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Introduction to Liquid Flow Metering and Calibration of Liquid Flowmeters

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Introduction to Liquid Flow Metering and Calibration of Liquid Flowmeters

Lief O. Olsen

Institute for Basic Standards
National Bureau of Standards
Washington, D.C. 20234

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Introduction to Liquid Flow Metering and Calibration of Liquid Flowmeters

Lief O. Olsen

These notes are intended to serve as an instruction manual for technicians and engineers engaged in metering liquids and calibrating liquid flowmeters. It is a condensed review of the properties of liquids and the mathematical relations required in this work. References to more complete sources of properties of liquids, theoretical relations and instructions for metering liquids are included. Separate chapters discuss liquids and their properties as they affect flow, the theory of incompressible flow of liquids and the measurements required in the metering of liquids. One chapter describes several different apparatus and their use in the calibration of liquid flowmeters. The last chapter contains brief descriptions of the many types of flowmeters such as differential pressure, positive displacement, electromagnetic and ultrasonic. It also includes a discussion of the physical principles involved in their design and use.

Key words: Calibration; flow measurement manual; liquid flow; liquid flowmeters; metering.

1. Introduction

These notes have been written primarily to serve as an instruction manual for military personnel engaged in the metering of liquids and calibration of liquid flowmeters. The intent has been to include a condensed review of the fundamental quantities and relations encountered in this work. References to more complete sources of properties of liquids, theoretical relations and instructions for metering and calibrating have been included.

Separate chapters discuss liquids and their properties as they affect flow, the theory of incompressible liquid flow and the measurements required in the metering of liquids. Other chapters are concerned with the methods of calibration of liquid meters and brief descriptions of the various types of meters.

Throughout this paper the system of units adopted by ASME has been used. This system uses pound for both the unit of force and unit of mass, which is at variance both with international practice and with the International System of Units (SI) which have been adopted officially by the National Bureau of Standards. However, the ASME system is followed because this is the system used by almost all involved in flow metering in the U.S.

2. Units and Symbols

Throughout the world, in both science and industry, two fundamental systems of dimensions are in general use. They are the "gravitational" system based on force, length and time and the "absolute" system in which mass, length and time are the primary units. In any coherent system of dimensions only three primary dimensions may be used and all other dimensions are defined in terms of these three. Both of these systems are in use in the United States. In the engineering profession customary or "English" units are commonly used. In most scientific work throughout the world the absolute system is generally used; originally in the C.G.S. system the mass length and time units were the gram, centimeter and second, respectively. The International System of Units (SI) was defined and given official status by the General Conference on Weights and Measures in 1956. It is an absolute system based on the kilogram, metre and second. Confusion resulting from this multiplicity of systems and units is not surprising.

At its annual meeting in 1963, the ASME Research Committee on Fluid Meters voted to use "absolute" dimensions in the equations and physical data presented in the Sixth Edition of its report [1]**. In that issue the pound is used to name both the unit of mass and

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** Figures in brackets indicate literature references at the end of this paper.

unit of force. To prevent confusion the abbreviations for "pound-mass" and "pound-force" are lbm and lbf. In the case of pressure abbreviations psi, psia, and psig "f" is omitted because it is obvious that pressure is force per unit area and "p" in these abbreviations is pounds force.

The major reason for using an absolute system based on mass rather than force in the gravitational system is the constancy of mass. The mass of a substance or body does not change with its location; it is the same on the surface of the earth or in space. Force, as represented by weight, is a measure of the gravitational pull of the earth upon the body; consequently the force may vary as the local value of the acceleration due to gravity, g_ℓ.

The system and units adopted by the ASME will be used exclusively in this work. This is done so as not to add to the current state of confusion. Table 1, a comparison of some of the systems of dimensions, is included only for information and in the hope that it and the following discussion will be of help in the understanding and use of the various systems. The reader is cautioned to confine his dimensions and units to those prepared by the ASME.

Table 1. Comparison of Force-Mass-Length-Time Systems

Item	Absolute customary M,L,t	Gravitational customary F,L,t	Absolute F,M,L,t	International System of Units [13] (SI) M,L,t
Force, F	poundal,pdl	pound force, lbf	pound force, lbf	newton, N
Mass, M	pound mass, lbm	slug	pound mass, lbm	kilogram, kg
Length, L	foot, ft	foot, ft	foot, ft	metre, m
Time, t	second, s	second, s	second, s	second, s
Velocity L/t	ft/s	ft/s	ft/s	m/s
Acceleration L/t^2	ft/s^2	ft/s^2	ft/s^2	m/s^2
Pressure F/L^2	pdl/ft^2	lbf/ft^2	lbf/ft^2	N/m^2

The relation between mass and force is derived from Newton's second law that force is proportional to mass times acceleration,

$$F \propto Ma = ML/t^2 \tag{1}$$

The force F due to the gravitational attraction between the earth and a mass, M, is numerically

$$F = M\, g_\ell / g_c \tag{2}$$

where g_ℓ is the local acceleration due to gravity and g_c is a gravitational conversion factor, the numerical value of which depends upon the units of F, M, and g_ℓ as follows:

g_c = 1, for F in poundals, M in pounds mass and g_ℓ in ft/s^2,
g_c = 1, for F in pounds force, M in slugs, and g_ℓ in ft/s^2,
g_c = 32.174, for F in pounds force, M in pounds mass, and g_ℓ in ft/s^2
g_c = 1, for F in newtons, M in kilograms and g_ℓ in m/s^2.

Thus, in the absolute customary or "English" system based on the pound mass, the poundal is defined as the force required to accelerate a mass of one pound at a rate of one ft/s^2 and

$$F = Ma \text{ (poundals)} \tag{3}$$

In the absolute F, M, L, t system advocated by the ASME and used in the Sixth Edition of Fluid Meters [1] and herein, the unit of mass is the standard pound mass (lbm), and the pound force (lbf) is defined as the force required to accelerate a mass of one pound at g_o, the standard acceleration of gravity of 32.174 ft/s^2. Stated another way, the lbf is the force required to support a standard lbm in vacuo against standard gravity. Thus in pounds force,

$$F = Ma/g_c = Ma/32.174 \tag{4}$$

From which it is apparent that

$$1 \text{ lbf} = 32.174 \text{ poundals} \tag{5}$$

Although g_c can be considered to be dimensionless, with only its numerical value a function of the units used, it is sometimes convenient to use the dimensions derived from equation (4) so that

$$g_c = 32.174 \text{ lbm}\cdot\text{ft/lbf}\cdot\text{s}^2 \tag{6}$$

This selected unit of force lbf will be used only as a measure of pressure or weight, never as a measure of the quantity of matter (mass). The use of the proportionality factor g_c will be required in computing weight of 1 lbm in the earth's gravitational field as

$$\text{Weight} = \text{lbf} = \text{lbm } g_\ell/g_c \tag{7}$$

where g_ℓ is the local acceleration of gravity.

"Weighing" is the process of determining either the mass or weight of a body depending on the apparatus employed. Weighing on a lever balance is a comparison between an unknown mass and selected standards of mass. Effects of variations in the acceleration of gravity are equal on both known and unknown mass; hence mass, not weight, of the unknown is determined directly. Spring balances and load cells will also indicate directly in mass if they have been calibrated with known masses at their place of installation. If calibrated elsewhere a correction for local gravity must be applied. Pressures as indicated by columns of manometric liquids will also require correction for local gravity. This will be shown in a later section.

A complete list of the various parameters used in this work is presented in Table 2. The letter symbols, definition, dimensions, customary units, (SI) units and conversion factors are included. Every effort will be made to confine all calculations, examples, and discussion to the customary units as listed in Table 2.

Table 2. List of Symbols

Symbol	Definition	Dimensions	Customary Units	Multiply by	To get SI Units
A	Area	L^2	ft^2	.092903	m^2
c	Velocity of sound in fluid	L/t	ft/s	0.3048	m/s
C	Coefficient of discharge	None			
D	Diameter	L	ft	0.3048	m
f	Frequency	t^{-1}	hertz		
g_c	Proportionality constant	None	32.174		
g_ℓ	Local acceleration of gravity	L/t^2	ft/s^2	0.3048	m/s^2
g_o	International standard acceleration of gravity	L/t^2	32.174 ft/s^2		9.80665 m/s^2
h	Height of liquid column	L	ft	0.3048	m
Δh	Differential height of liquid column (h_1-h_2)	L	ft	0.3048	m

Symbol	Definition	Dimensions	Customary Units	Multiply by	To get SI Units
K	Meter factor	(pulses per gallon)			
ℓ	Characteristic length	L	ft	0.3048	m
L	Length	L	ft	0.3048	m
m	Mass rate of flow	M/t	lbm/s	0.45359	kg/s
M	Mass	M	lbm	0.45359	kg
p	Gage pressure	M/Lt^2	lbf/ft^2	47.880	N/m^2
Δp	Differential pressure (p_1-p_2)	M/Lt^2	lbf/ft^2	47.880	N/m^2
P	Absolute pressure	M/Lt^2	lbf/ft^2	47.880	N/m^2
q[1]	Volume rate of flow	L^3/t	ft^3/s	.0283169	m^3/s
R	Reynolds number	None			
s	Time	t	s	-	s
T[2]	Temperature	-	°F or °R	see 5.1.	°C or K
V	Velocity	L/t	ft/s	0.3048	m/s
w	Specific weight		lbf/ft^3		
β	Diameter ratio	D_2/D_1	(throat/upstream)		
θ	Angular displacement of weigh beam, radians				
μ[3]	Viscosity	M/Lt	lbm/s·ft	14.8816	g/cm·s
ν[3]	Kinematic viscosity	L^2/t	ft^2/s	9.2903×10^2	cm^2/s
ρ	Density	M/L^3	lbm/ft^3	16.0185	kg/m^3
τ	Shearing stress	M/Lt^2	lbf/ft^2	47.880	N/m^2

Note:

1. q is also used as ft^3/min and gallons/minute. To obtain U.S. gallons per minute multiply ft^3/s by 448.8311.
2. Conversion of temperature units is covered in another section.
3. Since viscosity and kinematic viscosity in the reference literature are usually presented in poise and stokes, where poise is grams per centimeter second and stoke has the units of cm^2/s, it is more convenient to convert to the customary units as follows:

   μ in lbm/s·ft = 0.067197 x (number of poises), and
   ν in ft^2/s = 1076.39 x (number of stokes).

3. Liquids

3.1. Liquids Defined

Since this manual is concerned with the metering of liquids and the calibration of liquid flowmeters, a short discussion is in order about what is a liquid, and the properties of liquids which affect the flow. For most engineering purposes a liquid can be defined as a substance in such a state that its particles have sufficient cohesion to remain in one mass but are free to move about within the mass by the application of slightest force. This fluid property causes the liquid to conform to the shape of its container. When at rest the mass of the liquid is confined by the bottom and sides of the vessel and presents a level upper surface except for the effects of surface tension at the boundaries.

An ideal or perfect liquid is one which for purposes of developing theory is assumed to be both nonviscous and incompressible. Such liquids do not exist and theory based upon such assumptions is subject in its application to corrections for the effects of physical properties that have been neglected. This definition of liquids is seen to include a wide variety of substances of diverse properties. It will include light and heavy substances such as water and mercury, and it will also include materials of very different viscosities such as gasoline and heavy lubricating oils.

It must be obvious that density and viscosity of liquids have a profound effect upon the metering of liquids through conventional meters such as nozzles, orifices, variable area meters, turbine-type meters and others. These effects will be discussed later in Chapter 4. Definitions and measurements of density and viscosity will be treated in this chapter.

3.2. Density of Liquids

The densities of flowing liquids are frequently required to convert between mass and volumetric units of flow and flowrate. They are also required in the manometric measurement of liquid pressures.

The density of liquids is influenced only to a relatively small extent by variations in temperature and pressure; however, for accurate determinations of flowrate these small effects must be considered. The accepted definition of density is the mass of a substance contained in a unit volume. In customary or "English" units this will be pounds mass per cubic foot ($lbm \cdot ft^{-3}$) and in SI units kilograms per cubic metre ($kg \cdot m^{-3}$).

Specific gravity is an abstract number expressing the ratio of the density of the test liquid to that of some other standard liquid at a stated temperature. Water is usually used as the standard liquid. The temperature of both the test and standard liquids should be indicated.

