in series with a previously calibrated flow meter and record related data throughout their mutual flow range. The data to be recorded are described in Section 7.

Recalibration of the flow meter is recommended on a periodic basis because the metering section can have a change in coefficient due to a build-up of material on the interior walls. Care in upstream filtering and periodic cleaning can help minimize the need for recalibration.

5.3 Vortex Shedding Meters—Vortex shedding meters are those which detect the rate at which a continuous series of eddies are formed in the wake of a nonstreamlined body in a flow field. Boundary layer separation occurs alternately on one side of the body and then the other. The rate at which the vortices are shed has been shown to be a function only of the fluid velocity for Reynolds numbers above 1000 to 2000. Sensing of the vortex shedding frequency can be performed by several techniques and varies depending on the manufacturer and application.

5.3.1 METER SELECTION—Commercial units are available to cover a wide range of flows. Careful sizing and selection may enable the use of a single device over the entire flow range of the engine, since turn-down ratios of 10:1 and 20:1 can be achieved with an accuracy of 1% of reading.

5.3.2 CALIBRATION—Commercial vortex meters are generally supplied with a single calibration coefficient to be used over the entire flow range. This calibration should be verified with the meter installed as it will be used in an engine test. The accuracy goal should be determined by the uses of the data. Diesel engine inlet air flow is used in several basic engine performance calculations and can be required to be within 2% of reading. When the air flow measurements are to be this accurate, it is recommended to correct for changes in the calibration coefficient rather than using a single number.

The calibration data can be represented by a power series polynomial using a least-squares regression technique. Care should be taken that the resulting equation accurately represents the calibration data. This is best done by graphically displaying the equation and the original data on the same plot. The equation should not be used to compute flows outside the range of calibration. Generally a second- or third-order polynomial will provide an equation that will represent the calibration data within 1/2% (see 7.4.1 for a reference calculation).

There is more than one accepted technique for calibrating vortex flow meters. The necessity to calibrate the flow meter in its installation makes it desirable to place a calibrated flow meter such as a nozzle system in series and record related data throughout their mutual flow range. The data to be recorded are described in Section 7.

5.4 Other Flow Meters—Other types of flow meters may be used in addition to the previously named types. However, they must be capable of being calibrated to the required accuracy and must not have excessive pressure drop. Examples of other flow meters that could be used are:

5.4.1 ORIFICE METERS—These meters employ an abrupt change in cross-sectional area to produce a pressure differential. The flow is proportional to the square root of this pressure differential.

5.4.2 VENTURI METERS—These meters employ a converging section, a throat, and diverging section to produce a pressure differential. The flow is proportional to the square root of this pressure differential.

5.4.3 ROTARY POSITIVE DISPLACEMENT FLOW METER—Airtight, but free moving, impellers characterize this type of meter. The rotational speed of the impellers is proportional to the volume of flow rate.

5.4.4 MISCELLANEOUS FLOW METERS—Possible types of flow meters that could be used, but are not commonly used, are hot wire anemometers, mechanical anemometers, heat injection meters, chamber gas meters, and variable area meters.

6. Measurement System Preparation

6.1 Test for Airtightness of Air Metering System—Care must be exercised to prevent unmetered air from entering the engine. Even small leaks result in substantial errors when the flow rates are in the 20 to 200 kg/h (50 to 500 lb/h) range. Air leaks can be present in any of the air metering system's sections Figure 1. The following is an acceptable method for establishing the leakage rate for typical metering systems:

a. Cap both ends of the assembly (Figure 1) and pressurize or evacuate the system, depending on how it is used in normal operation, to about 3 kPa gage (12 in H_2O). Shut off the air supply and record the time for the pressure gage to reach about 1.5 kPa (6 in H_2O).
b. Calculate the leakage rate with the following formula:

$$\dot{m}_l = \frac{K_l \cdot \Delta P \cdot Vol}{Time} \quad \text{(Eq. 3)}$$

where:

m_l = mass flow of leak
vol = volume of system
time = time for pressure change
ΔP = amount of pressure change
K_l = unit conversion constant

c. Acceptable leakage rate for this procedure is 0.5% of the lowest air flow rate to be measured during testing.

An alternate technique for measuring leak rate is to seal both ends of the system and directly measure the leak rate with the installation shown in Figure 6. The system is pressurized to its maximum operating pressure or depressurized to its minimum operating pressure depending on normal operation using the throttling valve to regulate flow. The leakage rate is read directly off the flow meter since the "make-up" air flowing into the system to maintain the system at constant pressure is equal to the air leaking out of the system.

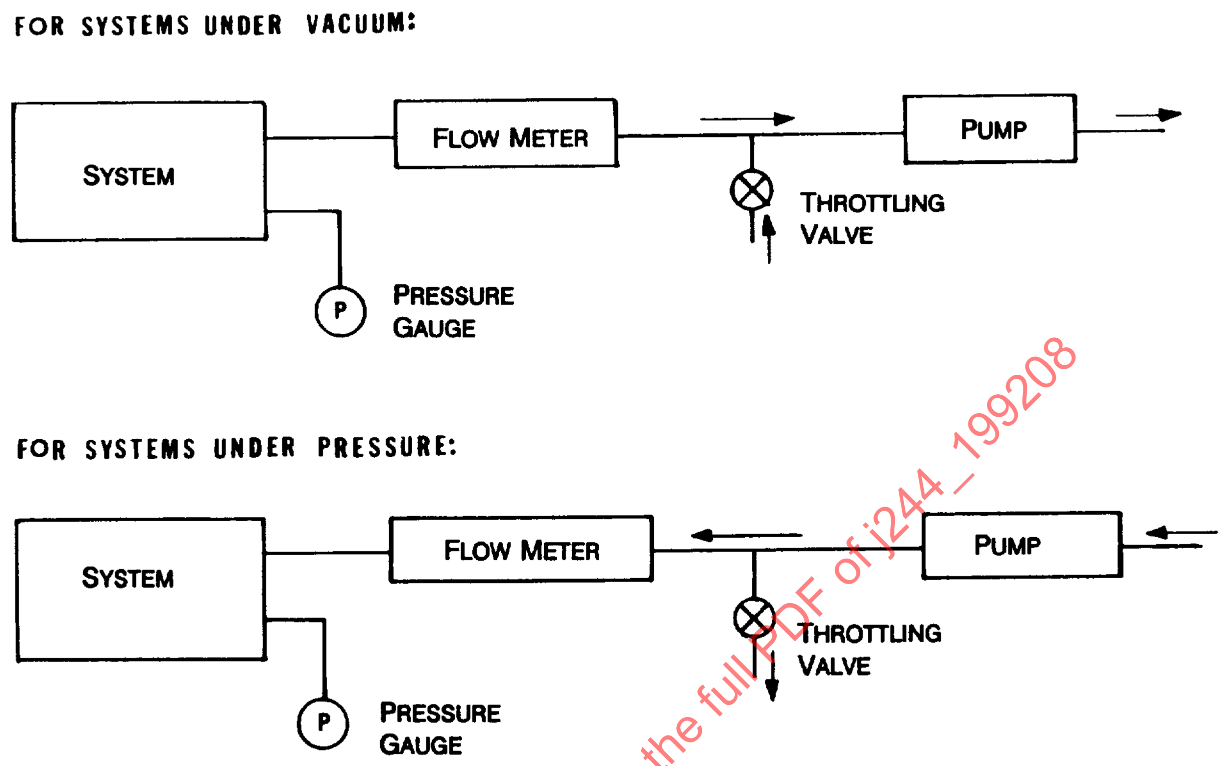


FIGURE 6—INSTALLATION FOR MEASURING LEAK RATE

6.2 Inclined Manometer Operation—There is more than one acceptable way to measure pressure drop across a flow meter. The procedure described here is recommended when using a liquid manometer.