Density and specific gravity, although fundamentally different, can be determined in the same way. A great number of methods of determination are indicated by Hidnert and Peffer [2]. Of the eleven methods described, use of the hydrometer is the most commonly used in flow laboratories and will be discussed herein.

3.2.1. Hydrometers

The accuracy of hydrometer observations depends upon the cleanliness of the instruments and of the liquids in which the observations are made. Extra care should be taken to keep the liquid surface free of contamination. In order that the readings shall be uniform and reproducible the surface of the hydrometers, and especially of the stem, must be clean, so that the liquid will rise uniformly and merge into an imperceptible film on the stem.

In order that a hydrometer may indicate correctly the specific gravity of a specified liquid, it is essential that the liquid be uniform throughout both in temperature and composition. It is also necessary that the hydrometer be at the same temperature as the liquid. For most accurate results, the observations should be made at the temperature specified on the hydrometer. If the observation is made at some temperature other than that for which the hydrometer is designed, the reading will be in error. The magnitude of the error will depend upon the thermal expansion of the hydrometer and of the liquid used.

If the latter properties are known, tables of corrections for temperature may be prepared for use with hydrometers at various temperatures. Such a set of tables [3] has been prepared for liquid petroleum by the American Society for Testing Materials.

3.2.2. Test Procedure with Hydrometers

a. Pour into a glass cylinder enough of the test liquid to float the hydrometer. Pour the liquid slowly along the side of the cylinder to prevent the formation of air bubbles.
b. Stir the liquid to assure that both liquid and hydrometer are at a uniform temperature and near that of the room. Stir carefully to avoid the formation of air bubbles.
c. Immerse the hydrometer slightly below the point where it floats naturally, then allow it to float freely.
d. Observe a point slightly below the plane of the liquid surface, then raise the line of vision until this surface seen as an ellipse becomes a straight line. The point where this fine line cuts the hydrometer scale is the reading of the instrument. Observe the temperature indicated by a thermometer immersed in the liquid.

e. Repeat c and d, average the readings and apply the scale correction to the average reading.

3.2.3. Application of ASTM-IP Petroleum Measurement Tables

1. It must be emphasized these tables are applicable only for liquid petroleum products.
2. Tables involving the reduction of a specific gravity reading to a standard temperature assume the reading has been made with a glass hydrometer. The hydrometer can be either a 60/60°F or an API type. Corrections for the thermal expansion of the glass as well as for the liquid hydrocarbons have been incorporated in the tables. When instruments other than glass hydrometers are used for the measurement of specific gravity, additional corrections will be required in reducing to the standard temperature. The magnitude of the correction will depend upon the temperature at which the observation is made and the expansion characteristics of the particular instrument involved.
3. In the United States, all commercial weights are required by law to be weights in air. The values listed in these tables are for weighings made in air and are in pound mass (lbm) units rather than pound force (lbf); however, as discussed herein, pounds per gallon (lb/gal) will refer to pounds mass per gallon as weighed in air (apparent density). Density as weighed in vacuo will be lbm/gal. The density of standard air for purposes of conversion from weights in vacuo has been taken as 0.001217 $g \cdot cm^{-3}$ at 60°F, 760 mm Hg pressure and 50 percent relative humidity. Weighings are assumed to be made with brass weights having a density of 8.40 $g \cdot cm^{-3}$ at 32°F. When density in vacuo is required, a correction for air buoyancy must be applied.
4. The density of air at standard conditions is, for practical purposes, 0.00915 lbm/gal. Its exact value can be determined, if required, by procedures outlined in paragraphs 3059 and 3060 of API Standard 1101. On a percentage basis, the correction for this effect depends on the density of the liquid. For liquids having specific gravities in the range 0.7 to 0.8, the correction is about 0.14 percent.
5. The density of water in vacuo at 60°F is 0.99904 g/ml. The mass of a gallon of water at 60°F in vacuo is computed as 0.99904 x 3785.3/453.59 = 8.3372 lbm in vacuo. The assumed apparent density of a gallon of water at 60°F in air of standard conditions against brass weights is 8.3282 lb/gal.
6. Since gravimetric calibrators weigh in air, for conversion of the data from gravimetric to volumetric units it is convenient to use lb/gal in air as obtained from the tables. No correction for air buoyancy need be included in following this procedure.
7. As an illustration of one application of the ASTM-IP Tables assume the following example. A volumetric flowmeter indicating in gallons is calibrated on a gravimetric calibrator using MIL-F-7024A, Type II at test temperatures in the range 80 to 85°F. It is desired to find the apparent density in lb/gal in air of the test liquid throughout this temperature range.

   The specific gravity of a sample of the liquid is measured with a 60/60°F glass hydrometer. A previous calibration of the hydrometer shows this particular instrument has a scale error of -0.0008.

The observed reading is	0.7654 at 74°F
Applying the scale error correction	-0.0008
The corrected observed specific gravity reading is	0.7646 at 74°F

   Table 23, page 239 [3] gives a corresponding 60/60°F specific gravity of 0.7705. Table 26, page 494 [3] gives an apparent density of 6.4146 lb/gal in air at 60°F for this liquid. Table 24, page 426 [3] gives the expansion factors for this 60/60°F specific gravity hydrocarbon between the temperatures of 60°F and the calibrating temperatures:

Calibrating Temp. °F	Expansion Factor	Apparent* Density lb/gal in air
74	.9922	6.3646
80	.9888	6.3427
81	.9883	6.3395
82	.9877	6.3357
83	.9872	6.3325
84	.9866	6.3286
85	.9860	6.3248

* The values of lb/gal in air at the listed temperatures were obtained by multiplying expansion factors times 6.4146, lb/gal in air at 60°F.

8. The above method is convenient in that apparent densities of the liquid hydrocarbons can be determined accurately at any temperature from a single specific gravity observation made at any known temperature. The temperature of the observation must be known to within 0.5°F.
9. The above method is inconvenient in that it requires the use of many tables and a calculating machine. When considerable calibration work is confined to one liquid, such as MIL-F-7024A, Type II, Tables 24 and 26 [3] can be given in chart form. An example, lb/gal in air versus 60/60°F specific gravity for temperatures in the range 60 to 100°F is shown in Figure 1.

   This chart requires that the 60/60°F specific gravity be known through the use of Table 23 and the observed specific gravity reading at an observed temperature. It will be found that the chart gives the same values of lb/gal in air vs. temperature as in the previous example for a liquid hydrocarbon having 60/60°F specific gravity of 0.7705.
10. Another method can be used to compute apparent density provided the specific gravity observation with the 60/60°F hydrometer is made at the same temperature at which apparent density is desired. Two factors must be considered in using this method.

   First, there is the thermal expansion of the glass in the hydrometer. A correction C must be made to the observed specific gravity, SG_o, to obtain the true specific gravity SG_t at temperature t; $C = 0.000025\ 5/9\ SG_o\ (60-t)$ is the correction for the expansion or contraction of the hydrometer from the reference temperature of 60°F. For liquid hydrocarbons having a specific gravity range 0.7 to 0.9 the approximate value C = 0.0001 per 10°F is usually adequate. Note that C has a negative value for temperatures above 60°F.

   The second factor is that an additional correction for the buoyancy force of the air is necessary when apparent density is desired, because true specific gravity is the ratio of the density of the liquid at the observed temperature in vacuo divided by the density of water at 60°F in vacuo.

   Consider the previous example of an observed specific gravity of 0.7646 at 74°F, corrections for the hydrometer scale error having been previously applied.

   SG_o = 0.7646 at 74°F
   C = -.00014
   SG_t = 0.76446 at 74°F

   Density in vacuo = 0.76446 x 8.3372 = 6.37345 lbm/gal at 74°F
   Correction for air buoyancy (par. 4)= -.00915
   Apparent density = 6.3643 lb/gal at 74°F

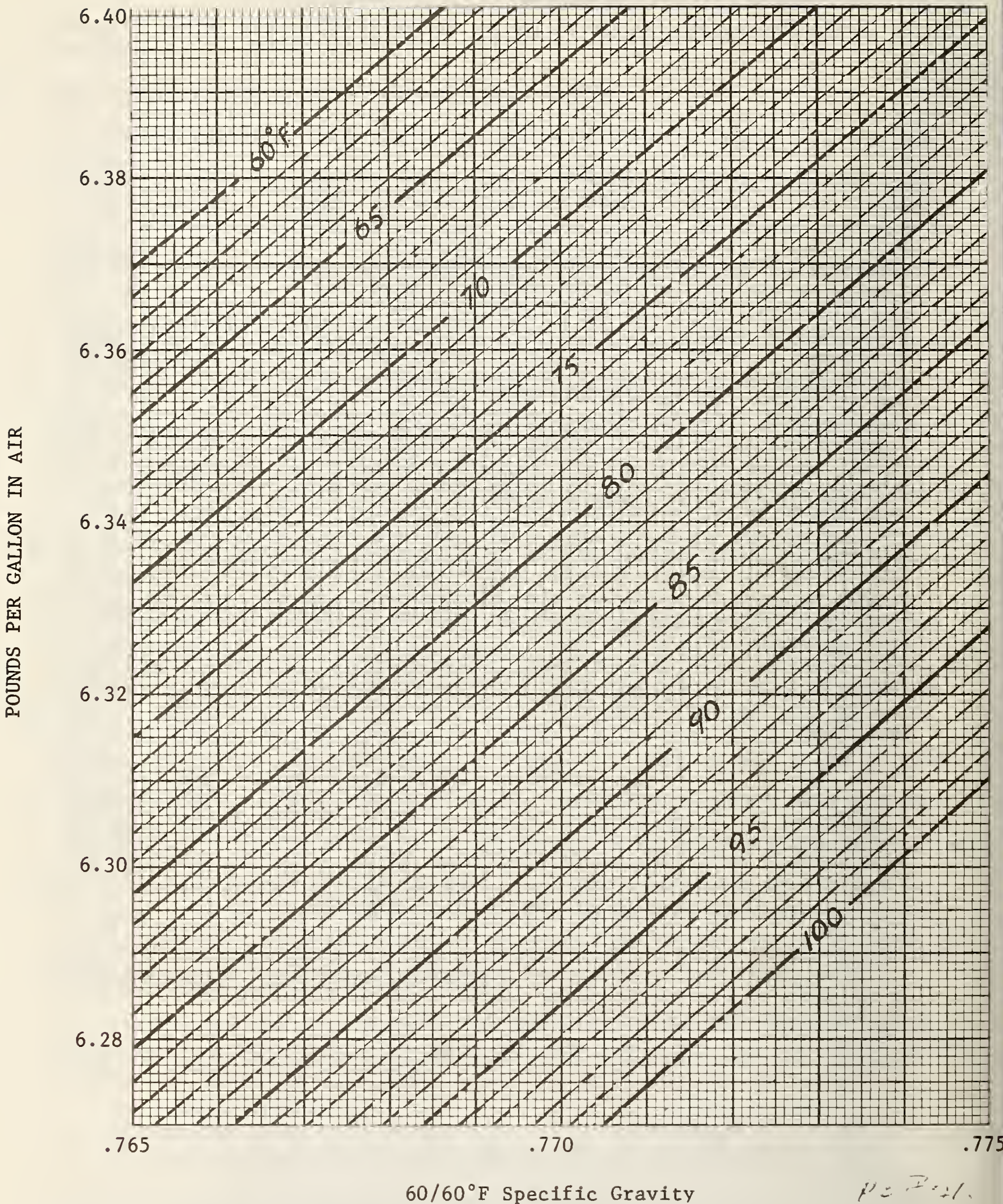


Fig. 1 Temperature - apparent density relation of a typical hydrocarbon.

This is in good agreement with the value obtained previously using the tables. Using the above procedure, specific gravity observations can be taken over the temperature range of interest with any particular liquid. The apparent density can be computed for each observation. A plot of apparent density versus temperature will then give apparent density at any desired temperature within the range investigated.

3.2.4. Density of Water

The density of pure water is usually determined from the measurement of temperature. Table 3 presents both mass in air and mass in vacuo for one gallon of pure water at a pressure of one atmosphere. The weights in air are for dry air at the same temperature as the water up to 40°C and at a barometric pressure of 760 mm Hg and against brass weights having a density of 8.4 $g\cdot cm^{-3}$. Above a water temperature of 40°C the temperature of the air is assumed to be 20°C, i.e., the water is allowed to cool to 20°C before the weighings are made. The volumetric computations are based on a water density of 1 kg per liter at 4°C; one liter = 1 $dm^3 = 10^{-3}\ m^3$. The density in grams per milliliter (g/ml) is included in the table.

Table 3. Density of Water

Temp °C	Temp °F	Density g/ml	Density lbm/ft^3	Density lbm/gal	Apparent density lb/gal
0	32	0.99987	62.418	8.3441	8.3346
2	35.6	.99997	62.424	8.3450	8.3355
4	39.2	1.00000	62.426	8.3452	8.3359
6	42.8	.99997	62.424	8.3450	8.3357
8	46.4	.99988	62.419	8.3442	8.3350
10	50	.99973	62.409	8.3430	8.3338
12	53.6	.99953	62.397	8.3413	8.3322
14	57.2	.99927	62.380	8.3391	8.3301
16	60.8	.99897	62.362	8.3366	8.3277
18	64.4	.99863	62.340	8.3337	8.3248
20	68	.99823	62.316	8.3305	8.3216
22	71.6	.99780	62.289	8.3269	8.3181
24	75.2	.99733	62.259	8.3229	8.3142
26	78.8	.99681	62.227	8.3187	8.3100
28	82.4	.99626	62.193	8.3141	8.3054
30	86	.99568	62.157	8.3092	8.3006
32	89.6	.99506	62.118	8.3040	8.2955
34	93.2	.99440	62.076	8.2985	[illegible].2900
36	96.8	.99372	62.034	8.2927	[illegible]2842
40	104	.99225	61.942	8.2805	8.2723
50	122	.98807	61.681	8.2457	8.2369
60	140	.98323	61.379	8.2054	8.1966
70	158	.97779	61.040	8.1600	8.1514
80	176	.97182	60.667	8.1101	8.1015
90	194	.96534	60.262	8.0560	8.0474
100	212	.95838	59.828	7.9979	7.9894

3.2.5. Compressibility of Liquids

For most metering of liquids the effect of pressure on the density can be safely ignored. However, for best accuracy at high pressures this effect should be considered and if necessary accounted for. A pressure of 1 psi (lbf/in^2) results in the compression of water, one part in 300,000; thus at a pressure of 1000 psi the water is compressed approximately 1 part in 300 or about 0.3 percent. The compressibility of typical hydrocarbons is approximately three times that of water; certainly the effect of pressure on density should be included at these higher pressures.

If ρ_1 and ρ_2 are the densities of liquids at pressures of p_1 and p_2 in atmospheres, respectively, at any temperature the ratio of densities is related to the coefficient of compressibility, b, by the equation

$$\rho_1/\rho_2 = 1-b(p_2 - p_1) \tag{8}$$

Table 4 is a tabulation of b for various liquids at a temperature of 20°C.

Table 4. Isothermal Compressibility of Liquids

Liquid	b, atm^{-1}
Acetone	128×10^{-6}
Benzene	95 "
Carbon disulphide	93 "
Carbon tetrachloride	105 "
Ethyl alcohol	111 "
Glycol	38 "
n-Heptane	144 "
n-Hexane	163 "
n-Octane	121 "
Water	46 "

Illustrative example:

Find the density of water at a pressure of 500 atmospheres and a temperature of 20°C. From Table 1 the density of pure water at 20°C and one atmosphere pressure is 8.3305 lbm per gallon in vacuo. The coefficient of compressibility b for water is 46×10^{-6}, thus

$$\frac{8.3305}{\rho_2} = 1 - 46 \times 10^{-6} (500 - 1)$$

$$\rho_2 = 8.5262 \text{ lbm/gallon}$$

3.3. Viscosity of Liquids

Liquids at rest may be regarded as having perfect fluidity; however, in a viscous slow-moving liquid internal shearing resistance arising from viscosity must be considered and allowance made for its effects. In such so-called laminar flow, viscous forces usually predominate. In a laminar flowmeter, for example, streamline flow occurs in the metering element; the pressure drop for a given volume rate of flow is proportional to viscosity. Thus in these applications viscosity should be determined with the best possible accuracy.

In turbulent flow, inertia forces resulting from liquid density will predominate, and viscous forces have only a rather small secondary effect. Orifice meters and nozzles are examples of instruments in which turbulent flow usually occurs, and values of viscosity to an accuracy of a few percent are usually adequate under these conditions.

Some flowmeters may have either laminar or turbulent flow at the metering element depending upon the size of the meter, the rate of flow, and the viscosity of the fluid. In this case, laminar flow is approached as meter size and rate of flow decrease or as viscosity of the fluid increases. Small variable-area meters are an example, especially when they are used to meter fluids of high viscosities.

Dynamic viscosity μ is a measure of the resistance which a fluid offers to change of shape, i.e., to shearing. The nature of this quantity μ, sometimes called the coefficient of viscosity, can be indicated clearly by considering the laminar motion of a viscous fluid bounded by two flat parallel plates, one of which is stationary and the other moving parallel to its surface with a constant velocity V as shown in Figure 2.

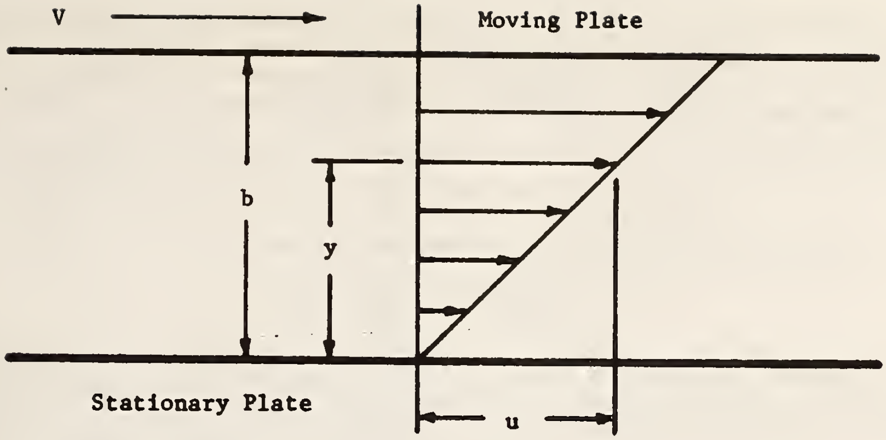


Fig. 2 Laminar flow between parallel plates in relative motion.

With no slip at the boundaries, the fluid layer at the lower plate will have zero velocity and the layer at the upper one a velocity equal to V. The particles in the uppermost layer are carried along with the moving plate and this layer in turn imparts a motion to the one immediately below it. At any point at a distance y above the lower plate the velocity is $u = Vy/b$ where b is the distance between plates. The rate of shear is $\partial u/\partial y = V/b$ and in this case is constant throughout the fluid. The shearing stress at any point is

$$\tau = \mu\frac{\partial u}{\partial y} = \mu V/b \tag{9}$$

The force necessary to move the plate is simply the value of τ multiplied by the area of the plate.

This arrangement of two parallel plates serves as the basis for the definition of the coefficient of viscosity when equation (9) is solved for μ

$$\mu = \tau\, b/V \tag{10}$$

A definition for the more general case is

$$\mu = \frac{\tau}{\partial u/\partial y} \tag{11}$$

In some problems it is convenient to introduce a modified form of the coefficient of viscosity, to be obtained by dividing μ by the density of the fluid, ρ. This quantity denoted by ν has the value

$$\nu = \mu/\rho \tag{12}$$

and is commonly known as the kinematic coefficient of viscosity.

3.3.1. Dimension and Units of Viscosity

The coefficient of viscosity Eq. 10 and the coefficient of kinematic viscosity Eq. 12 are not dimensionless quantities, and their values will depend on the units employed for their measurement. Introducing the fundamental dimensions of mass, length and time in Eq. 10

$$\mu = \tau\frac{b}{V} \propto \frac{\text{Force}}{\text{Area}} \cdot \frac{\text{Length}}{\text{Velocity}} \propto \frac{ML}{t^2} \cdot \frac{1}{L^2} \cdot \frac{Lt}{L} \propto \frac{M}{Lt} \tag{13}$$

thus μ has the dimension M/Lt. In the customary or "English" system μ has no assigned name but is usually expressed in pounds mass per foot second (lbm/ft·s). In the International system of Units (SI), the unit is the poise, which is 10^{-1} kg/m·s or one gram per centimeter second (g/cm·s). The conversion between these units of coefficient of viscosity is

$$1 \text{ lbm/ft·s} = 14.8816 \text{ g/cm·s or poise}$$

Similarly, introducing the fundamental dimensions into Eq. 12

$$\nu = \mu/\rho = \frac{M}{Lt} / \frac{M}{L^3} = \frac{L^2}{T} \qquad (14)$$

Thus in the "English" system of units the kinematic viscosity has the dimensions of ft^2 per second (ft^2/s). The unit in SI is the stoke (St) [13] which is equal to $10^{-4}m^2/s$ or cm^2/s. The conversion between these units is

$$1 \text{ ft}^2/\text{s} = 929.03 \text{ cm}^2/\text{s or stokes}$$

For more manageable numbers the coefficients of dynamic and kinematic viscosities are tabulated in centipoise and centistoke where

$$\text{centipoise} = \text{poise} \times 10^2$$

and

$$\text{centistoke} = \text{stoke} \times 10^2$$

The coefficients of dynamic viscosity in centipoise for a few common liquids at 20°C are tabulated in Table 5.

Table 5. Dynamic Viscosities of Liquids at 20°C

Liquid	Viscosity, Centipoise
Acetone	0.33
Benzene	.65
Carbon tetrachloride	.97
Ethyl alcohol	1.20
Ethylene glycol	19.9
Glycerin	1490.
Heptane	.41
Hexane	.33
n-Octane	.54
Turpentine	1.49
Water	1.00
Gasoline	.3 - .6
Kerosene	2.0
Light lubricating oil	2.5 - 150
Medium lubricating oil	150 - 350
Heavy lubricating oil	350 - 2000

3.3.2. Effect of Pressure on Viscosity

The effect of changes of pressure on the viscosity of liquids is practically negligible under ordinary conditions. Some liquids such as ether and benzene show a slight increase while water exhibits a decrease with increasing pressure. However, the change cannot be ignored when high pressure is used or when viscosity-sensitive meters are used. Results of viscosity tests by Oilwell Research, Inc. on MIL-F-7024A, Type II naphtha and MIL-H-5606A hydraulic oil show the following changes in viscosity with pressure:

For MIL-F-7024A Type II

$$\nu = \nu_a(1 + 0.11 \frac{psig}{1000}) \quad (15)$$

where ν_a is the kinematic viscosity at atmospheric pressure and ν is the viscosity at the elevated pressure in psig.

For MIL-H-5606

$$\nu = \nu_a(1 + 0.13 \frac{psig}{1000}) \quad (16)$$

3.3.3. Effects of Temperature on Viscosity

The viscosity of liquids decreases with increasing temperatures. The effect of temperature on the viscosity of water is shown in Table 6.

Table 6. Effect of Temperature on the Dynamic and Kinematic Viscosities of Water

Temperature °C	Dynamic Viscosity Centipoise	Density g/cm^3	Kinematic Viscosity Centistokes
0	1.787	0.9998	1.787
5	1.519	1.0000	1.519
10	1.307	0.9997	1.307
15	1.139	0.9991	1.140
20	1.002	0.9982	1.004
25	0.8904	0.9970	0.8931
30	0.7975	0.9956	0.8031
35	0.7194	0.9940	0.7237
40	0.6529	0.9922	0.6580
45	0.5960	0.9902	0.6019
50	0.5468	0.9880	0.5534
55	0.5040	0.9857	0.5113
60	0.4665	0.9832	0.4745
65	0.4335	0.9806	0.4421
70	0.4042	0.9778	0.4134
75	0.3781	0.9748	0.3879
80	0.3547	0.9718	0.3650
85	0.3337	0.9686	0.3445
90	0.3147	0.9653	0.3260
95	0.2975	0.9619	0.3093
100	0.2818	0.9583	0.2941

Unfortunately there is no such simple table for the hydrocarbon liquids used in military calibrating laboratories. These are not pure compounds but consist of various blends of liquid hydrocarbons. As a consequence, viscosity measurements of these liquids are required. For best accuracy the viscosity should be determined at the temperature of the flowing liquid. Where a lesser accuracy is permitted, such as its value for Reynolds number determinations, the temperature viscosity relationship can be shown on ASTM Viscosity-Temperature Charts [4]. These charts are a convenient means for the determination of viscosity of petroleum oils at any temperature, within a limited range, provided viscosities at two temperatures are known. The charts are so constructed that for any given petroleum oil the viscosity-temperature points lie on a straight line. There are six such charts whose viscosity and temperature ranges are shown in Table 7.