a. The air hoses should be as straight as possible to reduce pressure drop and safeguard the hose. The inlet to the meter should be placed in a region of undisturbed air and five diameters clearance provided if the inlet faces a wall. Nothing should be placed in front of the air nozzle.

b. Three adjustments must be made in the order listed before any readings are taken:

1. Level the inclined tube manometer (Figure 7).

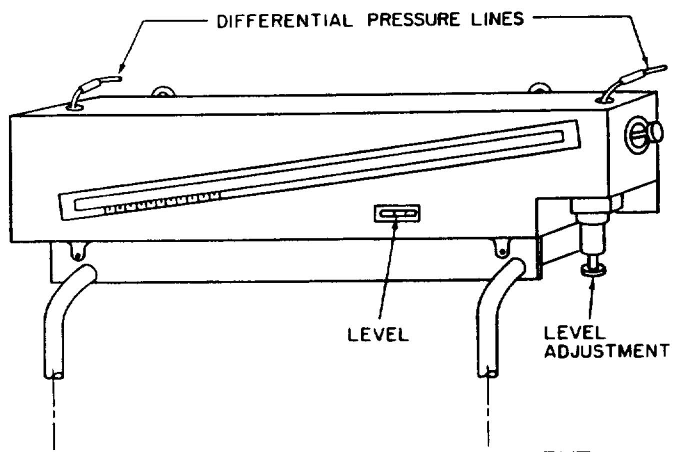


FIGURE 7—INCLINED MANOMETER ADJUSTMENT

2. If the inclined manometer has compensation adjustment screws, adjust settings to agree with the current meter inlet air temperature and absolute pressure per the manufacturer's instructions. (Figure 8 shows one example of a compensating manometer.)

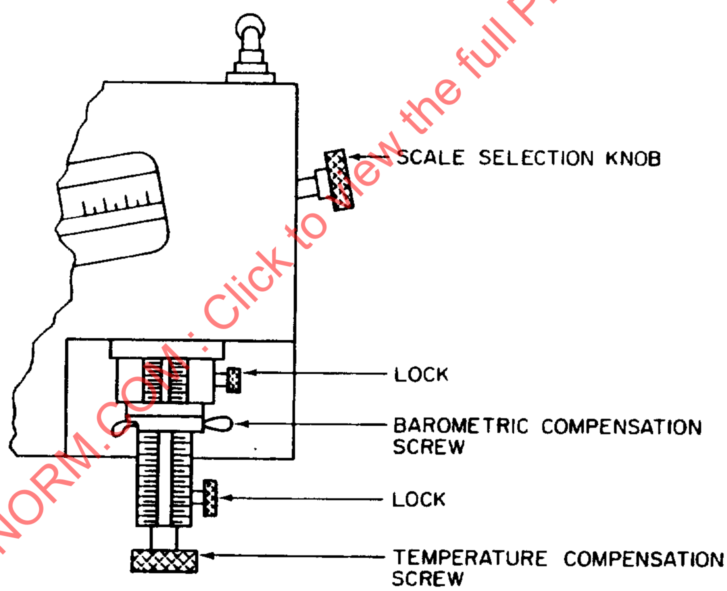


FIGURE 8—INCLINED MANOMETER ADJUSTMENT

3. Zero the meniscus (see Figures 9 and 10). The meniscus may be zeroed during running by venting to atmosphere. (Disconnect both pressure lines to the manometer.)

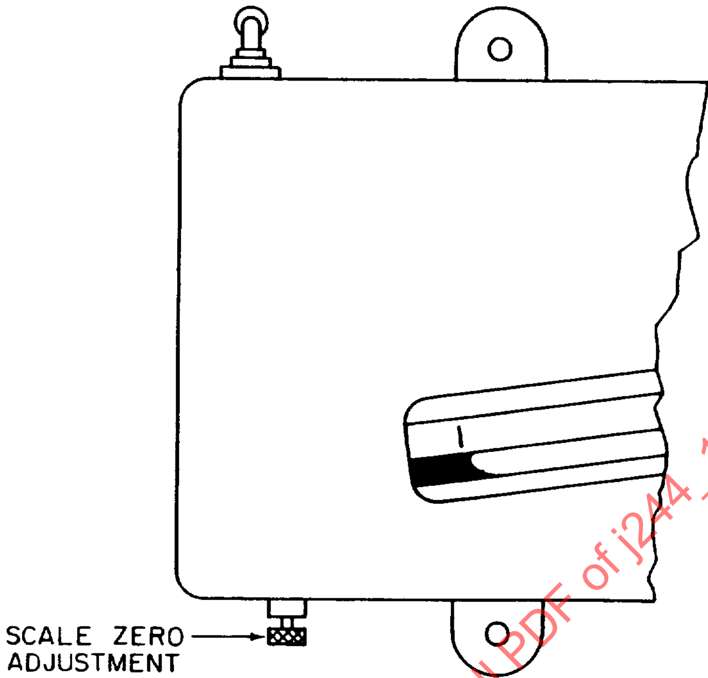
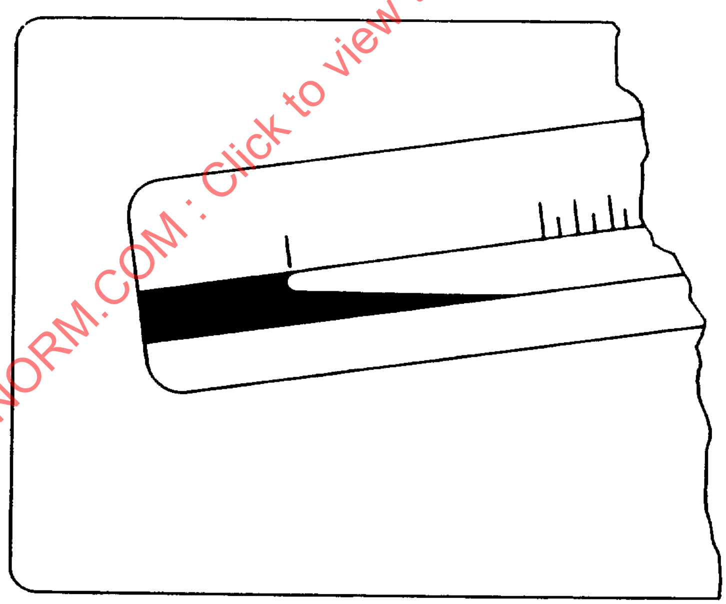