Table 7. ASTM Viscosity-Temperature Charts

Chart	Viscosity Range	Temperature Range
A	33 - 1x10^8 SAYBOLT UNIVERSAL SECONDS	-30 to +450°F
B	33 - 1x10^5 " " "	-30 to +350°F
C	2 - 2x10^7 Centistokes	-30 to +450°F
D	0.40 - 100 "	-30 to +450°F
E	2.0 - 2x10^7 "	-100 to +450°F
F	0.40 - 2x10^7 "	-100 to +700°F

A portion of Chart D is shown in Figure 3 which also includes an example of its use.

Illustrative example:

Find the kinematic viscosity at 75°F of a petroleum oil which has viscosities of 70 and 1.95 centistokes at -30 and 100°F, respectively. Plot the two known viscosity temperature points on the chart as shown. Draw a sharply defined straight line through them.

The desired viscosity at 75°F at the intersection of the straight line with the 75°F line is shown to be 2.75 centistokes.

If viscosities at two temperatures are not known they should be determined in accordance with the Method of Test for Saybolt Viscosity (ASTM Designation: D 88) or the Method of Test for Viscosity of Transparent and Opaque Liquids (Kinematic and Dynamic Viscosities) (ASTM Designation: D 445).

Conversion of centistokes to Saybolt seconds may be obtained from the Method for Conversion of Kinematic Viscosity to Saybolt Universal Viscosity or to Saybolt Fural Viscosity (ASTM Designation: D 2161).

More accurate measurements of kinematic viscosity are made with capillary-tube viscometers such as the straight tube (glue-type), Ostwald, Cannon-Fenske, Sil, Ubbelohde and Cannon master (this is not intended to be a complete listing of types). Directions for the use of these viscometers are available in [5] and [6].

3.4. Vapor Pressure of Liquids

Vapor pressure is defined as that pressure existing above a liquid in equilibrium with its own vapor. Vapor pressure is a function of the liquid and of its temperature. For instance the vapor pressure of water at 20° and 100°C is 0.339 and 14.696 lb/in^2, respectively. The maximum Reid vapor pressure of JP-4 Jet Fuel is specified to be 7 lb/in^2 at 100°F and that of MIL-F-7024A, Type I is 2 lb/in^2. The vapor pressure of MIL-F-7024A, Type II, a less volatile liquid, is considerably lower.

A minimum operating back-pressure for any flowmeter installation should be maintained to preclude a change in the meter calibration factor due to two-phase (liquid and air or vapor) conditions. This pressure is a function of the vapor pressure of the liquid and the presence of dissolved gases, and can be experimentally determined under actual test conditions if necessary. For turbine flowmeters it has been defined as the line pressure at which the calibration factor (pulses per gallon) at 125 percent of the nominal maximum flowrate increases 1/2 percent over the corresponding calibration factor obtained at the same flowrate but with a pressure 10 lb/in^2 higher. The operating back-pressure is measured four pipe-diameters downstream of the turbine flowmeter.

Where these tests are not made, the back-pressure should be set to a pressure not less than the sum of the vapor pressure plus three times the measured pressure drop across the flowmeter. For example, a turbine flowmeter having a pressure drop of 7 lb/in^2 at the maximum rated flow of JP-4 jet fuel should have a back-pressure of not less than

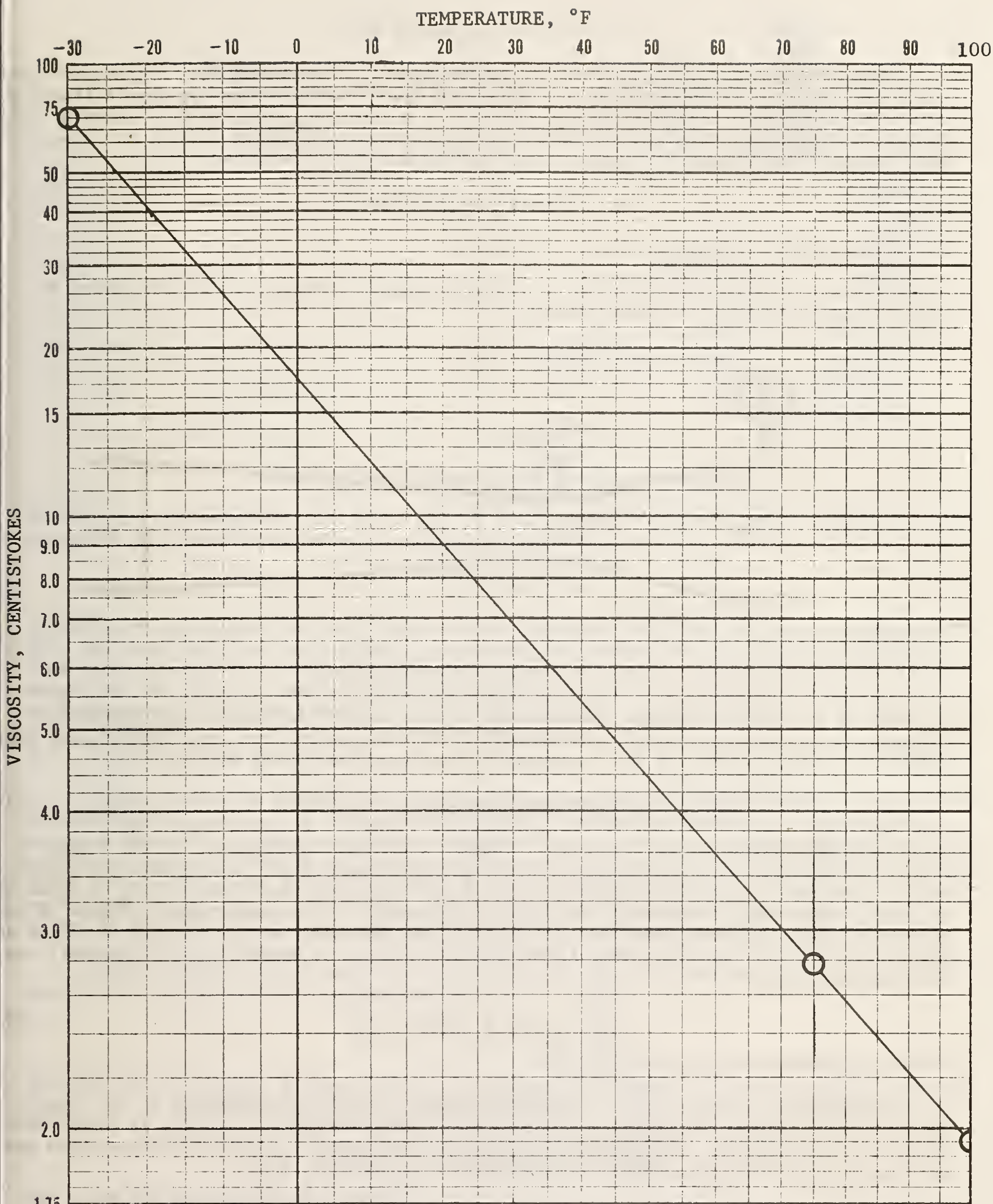


Fig. 3 Effect of temperature on the viscosity of a typical hydrocarbon liquid.

$$7 + (3 \times 7) = 28 \text{ lb/in}^2 \text{ psia}$$

Other flowmeters such as orifice, nozzle and Venturi meters are also subject to error due to cavitation. The pressure at the throat or downstream pressure tap should always be in excess of the vapor pressure of the liquid. Although it is conservative, whenever possible the minimum pressure recommended for turbine flowmeters should be used for these other types of flowmeters.

4. Flow in Closed Conduits

4.1. Conservation of Mass

Consider a steady state of flow of liquid through a conduit such as that shown in Figure 4, which might be a Venturi meter.

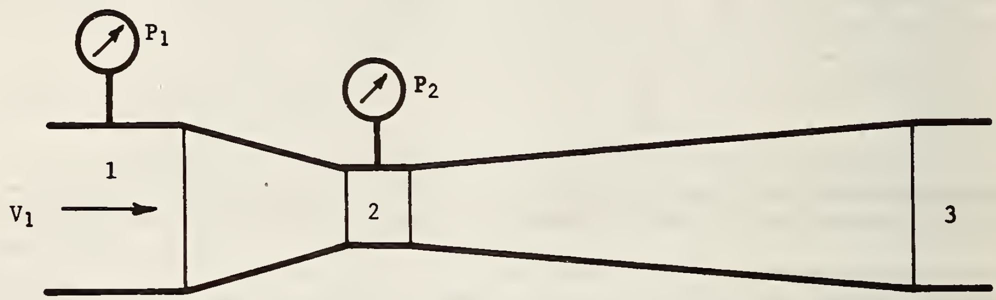


Fig. 4 Flow in a closed conduit.

If there is no flow through the walls either into or out of the conduit and further if there is no liquid accumulated or destroyed within the conduit, then the rate of mass flow passing any cross section of the tube must be the same. Referring to Fig. 4

$$m = \rho AV = \rho_1 A_1 V_1 = \rho_2 A_2 V_2 = \rho_3 A_3 V_3 \tag{17}$$

having the dimensions M/t such as lbm/s, where ρ represents the density of the liquid in lbm/ft^3, A the area of the cross section in ft^2 and V the average velocity of the liquid in ft/s at that section. The subscripts 1, 2 and 3 refer to the particular cross sections of the tube. Equation 17 represents the general statement of the conservation of mass or condition of continuity which must be satisfied in most problems in liquid flow. In flows in which the liquid can be considered incompressible (i.e., the density ρ is a constant) the equation above may be written

$$q_t = A_1 V_1 = A_2 V_2 = A_3 V_3 \tag{18}$$

having the dimension L^3/t such as ft^3/s.

Calibrations of fluid meters usually are based on either Equation 17 or 18. Gravimetric (mass vs time) calibrations utilize Eq. 17 while volumetric (volume vs time) calibrations may employ Eq. 18; however, for most accurate results especially where there may be temperature differences between stations Eq. 17 should be used.

Extending this reasoning to a calibration problem, consider a steady mass rate of flow through a system consisting of several flowmeters in series with a weigh-time calibrator shown in Fig. 5.

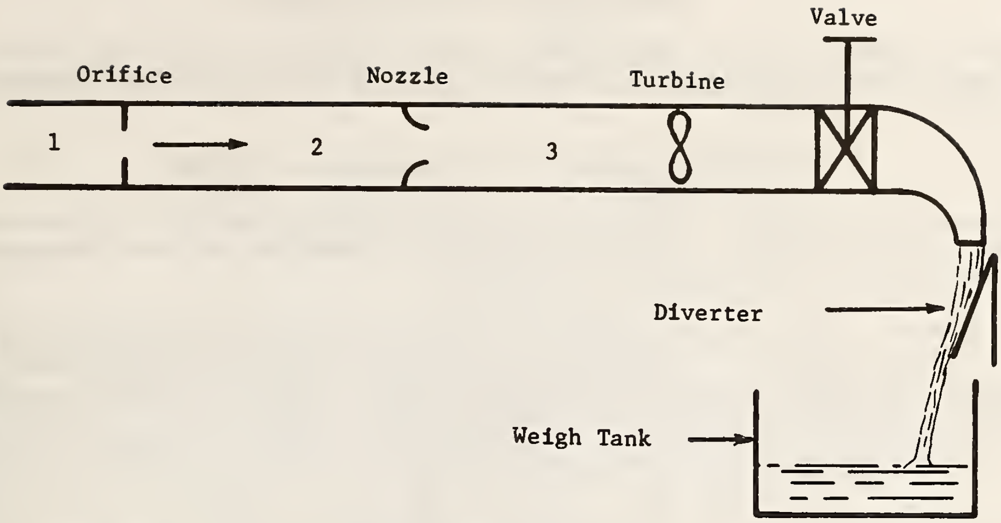


Fig. 5 Flow through several meters in series.