FIGURE 9—INCLINED MANOMETER ADJUSTMENT



MENISCUS PROPERLY ZEROED

FIGURE 10—INCLINED MANOMETER ADJUSTMENT

c. If the flow range is not known, start with a large nozzle opening and work down to the proper size to avoid drawing water out of the inclined manometer. If a meter has a choice of direct reading scales, match the proper scale on meter with nozzle opening used.
d. If a valve is provided on the flow meter outlet to control the air pressure to the engine, it should be fully open before drawing air through the hose or the hose may collapse.
e. The differential pressure tubing must be clear of all liquids and all connections must be absolutely leak free. If the manometer water is accidentally sucked into the lines, they must be cleaned thoroughly (4.3.1.3) before any readings are taken. If manometer float traps are used, they must drain back completely after being wetted by fluid.
f. The pressure differential (ΔP) must be measured directly, using an inclined manometer or micromanometer graduated to permit resolution of 0.1% of the smallest ΔP to be measured. The zero reading must be checked after readings are taken on the lower 25% of the manometer scale (it is recommended that the lower 10% of scale be avoided where possible), and must be less than 0.1% of the lowest value of ΔP measured.

6.2.1 MAINTENANCE

a. Manometers must be cleaned periodically to remove wall deposits. This is particularly important for inclined manometers where errors can be caused by changes in the force of adhesion between the liquid and the tube wall.
b. Inclined manometers should be calibrated with a deadweight tester or micromanometer after cleaning to assure accuracy and verify the use of the correct fluid and wetting agents.

6.3 Flow Nozzles—There are certain standard operating criteria which should be observed if maximum accuracy is to be obtained.

a. Fluid flow velocity should be in the turbulent region, but below sonic velocity. Calculations will be simplified and mistakes minimized by restricting the ΔP range of 0.25 to 2.5 kPa (1 to 10 in H_2O).
b. When a wide range of flows is to be encountered, the measuring element should be changed when necessary to remain within pressure differential limits.
c. For maximum accuracy, the element should be sized to produce as high a pressure differential as possible. However, if the ΔP exceeds the range specified in 4.3.2.1(a), then the adiabatic expansion factor should be considered to account for gas expansion at the nozzle throat.

6.3.1 PRESSURE MEASUREMENT—Since all flow measurements depend on the pressure drop across the nozzle, the following is recommended for accuracy:

a. Inlet Pressures

1. If the nozzle is installed at the inlet of a plenum chamber (Figure 2), or at the inlet of a pipe (Figure 3), no inlet pressure connections are required and the atmospheric pressure is considered to be the inlet pressure.
2. If the nozzle is installed in a continuous pipe (Figure 4), the inlet pressure connections shall be placed at one pipe diameter preceding the entrance plane of the nozzle.

b. Outlet Pressures

1. If the nozzle is installed at the inlet of a plenum chamber (Figure 2), the outlet pressure shall be considered to be pressure in the chamber.
2. If the nozzle is installed at the inlet of a pipe (Figure 3A), the outlet pressure throat taps shall be located 1-1/2 pipe diameters following the entrance plane. If the nozzle is installed at the inlet of a pipe (Figure 3B), the outlet pressure throat tap should be located in the same plane as the nozzle exit per Figure 3B.

3. If the nozzle is located in a continuous pipe (Figure 4) and outlet pressure connection is a pipe tap, it shall be located one-half pipe diameter following the nozzle entrance plane. If the outlet pressure connection is a throat tap, there shall be two or more taps located one-half pipe diameter following the nozzle entrance plane if the nozzle is a high β series, or 1–1/2 pipe diameters following the nozzle entrance plane if the nozzle is a low β series. (See ASME PTC 19.5:4-1959 and Appendix B for nozzle specifications.)

c. Pressure Differential Measurement—The difference between the nozzle inlet and outlet pressure (ΔP) must be read directly from the scale of a manometer. The manometer may be calibrated in pressure units or to read in flow units directly. See 4.3.3.2(f) for requirements.

6.4 Laminar Flow Meter

6.4.1 INSTALLATION REQUIREMENTS

a. An air filter is recommended, and is usually required in most applications upstream of the meter. Laminar flow meters must be protected from airborne dirt and oily vapors.
b. Instrumentation must be provided to measure P_1, T_1, and ΔP. See Figure 1. Commercial meter manufacturers usually provide proper instrumentation locations on the meters for these purposes.
c. If a compensating-type manometer is used (see Figures 7 and 8) to measure ΔP, the steps recommended by the meter manufacturer must be inserted in the appropriate order in 6.2. The pressure adjustment must compensate for losses upstream of the metering element such as filters, pipe elbows, etc.

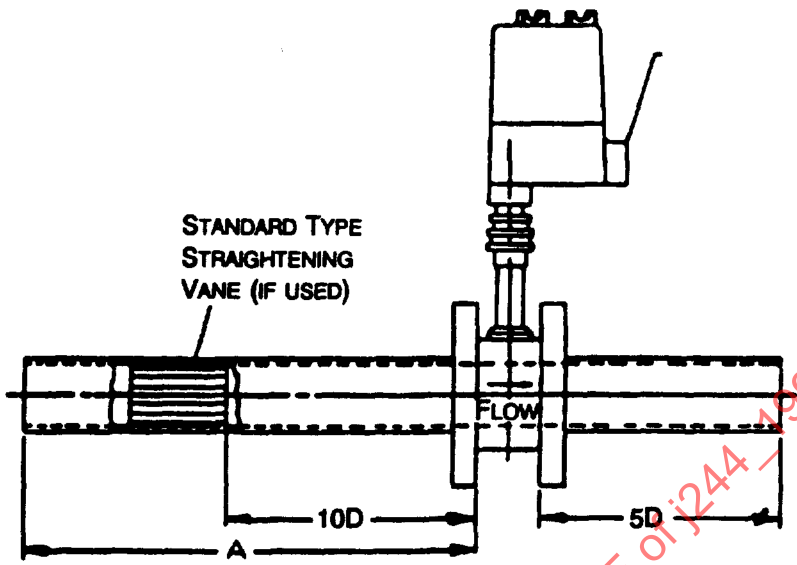
6.4.2 MAINTENANCE

a. Filters must be replaced as recommended by the meter manufacturer or when the total pressure loss through the intake system exceeds test requirements.
b. Frequent calibrations are required to assure accuracy.
c. Cleaning is required only when there is a large shift in flow between calibration periods. The meter should be cleaned by the manufacturer or by following the manufacturer's cleaning instructions.

6.5 Vortex Shedding Meters

6.5.1 INSTALLATION REQUIREMENTS—Due to the nature of the vortex shedding phenomenon and the sensing devices used, it is important that the velocity profile entering the metering section be uniform, fully developed and free of large-scale turbulence. This dictates the following requirements:

a. The piping both before and after the metering section shall be of the same diameter as the metering section.
b. The inside of the piping should be reasonably smooth and free of surface irregularities such as weld beads or gasket protrusions. All upstream surface irregularities should be less than 1/2% of the nominal pipe diameter.
c. The length of the straight pipe required before the meter section depends on the type of transition or obstruction. The user should follow standard installation recommendations for ASME orifice meters or the table in Figure 11.



Upstream Fitting or Obstruction	Recommended Dimension A Without Vanes	Recommended Dimension A With Vanes
90-degree Elbow	20 D	15 D
Two 90-degree Elbows Same Plane	25 D	15 D
Two 90-degree Elbows Different Planes	40 D	15 D
Reduction in Pipe Diameter	20 D	15 D
Expansion in Pipe Diameter	40 D	20 D
Valve Partially Closed or Regulator	Recommend Motor Upstream	Recommend Motor Upstream

FIGURE 11—INSTALLATION OF VORTEX SHEDDING METER

d. Any air inlet restriction control device should be installed at least five diameters downstream of the meter section.
e. Deviations from these installation recommendations should be used only if the user has experimentally verified that the accuracy of the meter has not been affected by the installation. Compensation for an apparent calibration shift is not recommended because this is usually caused by instability.

6.5.2 PRESSURE MEASUREMENT—Instrumentation shall be provided for monitoring the static pressure at the meter. The pressure tap should be located between two and six diameters upstream of the meter section.

6.5.3 TEMPERATURE MEASUREMENT—Instrumentation shall be provided for monitoring the air temperature at the meter. The sensor should be located between two and ten diameters downsteam of the meter section.

7. Air Flow Measurement

7.1 General Measured Data—Table 1 lists the data recommended to be obtained at test time to measure engine intake air flow with the common air meters.

TABLE 1—RECOMMENDED DATA MEASUREMENTS

	Metric	English
Engine Speed	rpm	rpm
Fuel Flow Rate	kg/s	lbm/s
Atmospheric Conditions		
Barometric Pressure (Pa)	kPa	in Hg
Dry Bulb Temp	°C	°F
Wet Bulb or Dew Point	°C	°F
Water Vapor Pressure (P_v)	kPa	in Hg
Pressures		
Flow Meter Inlet (P_1)	kPa	in Hg
Flow Meter Outlet (P_2)	kPa	in Hg
Differential Across Flow Meter (ΔP)	kPa	in H_2O
Temperatures		
Flow Meter Inlet (T_1)	K	°R
Flow Meter Outlet (T_2)	K	°R

The following meter specific parameters should be recorded:

Air meter — Make and Model Number

Serial Number

Calibration Date

7.1.1 FLOW NOZZLE —For nozzle-type air meters, the parameters shown in Table 2 will be needed should the flow method be utilized.

TABLE 2—NOZZLE FLOW PARAMETERS

	Metric	English
Molecular Weight of Air (MW_{air})	28.964 kg/kg-mole	28.964 lbm/lbm-mole
Molecular Weight of Water (MW_{H2O})	18.015 kg/kg-mole	18.015 lbm/lbm-mole
Universal Gas Constant (RU)	8314.41 J/kg-mole-K	1545.33 ft-lb/lb-mole-°R
Nozzle Inlet Pipe Diameter (D)	mm	in
Nozzle Throat Diameter (d)	mm	in
Nozzle Material		
Air Mass Flow (m)	kg/s	lbm/s
Coefficient of Discharge (C)	--	--
Expansion Factor (Y)	--	--
Velocity of Approach Factor (E)	--	--
Area Thermal Expansion Factor (Fa)	--	--
Compressibility Factor (Z)	--	--

7.1.2 LAMINAR FLOW METER—The following are important when using a laminar flow meter:

a. Pressure (P_1), temperature (T_1), and ΔP must be measured at the taps provided at the inlet and exit of the metering element by the manufacturer.
b. If a compensating-type manometer is used for measuring ΔP, an entry should be made on the log sheet affirming that the pressure adjustment screw was turned to current value of P_1 (in Hg, abs) before reading ΔP.

7.1.3 VORTEX SHEDDING METER—The principle of operation of the vortex shedding meters relates the volumetric flow rate directly to the vortex shedding frequency. It is recommended, therefore, that the meter output frequency be measured with a totalizing pulse counter. The gating period may be fixed or can be selected to provide optimum resolution. If the engine fuel rate is measured as a time average value, it is recommended that the gating period of the air flow meter corresponds to that of the fuel flow measurement.

In addition to the items listed in 7.1, the following items must be recorded:

a. Calibration coefficient: K; in $m^3/\text{pulse}(ft^3/\text{pulse})$ (Eq. 4)

b. Meter output frequency: f; in pulses/s (Eq. 5)

7.2 Calculation of Intake Air Flow — Nozzle Systems

7.2.1 GENERAL EQUATIONS—The following equations may be helpful for use in the air flow calculation sections or in setting up computer air flow calculation routines.

a. Water vapor pressure (P_v): See SAE J177 for humidity calculation equations, or determine the vapor pressure from a psychometric chart.
b. Ambient pressure (absolute, upstream of meter):

$$P_{abs} = B + P_I \text{ ; kPa(inHg), abs} \quad \text{(Eq. 6)}$$

c. Molecular weight of air-water vapor mixture:

$$MW_{mo} = \left[\frac{MW_{air} \cdot (P_{abs} - P_v) + MW_{H_2O} \cdot P_v}{P_{abs}}\right]; \text{kg/kg-mole (lbm/lbm-mole)} \quad \text{(Eq. 7)}$$

d. Gas constant of mixture:

$$R_{mo} = Ru / MW_{mo} ; \text{J/kg-k (ft-lbf/lbm-°R)} \quad \text{(Eq. 8)}$$

e. Density of mixture:

$$P_{mo} = \frac{P_{abs}}{K_p \cdot R_{mix} \cdot T_{pabs}} ; \text{kg/m}^3 (\text{lbm/ft}^3) \quad \text{(Eq. 9)}$$

where:

$K_p = 1.000 \times 10^{-3}$; SI units
$K_p = 1.414 \times 10^{-2}$; English units

f. Viscosity of air:

$$\mu = V_L + (NV^*(V_H - V_L)) \quad \text{(Eq. 10)}$$

where:

$NV = 3.895635 \times 10^{-4} + (1.083746 * NT) + (-8.467568 \times 10^{-2} \times (NT^{-2}))$
$NT = (T_t - T_L)/(T_H - T_L)$
T_t = Temperature of air at test conditions

Temperature Units	**T_L**	**T_H**
degree C	–17.78	87.78
degree F	0.0	190.00
degree K	255.37	360.93
degree R	459.69	649.69

Viscosity Units (µ)	**V_L**	**V_H**
Centipoise	1.626699E-2	2.212111E-2
lbm/sec-ft	1.093095E-5	1.425330E-5