If there is no leakage in the entire system and a steady state of flow is established past section 1 the conservation-of-mass equation states

$$m_1 = m_2 = m_3 = M/t \tag{19}$$

where m_1, m_2 and m_3 are the mass rates of flow through the three sections and meters and M is the mass collected in the weigh tank during collection time t. Thus either the orifice meter, nozzle or turbine meter or all of them can be calibrated with respect to the weigh-time calibrator. Another method of calibration is to use one of the three meters as a transfer standard and calibrate the other two with respect to it.

4.2. Energy of Liquids in Motion

Liquids either at rest or in motion must conform like all other matter to the law of conservation of energy. In the case of liquids in motion three forms of energy are of greatest importance. They are kinetic, pressure and potential energies. Thermal or internal energy in general is of no great consequence and in the case of liquid flows in which there is no addition or extraction of heat it can be safely ignored. Energy in all forms is defined as the ability to do work. Each of the three forms kinetic, pressure and potential described herein has that ability and the same fundamental dimensions.

Kinetic energy is that energy which a mass possesses by virtue of its velocity and is given by the relation, for the absolute F, M, L, t units,

$$\text{Total kinetic energy} = \frac{MV^2}{2g_c}$$

For the case of liquids flowing through a conduit and assuming a uniform velocity across a section and applying the same dimensional units

$$\text{Kinetic energy per unit mass} = \frac{V^2}{2g_c}$$

which has the dimensions of ft·lbf/lbm.

The pressure maintained in a confined liquid also represents the ability to do work. If a vertical tube is connected to the conduit, the liquid will rise to a height h equal to p/w. In other words, the liquid flowing within the conduit could be lifted to height h by virtue of its pressure p. In the dimensions and conventions applied herein

$$\text{Pressure energy} = p/\rho \ \text{ft·lbf/lbm}$$

The potential energy is that energy a mass possesses because of its elevation h above some arbitrary datum and will have the same dimensions as kinetic and pressure energies

$$\text{Potential energy} = hw/\rho = h\ g_\ell/g_c \ \text{ft·lbf/lbm}$$

Notice that all three forms of energy have the dimensions of ft·lbf/lbm which is proportional to the height of a column of liquid. To determine the total energy of the liquid simply multiply by the pounds mass involved.

The general energy equation is simply an accounting of the energy passing stations 1 and 2 shown in Fig. 4. In the case of liquid flow through a meter or meters in series where there is neither thermal nor mechanical energy addition or subtraction between station 1 and 2 the energies at the two stations must be equal.

$$\frac{V_1^2}{2g_c} + \frac{p_1}{\rho_1} + h_1\ g_\ell/g_c = \frac{V_2^2}{2g_c} + \frac{p_2}{\rho_2} + h_2\ g_\ell/g_c \tag{20}$$

Equation 20 was first proposed in 1738 by Daniel Bernoulli and is now known as Bernoulli's theorem.

4.3. Differential Head Meters

Since the liquid is virtually incompressible and the temperature does not change, $\rho_1 = \rho_2$ and from equation 18

$$A_1V_1 = A_2V_2$$

or

$$V_1 = \frac{A_2}{A_1}\ V_2 \tag{21}$$

If we assume the axis of the meter run to be horizontal, the elevations of section 1 and 2 are equal and the potential energy terms can be deleted. Substitute Eq. 21 in Eq. 20 to get

$$V_2^2 = 2\ g_c \left(\frac{p_1-p_2}{\rho}\right)\left(\frac{1}{1-(\frac{A_2}{A_1})^2}\right) \tag{22}$$

Let the diameter ratio

$$\frac{D_2}{D_1} = \beta$$

then

$$\beta^4 = \left(\frac{A_2}{A_1}\right)^2$$

and

$$V_2^2 = 2g_c \left(\frac{p_1-p_2}{\rho}\right)\left(\frac{1}{1-\beta^4}\right) \tag{23}$$

The factor p_1-p_2 is equal to the difference between the static pressures and stations 1 and 2; if these pressures are measured with columns of the flowing liquid then

$$\frac{p_1-p_2}{\rho} = (h_1 - h_2)\ g_\ell/g_c$$

This difference in the height of the two columns is generally referred to as the "head" of the meter and is thus responsible for the term "differential head meter." The term $1/(1-\beta^4)$ is called the velocity of approach factor. The theoretical velocity at section 2 from Eq. 23 is

$$V_2 = \left[\frac{2g_c(p_1-p_2)}{\rho} \right]^{1/2} \left[\frac{1}{1-\beta^4} \right]^{1/2} \quad (24)$$

and the theoretical volumetric rate of flow from Equations 18 and 24 is

$$q_t = A_2V_2 = A_2 \left[\frac{2g_c(p_1-p_2)}{\rho} \right]^{1/2} \left[\frac{1}{1-\beta^4} \right]^{1/2} \quad (25)$$

and the theoretical mass rate of flow from Eqs. 17 and 24

$$m_t = \rho A_2V_2 = A_2[2g_c\rho(p_1-p_2)]^{1/2} \left[\frac{1}{1-\beta^4} \right]^{1/2} \quad (26)$$

The actual flowrate, either mass or volumetric, is rarely if ever equal to the theoretical as predicted by the equations above. To obtain the actual flowrate it is necessary to introduce a factor called the "Coefficient of Discharge" defined by the equation

$$C = \frac{\text{actual rate of flow}}{\text{theoretical rate of flow}}$$

The actual volumetric and mass rates of flow through Venturi tubes, nozzles and orifices are then

$$q = CA_2 \left[\frac{2g_c(p_1-p_2)}{\rho} \right]^{1/2} \left[\frac{1}{1-\beta^4} \right]^{1/2} \text{ and} \quad (27)$$

$$m = CA_2 \left[2g_c\rho(p_1-p_2) \right]^{1/2} \left[\frac{1}{1-\beta^4} \right]^{1/2} \quad (28)$$

Equations 27 and 28 can be used to solve for the rate of flow through orifices, nozzles and Venturi meters provided the discharge coefficient is known. Unfortunately this coefficient C is not a constant for a given meter, but is found to vary with density, viscosity and velocity of the flowing liquid. However, it can be shown that C is a function of Reynolds number R, which is a dimensionless ratio of the aforementioned parameters plus a characteristic length ℓ, usually a diameter, either D_1 or D_2

$$R = \frac{\rho V\ell}{\mu} = V\ell/\nu \quad (29)$$

Of course the dimensions of all parameters must be consistent so that the numerical value of R is independent of the system of units used. For instance

ρ - lbm/ft^3 or gram/cm^3
V - ft/s or cm/s
ℓ - ft or cm
μ - lbm/ft·s or gram/cm·s

Thus, with either system of units R is the same and is truly dimensionless.

Typical curves showing the variation of C with R for orifice and nozzle meters are shown in Figure 6, and numerical values of C vs R for a wide variety of orifices and nozzles are presented in [1]. Because of the functional relationship between C and R it is evident that the calibration of such a meter requires measurements over the entire range of Reynolds numbers. In a weigh-time calibration, C can be determined from Eq 28 and R from Eq. 29 rewritten as

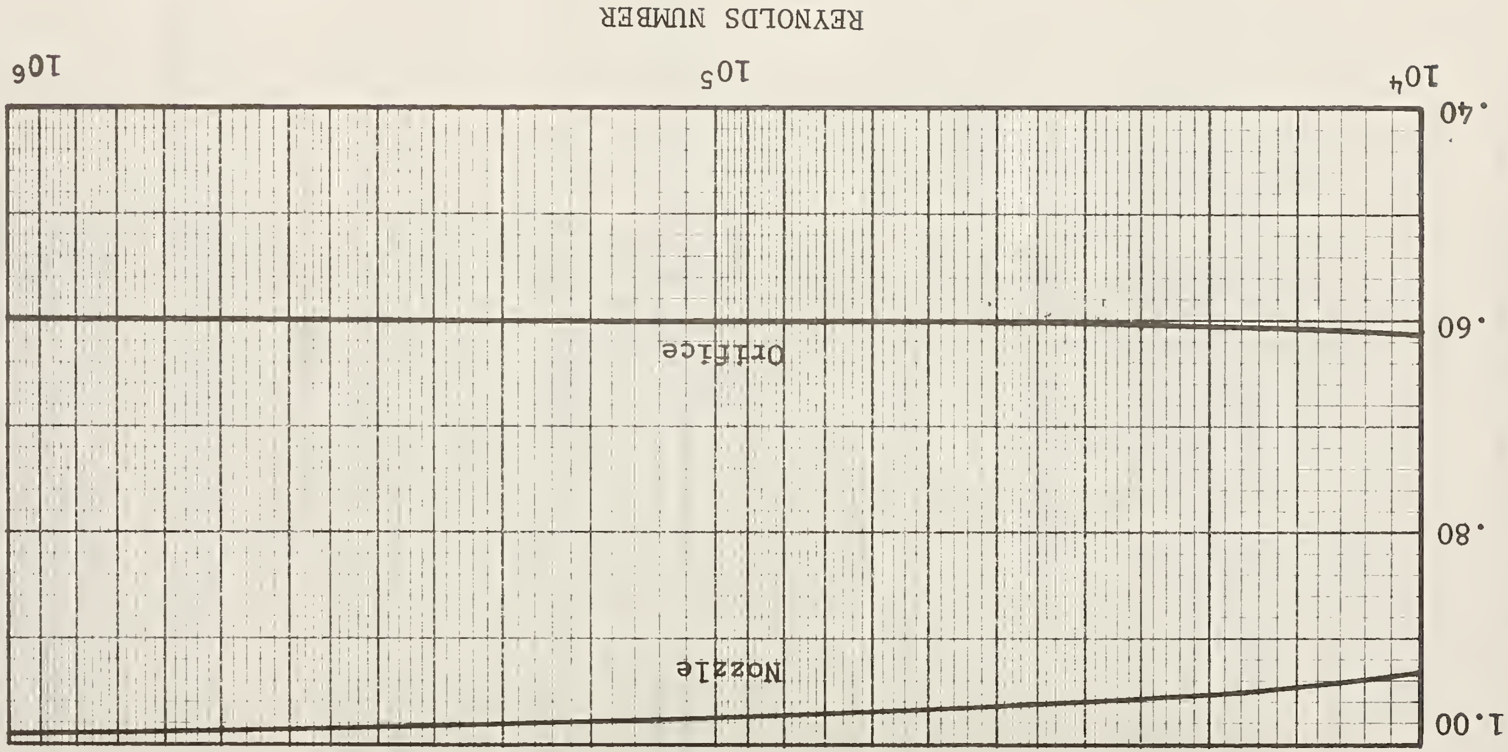


Fig. 6 Coefficients of discharge vs Reynolds number for typical orifice and nozzle meters.

$$R = \frac{\rho V_2 D_2}{\mu} = \frac{4\dot{m}}{\pi \mu D_2} \tag{30}$$

It is evident, for a given meter, R can be increased through an increase in the mass rate of flow and by a reduction in the viscosity of the flowing liquid.

5. Measurements Required

5.1. Temperature

Measurement of the temperature of flowing liquids is necessary for the accurate determinations of their densities and viscosities. For a typical hydrocarbon such as MIL-F-7024A Type II, an error of 1°F in the measurement of its temperature will result in an error of about 0.06 percent in density and 0.8 percent in viscosity.

The units of temperature commonly used are degrees Fahrenheit (°F), degrees Celsius (°C) and the corresponding absolute temperatures degrees Rankine (°R) and Kelvin (K). In liquid flow problems, absolute temperatures are seldom required, however, they are included for information and completeness. In engineering work in liquid flow problems, the Fahrenheit temperature scale is the one most frequently used. However, a working knowledge of converting from one scale to the other is required because properties of the various liquids found in the literature are frequently referred to the Celsius scale of temperature.

The relative sizes of the degree Fahrenheit or Celsius is a result of the defined fixed points on the temperature scales. The temperature of equilibrium between ice and air-saturated water is (32°F) (0°C) and the temperature of equilibrium between liquid water and its vapor (steam point) is (212°F) (100°C). Both fixed points are at a pressure of one standard atmosphere (14.6959 lbf/in^2), (101325 N/m^2).