NOTE—Equation 10 is with ± 0.01% of NBS data over the range of -18 to 88 °C (0 to 190 °F).

g. Reynolds number:

$$N_R = \frac{K_{NR} \cdot \dot{m}}{\pi \cdot d \cdot \mu} \quad \text{(Eq. 11)}$$

where:

$K_{NR} = 4.0 \times 10^6$ (SI Units)
$K_{NR} = 48.0$ (English Units)

7.2.2 NOZZLE CALIBRATION

a. Calibrated Nozzle System—From the calibration data of the flow nozzle a table or curve should be constructed of ΔP versus air mass flow (or volume flow—if it is referenced to the calibration air density). If the air flow is being used in computerized data reduction routines, the calibration data may be represented by a power series least-squares polynomial equation. It generally takes fourth- to eighth-order equations to accurately fit the calibration curve. The calibration data may also be plotted on log-log coordinates in which case a linear curve is obtained. It is recommended that the calibration data for one nozzle not be used for other similar-sized nozzles unless it has been shown that the flow characteristics, meter surface finish, and throat diameters are identical. If the nozzle is used at air densities other than that at which the measurement system was calibrated, the air flow determined from the calibration chart or equation must be multiplied by the correction factor shown in 7.2.4.2.

b. Uncalibrated Nozzle System—If the nozzle has unknown flow characteristics or is to be used in a measurement system not conforming to the recommendations shown in Figures 2, 3, or 4, then the measurement system must be calibrated. If the nozzle was made according to the specifications for the ASME long-radius nozzle or the true-radius nozzle, and it is installed in a flow measurement system equivalent to one of those shown in Figures 2, 3, or 4, then as a second alternative to calibration the air flow can be calculated using the General Flow Equation. The General Flow Equation will produce calculation results within about ± 2%.

7.2.3 GENERAL FLOW EQUATION—CALCULATED NOZZLE FLOW—The General Flow Equation for nozzles is the result of combining several fundamental flow principles such as conservation of energy, ideal gas relationships, flow continuity, etc., into a basic equation that describes the flow of ideal gases through a nozzle. However, in order to account for the real world characteristics of gases, such as compressibility, viscosity, etc., the basic equation is generalized by including various factors that account for the differences between ideal and real gases. Since these modifying factors affect the basic equation in various degrees, the user must determine which factors are significant enough to be included in the flow calculation after considering the desired calculation accuracy, the repetitiveness of the calculation, and the availability of computers.

a. General Flow Equation:

$$\dot{m}_{mo} = Kg \cdot C \cdot Y \cdot E \cdot Fa \cdot d^2 \sqrt{\frac{\rho_{mo} \cdot \Delta P}{Z}} \qquad \text{(Eq. 12)}$$

where:

$Kg = 3.5124 \times 10^{-5}$ (9.9702×10^{-2})

b. Coefficient of Discharge:

$$C = \frac{\text{Actual Rate of Flow}}{\text{Theoretical Rate of Flow}} \qquad \text{(Eq. 13)}$$

The coefficient of discharge should in all cases be taken into account in the General Flow Equation 12 since its absence introduces a 1 to 4% calculation error for typical nozzles used for measuring diesel engine air flows. In other cases the error may be as great as 8% for the flow nozzles. The coefficient of discharge can best be determined by calibrating the nozzle as in Appendix B, and dividing the actual mass flow rate determined from the calibration procedure by the theoretical mass flow rate from Equation 12 with the C set equal to one. If the nozzle in use was made according to the specifications for an ASME long-radius nozzle or a true-radius nozzle (see Appendix A), as a second alternative to an actual calibration of the nozzle, one of the coefficient of discharge equations as follows can be used:

1. ASME Long-Radius Nozzle

$$C = 0.19436 + (0.152884 \times (\ln N_R)) - (0.0097785 \times (\ln N_R)^2) + (2.093 \times 10^{-4} \times (\ln N_R)^3) \qquad \text{(Eq. 14)}$$

2. True-Radius Nozzle

$$C = 1 - \frac{8.36}{\sqrt{N_R}} \qquad \text{(Eq. 15)}$$

c. Expansion Factor — Y:

$$Y = \left[r^{(2/\gamma)} \left(\frac{\gamma}{\gamma - 1} \right) \left(\frac{1 - r(\gamma - 1/\gamma)}{1 - r} \right) \left(\frac{1 - \beta^4}{1 - (\beta^4 \cdot r^{(2/\gamma)})} \right) \right]^{1/2} \qquad \text{(Eq. 16)}$$

where:

$$r = 1 - \frac{\Delta P}{P_A} \text{ or } \left(\frac{P_A - \Delta P}{P_A} \right)$$

P_A = ambient absolute pressure (upstream of meter)
ΔP = nozzle pressure drop (same units as P_A)
γ = ratio of specific heats (1.40 for air)

$$\beta = \frac{d}{D} = \frac{\text{diameter of nozzle throat}}{\text{diameter of approach pipe}}$$

The density of compressible fluids changes when passing through a flow nozzle. The effect of this density change is accounted for in the expansion factor. The change in fluid density will be proportional to the pressure differential across the nozzle, therefore, the higher the ΔP the more compensation that takes place. Ignoring the expansion factor can introduce over a 1% calculation error in the 0.25 to 2.5 kPa (1 to 10 in H_2O) ΔP range. If the nozzle system in use is like that shown in Figure 2, D (in the Beta calculation) becomes very large, in which case assume a value of D of at least 10 times the nozzle throat diameter.

d. Velocity of Approach Factor:

$$E = \frac{1.0}{\sqrt{1 - \beta^4}} ; \beta = \frac{d}{D} \qquad \text{(Eq. 17)}$$

In most diesel-engine air flow measurement systems using flow nozzles, the air drawn into the nozzle will most likely be initially at rest or close to it. In such cases (very small Beta (β)) the velocity of approach factor is very close to one and can be omitted from calculations. However, if the nozzle is used in a system in which the air is piped to the nozzle (as in Figure 4), this factor should be evaluated by the user to determine if it is significant enough to take into account. In general, if the Beta (β) factor is greater than 0.25, it is recommended that the velocity of approach factor be included in air flow calculations using the General Flow Equation.

e. Area Thermal Expansion Factor:

(Metric)
$$F_a = \frac{[1.0 + (A \cdot T_C) + (B \cdot T_C^2)]^2}{[1.0 + (A \cdot T_{CR}) + (B \cdot T_{CR}^2)]^2} \quad \text{(Eq. 18)}$$

(English)
$$Fa = \frac{\left[1.0 + C\left(\frac{T_F - 32}{1000}\right) + D\left(\frac{T_F - 32}{1000}\right)^2\right]^2}{\left[1.0 + C\frac{(T_{FR} - 32)}{1000} + D\left(\frac{T_{FR} - 32}{1000}\right)^2\right]^2}$$

where:

Factor = A 2.2644 x 10^{-5} for (Aluminum) 1.1182 x 10^{-5} for (Steel)
Factor = B 9.720 x 10^{-9} for (Aluminum) 5.2585 x 10^{-9} for (Steel)
Factor = C 1.258 x 10^{-2} for (Aluminum) 6.212 x 10^{-3} for (Steel)
Factor = D 3.00 x 10^{-3} for (Aluminum) 1.623 x 10^{-3} for (Steel)
T_c and T_F — Meter temperature at test conditions in °C and °F, respectively.
T_{CR} and T_{FR} — Meter temperature at reference conditions in °C and °F, respectively.

If a nozzle is used at a temperature other than that at which it was calibrated, or at which the throat diameter was measured, the temperature difference will cause the area of the nozzle throat to change. The amount of error due to the change in area for aluminum nozzles will be about 0.1% for every 22 °C (40 °F) change from the reference temperature and even less for steel nozzles. For typical diesel engine air flow measurements made at normal room temperatures this factor may be omitted.

f. Compressibility Factor—Z—One of the fundamental equations used to derive the General Flow Equation was the ideal gas law. All real gases deviate from the ideal gas relationship by an amount called the compressibility factor, or Z. Under normal room temperatures and pressures, the compressibility factor is about 0.9997 or about 0.03% correction to the flow calculation. Under normal conditions this factor is ignored, but if temperature or pressure extremes are encountered the effect of this factor should be investigated in a fluid metering handbook.

7.2.4 AMBIENT CONDITIONS—Record the ambient environmental conditions surrounding the flow nozzle at its operating conditions. Included in these readings shall be the following items:

a. Barometric Pressure — P_B: The pressure should be made in the same area that the nozzle is located.
b. Air Meter Pressure (upstream of nozzle) — P_1: This pressure is made one pipe diameter (D) upstream of the nozzle. If the nozzle is used as shown in Figure 2, P_1 = 0.
c. Air Meter Temperature — T_1 or T_2: Record the temperature of the air five to six pipe diameters downstream of the nozzle. If an upstream location is desired, it must be located at least 200 temperature-probe diameters upstream of the nozzle. The temperature probe must not interfere with the flow patterns surrounding the nozzle, both upstream or downstream.
d. Air Meter Pressure Differential — ΔP: Record the pressure drop across the nozzle.
e. Humidity Parameters: Record either wet bulb or dry bulb or dew point temperatures of the air flowing through the nozzle. If these parameters are unavailable, assume a water vapor pressure (P_v) of 2 kPa (0.6 in Hg) for use in the calculations. This is equivalent to 50% relative humidity at 29 °C (85 °F).

7.2.4.1 Calculations—Calibrated Nozzle Systems—For calibrated nozzle systems, the air flow determined from the calibration curve or equation must be corrected according to the correction factors that follow. Correcting observed air flow values with these correction factors also applies in cases where: (a) the manometer was calibrated to read flow directly, but is of the fixed gradient type, or (b) the manometer was calibrated to read out in pressure units at the actual test conditions.

$$K_f = (\rho_{mo}/\rho_{cal})^{1/2}\text{; for flow in mass units} \quad \text{(Eq. 19)}$$

$$K_f = (\rho_{cal}/\rho_{mo})^{1/2}\text{; for flow in volume units} \qquad \text{(Eq. 20)}$$

where:

actual air flow = observed air flow x K_f
ρ_{mo} = observed wet air density at test conditions
ρ_{cal} = air density at which nozzle (or manometer) was calibrated

7.2.4.2 *Calculations—Uncalibrated Nozzle Systems*—For uncalibrated nozzle systems the General Flow Equation should be utilized. If the nozzle was constructed according to ASME standards, or equivalent, the Coefficient of Discharge equations of 7.2.3(b) may be used. Should the value of C be unknown, or the nozzle made to an unknown design, the meter should be calibrated. If this is not practical, assume a value of C of 0.98 and consider the resulting calculated air flow value as approximate. The following calculation sequence is recommended:

a. Determine the water vapor pressure — P_v.
b. Determine the ratio of specific heats (l = 1.40 for air).
c. Determine the pipe diameter (D) upstream of the nozzle. If the nozzle is used as in Figure 2 (no upstream pipe), assume a pipe diameter of at least 10 times the (largest) nozzle throat diameter.
d. Calculate the Beta ratio. $\beta = d/D$
e. Calculate the ambient pressure (abs) upstream of the nozzle (Equation 6).
f. Calculate as required for calculation accuracy:

   Y — Expansion Factor
   E — Velocity of Approach Factor
   Fa — Area of Thermal Expansion Factor
   Z — Compressibility Factor

g. Assume a coefficient of discharge (C) of 0.98. Utilizing this value in the General Flow Equation (Equation 12), calculate an approximate air mass flow value. With experience better estimates for the value of C should be made and used at this point.
h. Calculate the viscosity of the air entering the nozzle (Equation 10).
i. Calculate the Reynolds Number (N_R) (Equation 11) using the approximate air mass flow rate determined from (g).
j. Calculate the actual Coefficient of Discharge (C) from the appropriate equation (Equation 14 or 15).
k. Calculate the actual air mass flow rate (m) by using the actual (C) value in the General Flow Equation (Equation 12).
l. The actual volume flow rate may be calculated according to the following equation:

$$Vol(Q) = \dot{m}/\rho_{mo}\ ;\ m^2/s(ft^3/s) \qquad \text{(Eq. 21)}$$

7.2.5 SOURCES OF ERROR—The elemental sources of error are listed in Table 3. The recommended technique to estimate the error of a nozzle air flow measurement is to take the RSS (Root-Sum-Squared) of the elemental bias errors (error components that remain fixed during a test) and the RSS of the elemental precision errors (error components that vary randomly during a test) and add them using the equation:

$$U = b + 2\sigma \qquad \text{(Eq. 22)}$$

where:

U = measurement uncertainty
b = RSS of elemental bias errors
σ = RSS of elemental precision errors (σ is equivalent to one sample standard deviation of the random error)

See Reference 3 for detailed explanation of uncertainty technique.

Other sources of error are considered negligible when following recommended practice.

The estimated error of a direct reading (mass flow) inclined manometer includes all sources of error in Table 3 and U = 1.8%–1.9% rdg.

Using the equations presented in 7.2.1, calculations can be made to minimize error sources 2, 3, and 8, thereby improving the estimated uncertainty to U = + 1.2%/–1.4% rdg.