Thus

Temperature °F = 9/5 Temperature °C + 32 (31)
Temperature °C = 5/9 (Temperature °F − 32) (32)
Temperature °R = Temperature °F + 459.67 (33)
Temperature K = Temperature °C + 273.15 (34)

5.1.1. Illustrative examples:

1) A thermometer reads 72.5°F. What is the absolute temperature in °R?

   T = °F + 459.67 = 72.5 + 459.67 = 532.17 °R.

2) A thermometer reads −72.5°F. What is the absolute temperature in °R?

   T = °F + 459.67 = −72.5 + 459.67 = 387.17 °R.

3) A thermometer reads 35°C. What is the temperature in °F and absolute temperature in °R?

   T = 9/5 (35) + 32 = 95 °F.
   T = 95 + 459.67 = 554.67 °R.

5.1.2. Temperature Measurements

Usually the temperature of liquids is measured with immersion sensors such as thermometers, thermocouples and thermistors. In general, the accurate measurement of temperature of liquids with calibrated sensors of these types is not difficult providing a few precautions are taken. Any of these sensors, when immersed in a fluid, attain a state of thermal equilibrium with the fluid but do not necessarily arrive at the same temperature as the fluid. At equilibrium the transfer of thermal energy between the sensor and surrounding fluid by convection is equal to the transfer of thermal energy between the sensor stem and its surroundings by conduction and radiation. The difference between the temperatures of the sensor and liquid is reduced by increased convective transfer between sensor and liquid and reduced thermal transfer through the sensor stem. Both of these are attained through intimate thermal contact between sensor and liquid and through increased depth of immersion of the sensor. In meters equipped with thermometer wells the thermometer should not be placed in a dry well. To improve thermal contact the well should be filled with liquid.

When measuring the temperature of liquid with a thermometer as when hydrometer observations are being made, throughly stir the liquid to eliminate thermal gradients and wait several minutes before making observations to ensure thermal equilibrium between liquid, hydrometer and thermometer.

5.2. Pressure Measurements

The unit of pressure to be used in the calculations of this work is pounds force per square foot (lbf/ft^2). Pressure gages are usually calibrated in lbf/in^2; however, lbf/ft^2 is determined by multiplying lbf/in^2 by 144 in^2/ft^2. It will be necessary to designate whether the value of pressure is

a) Pressure difference between two points in a flow system, (Δp) in psid (pounds per square inch differential);
b) A pressure relative to the existing atmospheric pressure, using negative values to indicate pressures below atmosphere, (p) in psig (pounds per square inch gage);
c) Absolute pressure, (P) in psia (pounds per square inch absolute) where $P = p +$ barometric pressure.

In the direct measurement of pressure difference Δp, it is necessary that both sides of the pressure sensing element be connected to pressure taps in the flow system. The difference in pressures at these two taps will be derived from the indication of the sensor. Instruments used for the measurement of pressure difference include manometers, differential pressure gages of the corrugated diaphragm capsule or Bourdon tube design, and differential pressure transducers of the pre-stressed diaphragm type.

Instruments used for the sensing of pressure p relative to atmospheric pressure must have one side of the pressure sensing element vented to atmosphere. Instruments used for this purpose include manometers, Bourdon tube gages, and aneroid capsule-type gages.

For the direct measurement of absolute pressure P, it is necessary that one side of the pressure sensing element be exposed to zero absolute pressure. Barometers are one form of such instruments. However, the absolute pressure of a point in the flow system usually is not measured directly. Rather, gage pressure and barometric pressure are measured separately and the absolute pressure is the sum of gage and barometric pressures.

In nearly all work in metering liquids and in calibrating liquid flowmeters the measurement of Δp usually will be the only pressure measurement of interest. Gage and absolute pressures will be needed only when these pressures are sufficiently great to alter the properties of the flowing liquid, or when two-phase flow is possible at low pressure.

It was shown in Fig. 4 and Equations 27 and 28 in Chapter 4 that both the volumetric and mass rates of flow through a calibrated meter (orifice, nozzle and venturi types) can be determined from the measurements of p_1 and p_2 or Δp. Conversely, in the calibration of such meters either the mass or volumetric rate of flow and Δp must be measured in order to determine C, the coefficient of discharge.

Gage pressures p_1 and p_2 can be measured separately and the difference obtained through subtraction; however, generally it is more accurate and convenient to directly measure the pressure difference with a differential gage such as a manometer.

5.2.1. Manometers

Manometers contain a liquid such as water or mercury in which the difference in liquid levels increases with increased pressure difference. The positions of the liquid levels are indicated by a scale, calibrated in units of length, placed beside the manometer column(s). Thus, this device senses pressure directly, but its indication, the difference in liquid levels, is only proportional to pressure. The manometer like the pressure gage will measure pressure difference, gage pressure, or absolute pressure depending upon its design.

If the pressure gages shown in Fig. 4 are replaced with vertical tubes, the liquid will rise in the tubes to heights $h_1 = p_1/w$ and $h_2 = p_2/w$ shown in Fig. 7a where w is the specific weight of the liquid in lbf/ft^3, p is the pressure in lbf/ft^2 and h is the column height in feet, thus

$$\Delta p = w\Delta h$$

and if the density of the liquid is known, as is usually the case,

$$\Delta p = \Delta h \rho g_\ell / g_c$$

This is a very important relation; unfortunately, it also is one that is frequently neglected. To reiterate, conversion of a measured column of liquid to pressure or differential pressure requires both the density of the liquid and the local acceleration of gravity.

Obviously at high pressures these columns will be too long to measure conveniently. Two forms of manometers that circumvent this difficulty are shown in Figures 7b and 7c. Fig. 7b shows a U-tube as used in practice as a differential gage with heavy liquid such as mercury in the bend of the U-tube, as compared to the light liquid flowing through the Venturi meter. Fig. 7c shows an inverted U-tube used as a differential gage, with a light liquid (non-miscible) or a gas (air) in the bend of the U and the heavier liquid flowing through the Venturi meter. It can be shown that in figure 7b

$$\Delta p = \Delta h_m(\rho_m - \rho_1)\ g_\ell/g_c \qquad (35)$$

where Δh_m is the differential height of the manometric liquid, ρ_m and ρ_1 are the densities of the manometric and flowing liquid respectively, and in figure 7c

$$\Delta p = \Delta h_m\ (\rho_1 - \rho_a)\ g_\ell/g_c \qquad (36)$$

where ρ_a is the density of the lighter liquid or gas above the manometric liquid which is the same as that flowing through the meter. In this case with gas in the upper portion of the inverted U-tube, the absolute pressure and temperature of the gas will be required to determine its density.

Errors will be introduced in the pressure measurements if any air or vapor is trapped in any part of the pressure connecting lines between the pressure holes in the meter and the manometer or differential pressure gage. These lines including manometer or pressure gage must be completely filled with the flowing liquid. In the case of meters installed in a horizontal line the pressure holes or taps should be in the horizontal plane of the center line of the pipe, or any other convenient position in the lower half of the pipe.

Recommended arrangements for piping between the meters and pressure sensing elements are shown in Fig. 8. The piping should include air or vapor vents, a by-pass or equalizer valve and the piping should be sloped as shown to facilitate purging the lines of air or vapor and to minimize the possibility of trapping same.

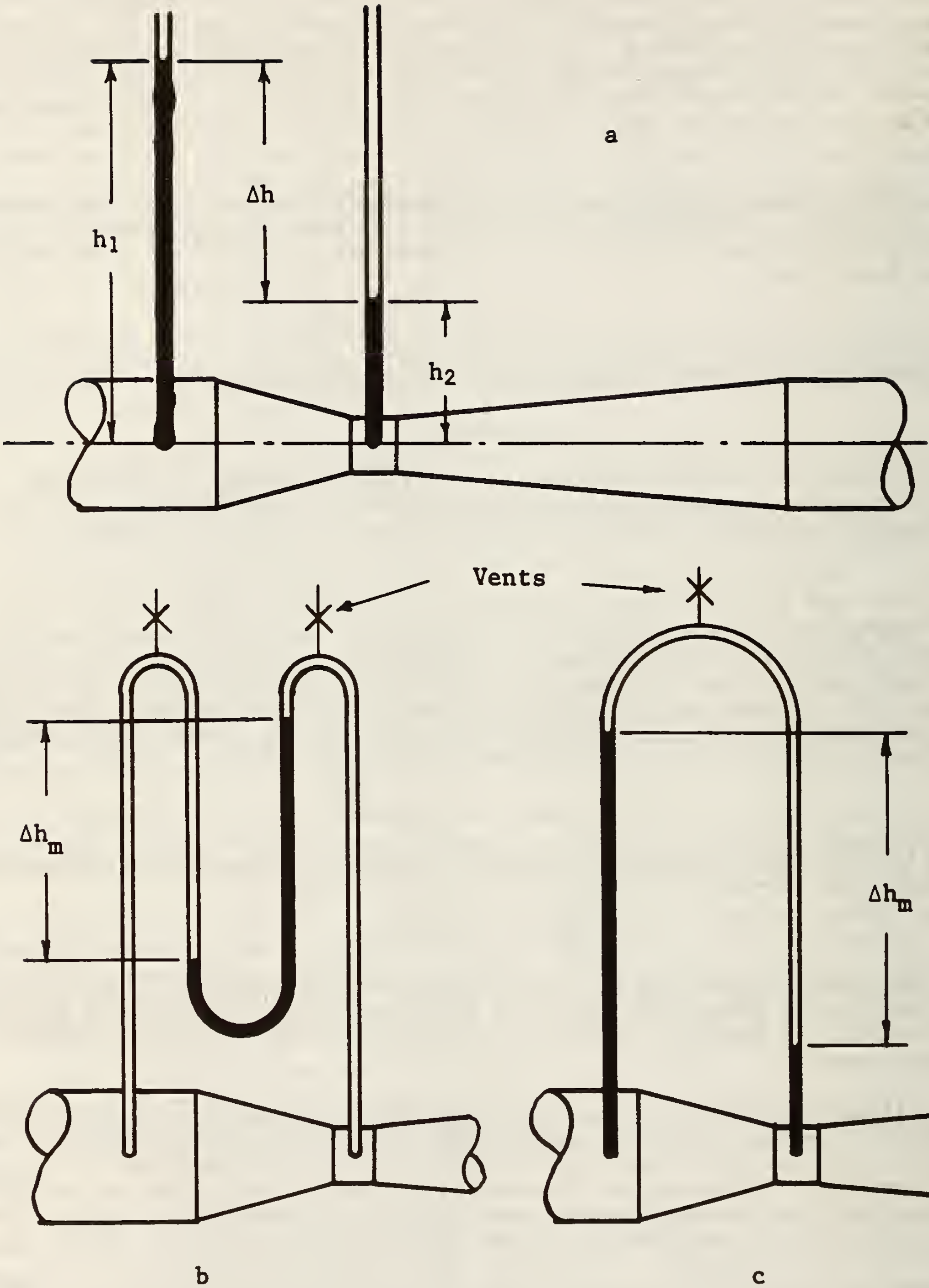
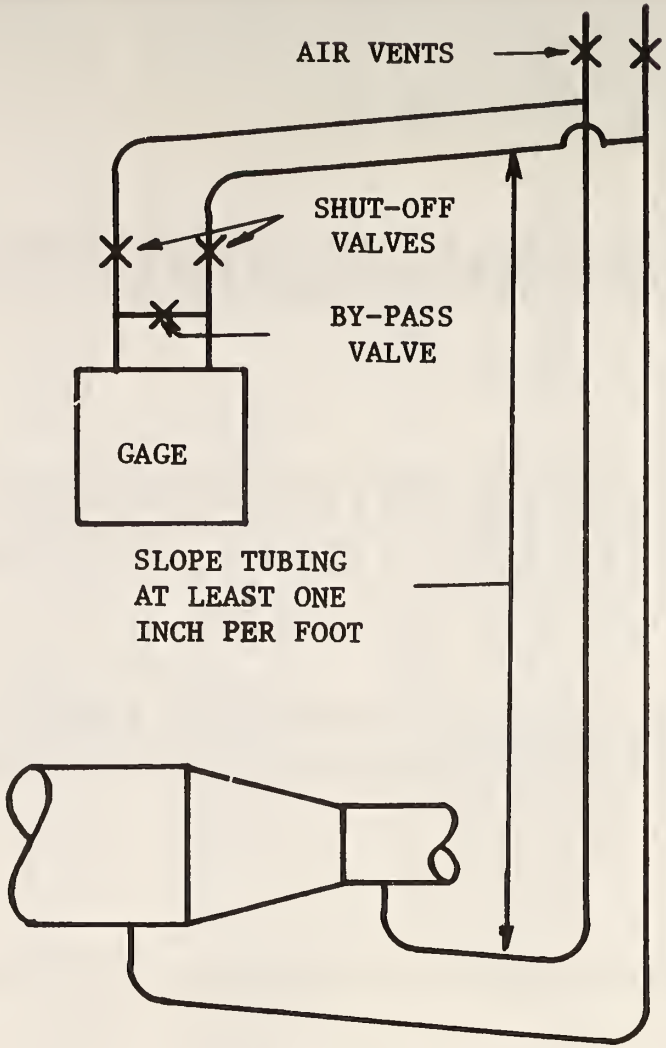
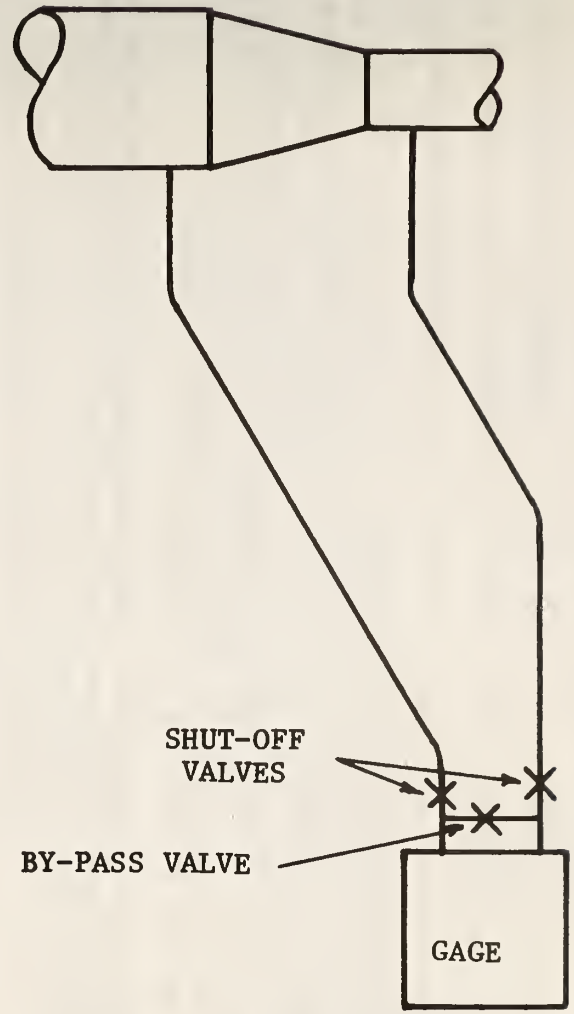