TABLE 3—SOURCES OF ERROR—NOZZLE AIR FLOW MEASUREMENTS

Source of Error	Error in Flow Measurement Bias (b)	Error in Flow Measurement Precision (2σ)
1. Calibration (Recommended Tolerance)	± 0.5% rdg	
2. Variation of CΔ and Y over 8:1 Range [1]	±0.3% rdg	
3. Density Changes Due to Humidity (20 to 90% RH)		±0.5% rdg
4. Pressure Drop - P(b = 0.5%, 2σ = 0.5% min rdg)	±0.25% min rdg	±0.25% min rdg
5. Ambient Pressure - P_A(b = 0.2 kPa (0.06 Hg), 2σ = 0.2 kPa)	±0.1% rdg	±0.1% rdg
6. Temperature - T(b = 1 °C (2 °F), 2σ = 1 °C)	±0.15% rdg	±0.15% rdg
7. System Leaks (Recommended Tolerance)	–0.5% min rdg	
8. Scale Conformance to Flow Equation (for Direct Reading Manometers)	1% rdg	

1. Can be eliminated using equations presented in 7.2.1.

7.3 Laminar Flow Meter

7.3.1 BASIC FLOW EQUATION—The mass air flow relationship can be simplified to:

$$m_t = \frac{\rho_{1t}}{\rho_{1cal}} \cdot \frac{\mu_{cal}}{\mu_{1t}} \cdot m_{cal} \qquad \text{(Eq. 23)}$$

where:

m_{cal} = a function of ΔP across the meter read from the calibration data at ΔP(test)
μ = viscosity of air (Eq. 10)
ρ = density of air (Eq. 9)

NOTE— Density may be either wet or dry, but must be consistent.

7.3.2 CALCULATION WITH STANDARD INSTRUMENTATION

a. Air flow $m_{(cal)}$ corresponding to the observed $\Delta P_{(test)}$ is found from a calibration curve (Figure 12) or calibration curve fit equation.

b. Calculate density and viscosity correction factor using:

$$cf = \frac{\rho_{1(test)}}{\rho_{1(cal)}} \times \frac{\mu_{1(cal)}}{\mu_{1(test)}} \qquad \text{(Eq. 24)}$$

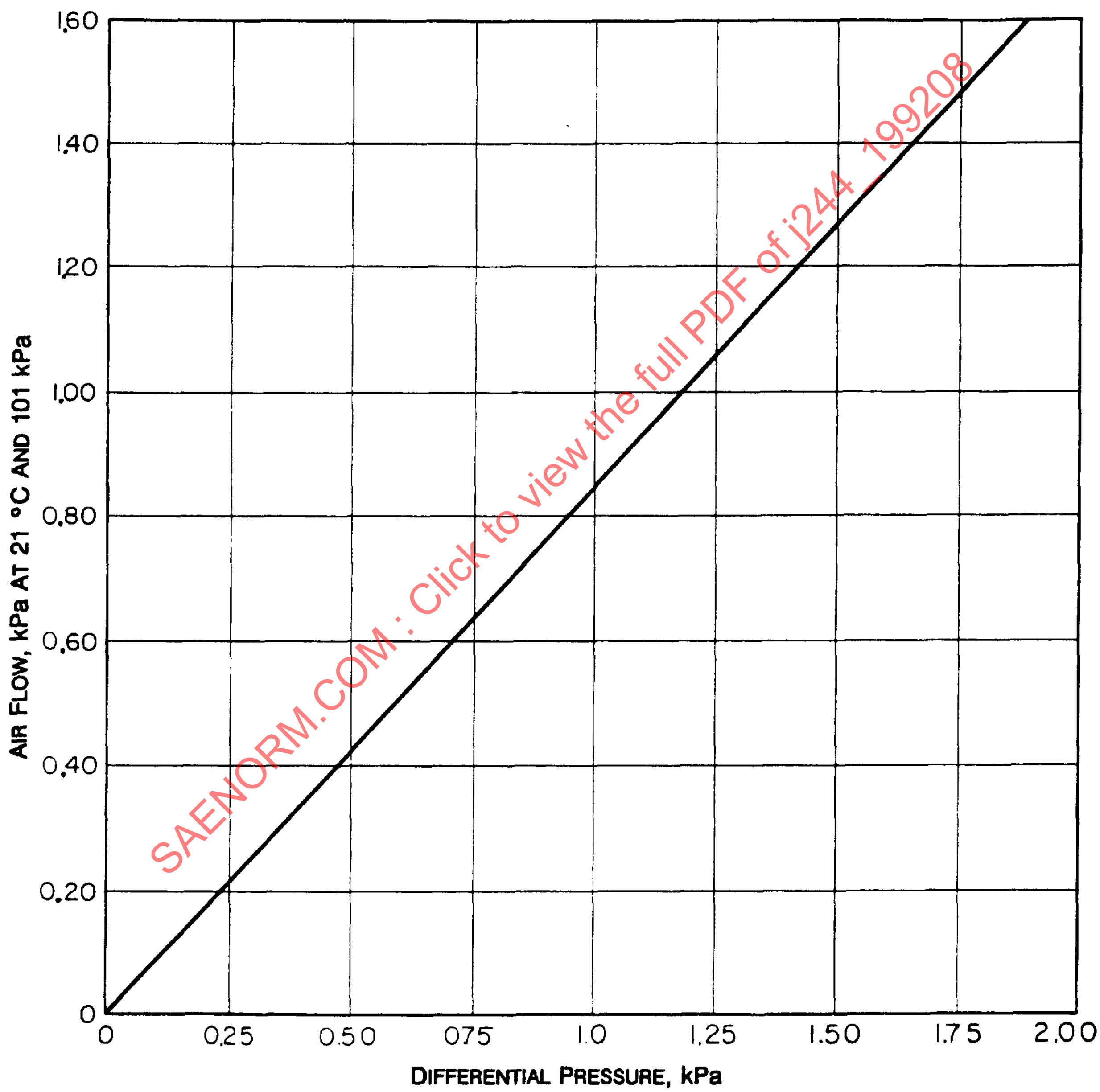


FIGURE 12—EXAMPLE OF LAMINAR FLOW METER CALIBRATION CHART

c. Calculate mass flow rate:

$$m_{test} = m_{cal} \bullet CF \quad \text{(Eq. 25)}$$

7.3.3 CALCULATION STEPS WITH COMPENSATING INSTRUMENTATION—The manufacturer's instructions must be followed depending on the scale of the compensating manometer used.

a. For a manometer reading values of corrected ΔP, the value of $m_{(test)}$ is read directly from the appropriate calibration curve.
b. For a manometer reading values of kg/s, the value of $m_{(test)}$ is read directly. (Corrections must be made if there is any shift from the original meter calibration.)

7.3.4 SOURCES OF ERROR—The elemental sources of error are listed in Table 4. The recommended technique to estimate the error of a laminar air flow measurement is to take the RSS of the elemental bias errors (error components that remain fixed during a test) and the RSS of the elemental precision errors (error components that vary randomly during a test) and add them using the equation:

$$U = b + 2\sigma \quad \text{(Eq. 26)}$$

where:

U = measurement uncertainty
b = RSS of elemental bias errors
σ = RSS of elemental precision errors (σ is equivalent to the sample standard deviation of the random error)

Other sources of error are considered negligible when following recommended practice.

The estimated error of a direct reading manometer includes all the errors listed in Table 4 and results in U = +2%/–2.2% rdg. Using the equations, correcting for humidity and calculating flow, can minimize error sources 2 and 7, thereby improving the estimated uncertainty to U = +1.2%/–1.4% rdg.

TABLE 4—SOURCES OF ERROR—LAMINAR FLOW MEASUREMENTS

Source of Error	Error in Flow Measurement Bias (b)	Error in Flow Measurement Precision (2σ)
1. Calibration Data	±0.5% rdg	
2. Density Changes Due to Humidity (20 to 90% RH)		±1% rdg
3. Pressure Drop, ΔP(b = ±0.5%, 2σ = ± 0.5% min rdg)	±0.5% min rdg	±0.25% min rdg
4. Temperature (b = ±1 °C, 2σ = ±1 °C)	±0.3% rdg	±0.3% rdg
5. Pressure, P_1(b = ±0.2 kPa, 2σ = ±0.2 kPa)	±0.2% rdg	±0.2% rdg
6. System Leaks (Recommended Tolerance)	–0.5% min rdg	
7. Scale Conformance to Flow Equation (for Direct Reading Manometers	±0.5% rdg	

7.4 Vortex Shedding Meter—The vortex shedding principle results in a simple linear relationship between volumetric flow rate (Q) and vortex shedding frequency (f).

$$Q = K \times f;\ m^3/s(ft^3/s) \quad \text{(Eq. 27)}$$

7.4.1 ALTERNATE CALIBRATION—If calibration facilities are available and machine computation of flow rates is performed, additional accuracy can sometimes be obtained by using a least-squares curve fit to the calibration data. In this case the flow equation takes the more complex form of a polynomial, for example:

$$Q = K1 + K2*f + K3*f^2 \quad \text{(Eq. 28)}$$

where:

K1, K2, K3 are the coefficients derived from a second-order least-squares curve fit.

7.4.2 SOURCES OF ERROR—The elemental sources of error are listed in Table 5. The recommended technique to estimate the error of a vortex shedding flow measurement is to take the RSS of the elemental bias errors (error components that remain fixed during a test) and the RSS of the elemental precision errors (error components that vary randomly during a test) and add them using the equation:

$$U = b + 2\sigma \quad \text{(Eq. 29)}$$

where:

U = measurement uncertainty
b = RSS of elemental bias errors
σ = RSS of elemental precision errors (σ is equivalent to the sample standard deviation of the random error)

Other sources of error are considered negligible when following recommended practice. It is stressed that the installation requirements outlined in 6.5.1 must be followed to assure a uniform flow profile. Flow profile variations in duct work can cause errors in excess of 2% of reading.

The estimated error of a vortex shedding flow measurement without humidity corrections includes all of the errors listed in Table 5 and results in U = +1.8%/–2% rdg. If humidity corrections are made to the data, error 2 is minimized, improving the measurements to U = +1.1%–1.3% rdg.

TABLE 5—SOURCES OF ERROR—VORTEX SHEDDING FLOW MEASUREMENT

Source of Error	Error in Flow Measurement Bias (b)	Error in Flow Measurement Precision (2σ)
1. Calibration	±0.5% rdg	
2. Density Changes Due to Humidity (20 to 90% RH)		±1% rdg
3. Pressure, P_1 (b = ±0.2 kPa, 2σ = ±0.2 kPa)	±0.2 rdg	±0.2% rdg
4. Temperature, T_1 (b = ±1 °C, 2σ = ±1 °C)	±0.3% rdg	±0.3% rdg
5. System Leaks (Recommended Tolerance)	–0.5% min rdg	
6. Nonlinearity of Flow Coefficient (20:1 Range)	±0.5% min rdg	

8. ***Exhaust Gas Flow Calculation***—(See 8.1 for alternate method.) In the general case, the mass flow out of an engine equals the mass flow into the engine. Therefore, exhaust mass flow rate equals the intake air mass flow rate plus the fuel mass flow rate. Typical units for mass flow rate would be kg/h, kg/min, or kg/s. The basic equation is:

$$\dot{m}_{exh} = \dot{m}_{air} + \dot{m}_{fuel} \quad \text{(Eq. 30)}$$

An exception to the previous relationship would be any air flow into the engine which was diverted before the exhaust system to leave the engine by an auxiliary path. Such a flow would have to be measured and subtracted from the intake air flow in order to calculate the exhaust mass flow (see Figure 13).

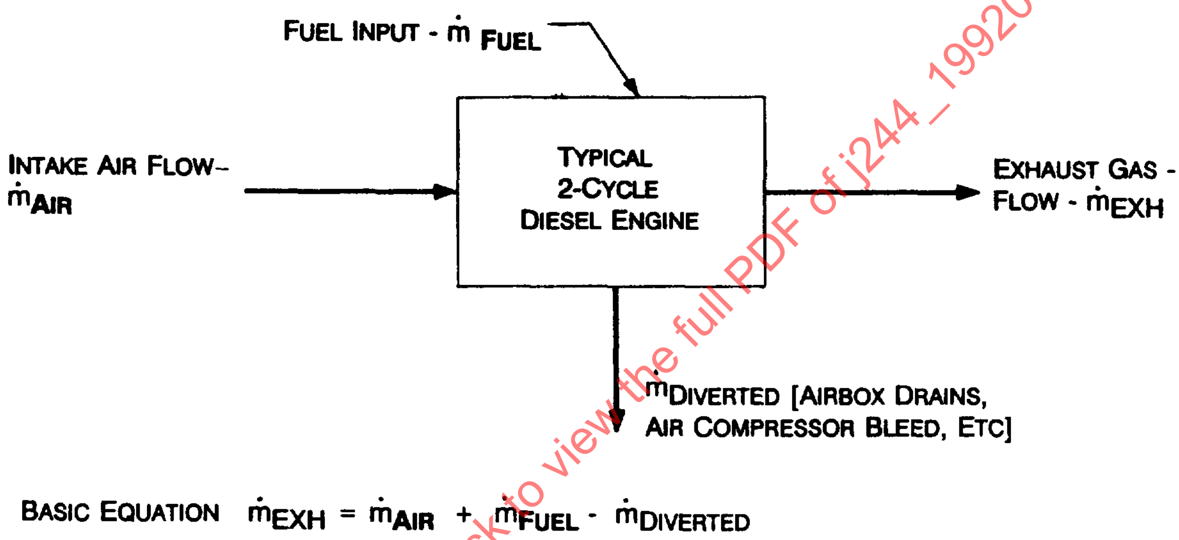


FIGURE 13—MASS BALANCE FOR 2-STROKE/CYCLE ENGINE

8.1 Alternate Method of Obtaining Exhaust Mass Flow—When it is desired to measure exhaust mass flow, the technique in Appendix C is recommended. Due to the nature of the exhaust gas, it is recommended that the flow meter be cleaned for each use. If this is impractical, the meter may be calibrated in place in a "dirty," but stable condition. Knowledge of the molecular weight of the exhaust becomes a factor in obtaining the best results with this method.

9. ***Notes***

9.1 Marginal Indicia—The change bar (l) located in the left margin is for the convenience of the user in locating areas where technical revisions have been made to the previous issue of the report. An (R) symbol to the left of the document title indicates a complete revision of the report.

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