Fig. 7 Manometers.



a GAGE ABOVE METER



b GAGE BELOW METER

5.2.2. Corrections and Use of Conversion Factors for Manometers

In converting an indicated level difference or height Δh_m of a manometer column to pressure in lbf/ft^2, it is necessary to consider the following:

a) The units of length in which the height Δh is expressed (inches, centimeters, etc.).
b) The manometer liquid (water, mercury, hydrocarbon, etc.) and the flowing liquid (water, hydrocarbon).
c) The density of the manometer liquid(s) and the density of the gas above the liquid as in Fig. 7c.
d) The local acceleration of gravity g_ℓ.

The pressure differential Δp in lbf/ft^2 can be determined from Eq. 35 as follows:

When the scale of the manometer is calibrated in units of length other than feet, i is necessary to convert to the equivalent of length in feet with appropriate conversion factors. When the scale is graduated in centimeters divide the observed Δh by 30.48 to obtain Δh_m in feet; when graduated in inches divide the observed Δh by 12.

Densities required in Eq. 35 of three common manometric fluids-water, mercury and air are shown in Table 8. The density of hydrocarbons can be determined as discussed in Chapter 3.

Table 8. Densities of Water, Mercury and Air

Temperature °F	Water lbm/ft^3	Mercury lbm/ft^3	Air at 14.696 psia lbm/ft^3
32	62.418	848.719	.08073
34	62.422	848.547	.08040
36	62.425	848.375	.08008
38	62.426	848.203	.07976
40	62.426	848.031	.07944
42	62.425	847.860	.07912
44	62.423	847.690	.07880
46	62.420	847.520	.07849
48	62.415	847.349	.07818
50	62.410	847.178	.07788
52	62.403	847.008	.07757
54	62.395	846.837	.07727
56	62.387	846.666	.07697
58	62.377	846.494	.07667
60	62.367	846.324	.07638
62	62.355	846.154	.07609
64	62.343	845.984	.07579
66	62.330	845.814	.07551
68	62.316	845.644	.07522
70	62.302	845.473	.07494
72	62.286	845.303	.07465
74	62.270	845.133	.07437
76	62.253	844.964	.07410
78	62.235	844.794	.07382
80	62.217	844.623	.07355
82	62.198	844.452	.07328
84	62.178	844.282	.07301
86	62.157	844.112	.07274
88	62.136	843.942	.07247
90	62.114	843.772	.07221
92	62.091	843.603	.07195

Temperature °F	Water lbm/ft³	Mercury lbm/ft³	Air at 14.696 psia lbm/ft³
94	62.068	843.434	.07169
96	62.044	843.265	.07143
98	62.020	843.095	.07117
100	61.995	842.926	.07092

5.2.3. Illustrative examples:

1. Consider first a manometer of the type shown in Fig. 7b in which the manometric liquid is mercury and the lighter liquid flowing through the meter and filling the manometer above the mercury is water. Let the temperature of the manometer liquids be 72°F, the differential mercury column 52.8 cm of mercury and the local acceleration of gravity 32.120 ft/s^2. Δp in lbf/ft^2 is determined by solving Eq. 35 with the densities obtained from Table 8 as follows

$$\Delta p = \frac{52.8}{30.48}\,(845.303-62.286)\,\frac{32.120}{32.174} = 1354.13 \text{ lbf/ft}^2$$

2. A water manometer of the type shown in Fig. 7c is used to measure the differential pressure between the two stations in a water meter. Temperature of the water in the manometer is 72°F. The differential height is 36.30 inches of water, the pressure of the compressed air above the water columns is 151.690 psig and g_ℓ is again 32.120 ft/s^2. Find Δp in lbf/ft^2.

Everything is known for the solution of Eq. 36 except the density of the air (ρ_a) above the water columns. It can be determined from the density at 14.696 psia as given in Table 8 and the principle that the density of ideal gases is directly proportional to the absolute pressure.

Thus,
$$\rho_a = \rho_s \frac{P_a}{P_s}$$

where P_a is the absolute pressure above the water columns and ρ_s is the density of air as listed in Table 8 at the absolute pressure P_s of 14.696 lb/in^2;

$$\rho_a = .07465 \times \frac{151.690 + 14.696}{14.696} = 0.84518 \text{ lbm/ft}^3$$

and
$$\Delta p = \frac{36.30}{12}\,(62.286 - .845)\,\frac{32.120}{32.174} = 185.55 \text{ lbf/ft}^2$$

5.2.4. Mechanical Pressure Gages

When a mechanical pressure gage of the Bourdon tube or corrugated capsule type is used to measure either pressure or pressure differential in a liquid flow system, no correction is necessary for the local acceleration of gravity provided the gage was calibrated in force units. If the gage is calibrated with a dead-weight gage at a location having other than a standard acceleration of gravity (32.174 ft/s^2), allowance must be made for the local value of the weights of the calibration masses.

In the measurement of pressure at a pressure tap with a mechanical pressure gage, the indicated pressure must be increased or decreased by a pressure equivalent to the hydrostatic head of the vertical distance of the gage above or below the pressure tap. This correction is

$$p = h\rho\; g_\ell / g_c$$

However, this correction is valid only if the pressure tubing between the tap and gage is filled completely; if not, the proper correction cannot be determined.

In the measurement of differential pressure with a mechanical gage no such correction is to be applied. The connecting tubes should be installed as in Fig. 8 and must be completely filled with liquid.

5.3. Volume Measurements

Obviously an initial determination of the volume of volumetric calibrators or provers is necessary. Subsequent measurements of the volume are required in the event of damage or suspected damage to the prover. Finally, good calibration practice requires routine repeat measurements of this volume at fixed time intervals. Two general methods for the calibration of volumetric provers are used. These are: 1. calibration by means of test measures, and 2. calibration by means of master meters. The first is the preferred method in which the volume of the liquid is withdrawn from the prover into certified test measures or the prover is filled with liquid from the test measures. The procedures for calibrating volumetric provers is treated in detail in [7].

Test measures used for calibrating volumetric provers are ordinarily of 1, 5, 10, 50 and 100 gallon capacity. These measures can be calibrated either "to contain" or "to deliver." Measures certified "to contain" will contain the volume specified, regardless of the type of liquid used. Measures certified "to deliver" will deliver accurately only when water is used and must be wetted and drained before each use. The drainage time for measures 10-gal and smaller is 10 seconds from the time flow ceases and dripping begins, and 30 seconds for measures exceeding 10 gallons.

The volume of the standpipe calibrator is determined from the volume of the test measures required to fill the volume between the two level sensors. The volume of the ballistic calibrator is measured by the volume of liquid discharged into test measures by the passage of the piston or spheroid between the two position sensors.

In these calibrations it is necessary to accurately determine the volume of a partially filled test measure. This may be done with glass graduates or gravimetrically.

Temperatures of the liquid in the test measures and in the prover must be measured to enable volume corrections due to changes in density of the liquid.

Detailed instructions for these volume determinations are beyond the scope of this manual. When these measurements are required the instructions in [7] should be followed.

5.4. Time Measurements

Electronic-counter timers are preferred for measuring the time interval of either gravimetric or volumetric collection of the liquid. Many makes are available which operate on the principle of counting the pulses from a quartz-crystal oscillator. They usually indicate in units of 0.001 second and have provision for electronic actuation. They are considered to be preferable to synchronous clocks and stop watches actuated mechanically. Standards of time and frequency are broadcast by the National Bureau of Standards over station WWV near Fort Collins, Colorado. These signals, accurate to a few parts in 10^{13}, are convenient references for the calibration of timers.

5.5. Mass Measurements

Gravimetric-type calibrators use a number of different types of scales. For the smaller capacities equal-arm balances and straight lever systems are used. Because of their inherent stabilities torsion-tape and flexure-plate balances are also used. In general, free-swinging lever scales of conventional design are preferred; however, quick-weighing and automatic indication devices are sometimes employed. Before using the scale for calibration purposes a test extending over the load range at which it will be used should be conducted. For large weighing scales this calibration should be done with test weights that meet class F tolerances and not by the comparison of one scale with another.

Test weights may be secured from state or city Weights and Measures Departments. For the smaller weighing scales and balances and for substitution weighing procedures, the more accurate laboratory weights such as class P or Q are preferred.

Before applying the test weights make sure the scale is free from binding of any of its knife edges and calibrator connections. Following the calibration make a sensitivity measurement at full load of the scale. Any reduction in sensitivity in future measurements is probably caused by binding or damaged knife edges.

Weighings are usually made in air; consequently, a correction for air buoyancy must be made to determine the mass of the material being weighed. In the case of water such corrections have been made and the apparent density of water weighed in air is available in tables such as Table 3. When the specific gravity of a hydrocarbon is known the apparent density of the liquid can be determined from Table 26 [2] or as described in 3.2.3.

6. Methods of Calibration

6.1. Introduction

Liquid flow measurements having the best accuracy are usually made in apparatus that collects and measures the total flow delivered during a finite interval of time. The quantity of the collected liquid is measured either gravimetrically or volumetrically and the liquid density is usually required in either case. In the gravimetric system, measurements of the collected mass and time of collection yields mass rate of flow and a density determination permits conversion to a volume rate of flow. In a volumetric apparatus, measurement of collected volume and time of collection yields the volume rate of flow directly. In this case a measurement of the density of the flowing liquid is required to convert to a mass rate of flow.

Uncertainties in the measurements of mass, volume, time and density can be estimated; however, the uncertainty in the flowrate is usually greater than the combined uncertainties in the parameters listed above. One source of uncertainty common to all methods of metering liquids is introduced by the inability to set flowrate absolutely steady and to meter without error. As some meters have measurement precision equal to or better than the calibration precision, it becomes impossible to separate the imprecision in the meter indication from that of the calibration flow standard. Another source of imprecision in the indicated flowrate of the meter is the influence of the character of the upstream flow. Variations in Reynolds number, velocity profile and degree of swirl are usually responsible for decreased precision in the measurement of flowrate.

6.2. Gravimetric Calibration Systems

In a gravimetric calibrating apparatus, calibration of a liquid flowmeter involves the determination of the time interval required for the measured mass of liquid to pass through the meter, at a constant indicated rate, under the specified conditions of calibration. Since extreme accuracies are possible in the measurement of mass and time, the limiting factors in the procedure are the technique, sensitivity of the meter, constancy of the indicated flowrate, method of collecting the liquid and the method of timer actuation.

There are two distinct types of gravimetric calibrators, these are "static" weighing calibrators and "dynamic" weighing calibrators.

6.2.1. Static Weighing Calibrators

Gravimetric calibrations of liquid flowmeters of the best accuracies are made in apparatus in which the collected liquid is weighed under "static" conditions of no flow into the collection tank. Such an apparatus is shown schematically in Fig. 9.

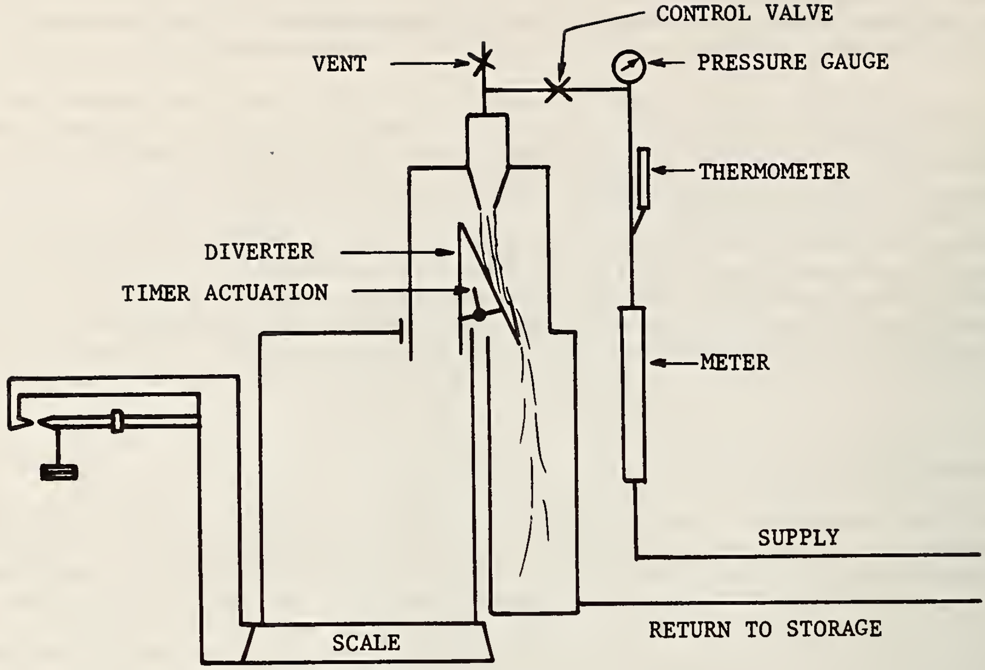


Fig. 9 Static weighing calibrator.

The primary function of the flow supply and control system is to deliver filtered liquid of known physical properties at a constant controlled and measured temperature to the meter under test. It should also serve to eliminate surges and pulsations and to provide a sensitive method of control over the entire range of flowrates. This system must also prevent any gas or vapor from entering the meter. Special care should be taken to prevent the formation of vapor during the throttling action of the flow control valve, and whenever possible this valve should be located downstream from the meter. The piping between the meter and nozzle of the diverter should be sized as small as possible to minimize the possibility of storage of gas and/or vapor during the collection period of a flowrate measurement. During this period the flowrate discharging from the nozzle must be equal to that through the meter.

The diverter directs the flow either to storage or to the weigh tank without disturbing the flow through the meter. The diverter should actuate the timer in both directions when the splitter bisects the nozzle. It should pass through the liquid stream as rapidly as possible (30 milliseconds or less) to minimize possible diverter error. This can be accomplished by rapid diverter travel through a thin liquid sheet formed by the nozzle slot. Generally, this liquid sheet has a length 25 to 50 times its thickness.

Calibration of a meter at a selected rate of flow is performed by a tare weight measurement with the diverter in the "return to storage" position. The diverter is then actuated to direct the liquid into the weigh tank and to simultaneously start the timer. When an appropriate quantity of liquid is collected, the diverter is returned to its original position automatically stopping the timer. The gross weight is then recorded along with the indicated time interval.

6.2.2. Dynamic Weighing Calibrators

The static weighing method requiring tare and gross weight measurements is time consuming and thus not well-suited for applications where convenience and speed of operation is important. For these applications "dynamic" weighing is frequently utilized. In this method the time interval required to collect a preselected weight of liquid is measured; the weighing is performed while the liquid is entering the tank. Experience has demonstrated that accuracies as good as in the "static" calibrators can be achieved; however, additional dynamic factors must be considered.

A typical dynamic weighing calibrator is shown schematically in Fig. 10.

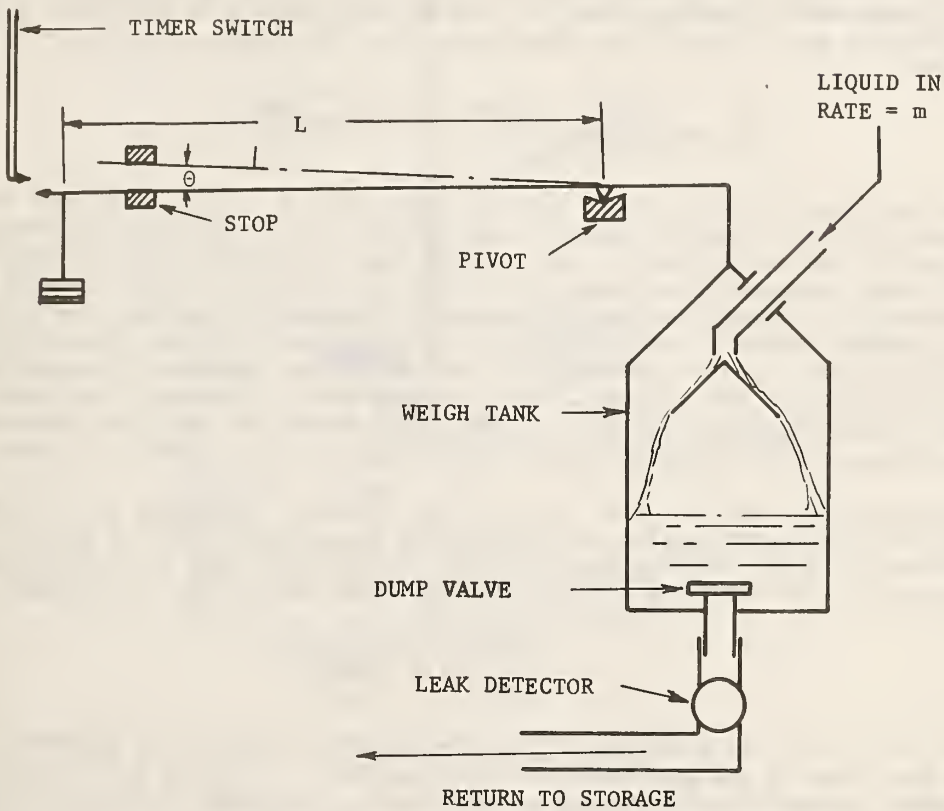


Fig. 10 Dynamic weighing calibrator.

In this apparatus, the weight of the liquid in the tank increases until it overcomes the resistance of the counterpoise weights on the end of the weigh beam which then rises and actuates the timer. At this time an additional counterpoise weight is added to the pan thereby depressing the weigh beam. When it rises again the timer is stopped.

During the weigh cycle, three dynamic phenomena take place and their effects must be considered. One, there is a change in the impact force of the falling liquid between the initial and final weigh points as a result of the reduced distance between the point of discharge and the liquid level in the tank. Two, there is a collection of a greater mass of liquid than predicted by mt. The additional amount is equal to the mass contained in the falling column between the liquid levels in the tank at the initial and final weigh points. Three, the change in inertia of the scale and weigh tank with the resultant change in the time required to accelerate the weigh beam past the timer trip point. It can be shown that the decrease in impact force is equal and opposite to the additional weight collected from the falling column. Thus, even though these effects can be appreciable they completely cancel each other.

The effect of change of inertia between the initial and final weigh points can become appreciable when the mass of collected liquid is a significant part of the total mass of the weigh system and/or a large travel of the weigh beam to the point of timer actuation is required. The error caused by this effect is shown in the difference Δt between the time t_2 required for the deflection of the weigh beam at the final mass M_2 and the time t_1 for the tare mass M_1. This error has been shown to be approximately

$$\Delta t = t_2 - t_1 \simeq \left(\frac{6L\theta}{g_\ell}\right)^{1/3} \left(\frac{M_2^{1/3} - M_1^{1/3}}{m^{1/3}}\right) \tag{37}$$

where L is the length of the weigh beam as shown in Fig. 10, θ is the angular displacement of the weigh beam in radians from the bottom rest position to the timer trip position, and m is the mass rate of flow discharging into the weigh tank. In terms of percentage error

$$\left(\frac{\Delta t}{t_c}\right) 100 \simeq 100 \left(\frac{6L\theta}{g_\ell}\right)^{1/3} m^{2/3} \left(\frac{M_2^{1/3} - M_1^{1/3}}{M_2 - M_1}\right) \tag{38}$$

where t_c is the time for the collection of the mass $(M_2 - M_1)$. It is obvious from the relation above that for a given scale the percentage error in flowrate determinations is a function of beam deflection θ, mass rate of flow m and gross and tare masses M_2 and M_1 of the liquid, tank and other masses supported by the scale. In an existing dynamic weighing apparatus, in which the maximum possible flowrate is required, the only practical means to reduce dynamic error is through the reduction of Θ which should be made as small as practicable. Shafer and Ruegg [8] have shown good agreement between the inertia error determined from Eq. 38 and the error as determined by comparing the dynamic calibrator with a static calibrator. Such an evaluation should be made when possible; certainly some attempt at evaluation is necessary whenever Eq. 38 predicts a large error.

The quantity $(M_2 - M_1)$ for both "static" and "dynamic" weighings is an apparent mass, i.e., it is the mass determination uncorrected for the buoyant force of the air displaced by the collected liquid. To determine the mass rate of flow this correction along with a possible correction for error in the time of collection can be made as follows:

$$m = \left(\frac{M_2 - M_1}{t_c \pm \Delta t}\right) \left(\frac{1 - \rho_a/\rho_p}{1 - \rho_a/\rho}\right) \tag{39}$$

where ρ, ρ_a and ρ_p are the densities of the liquid, of air and of the weights. The quantity Δt is the error in the measured time of collection. It may be $\pm\,\Delta t$ in the case of static weighing and must be determined by experiment. In dynamic weighing it is $-\Delta t$ as shown in Eq. 38. The volume rate of flow can be determined from

$$q = m/\rho \tag{40}$$

Where the apparent density of the liquid is known as in Table 3 for water and Table 26 [3] for hydrocarbons, the volume rate of flow can be determined directly from

$$q = (M_2 - M_1)/\rho(t_c \pm \Delta t) \tag{41}$$

Another dynamic calibrator, shown in Fig. 11, collects the liquid in a tube of known cross-sectional area and uses the pressure existing on the bottom as a measure of the mass of liquid collected. The vertical rise in liquid between the initial or tare and the final weigh positions is usually in the range of 2 to 20 feet. Thus it is necessary to measure this pressure difference to an accuracy of better than 0.1 percent. The apparatus illustrated uses a mercury manometer as the pressure measuring device; electrodes spaced to correspond to different collected weights provide the impulse for the actuation of the timer.

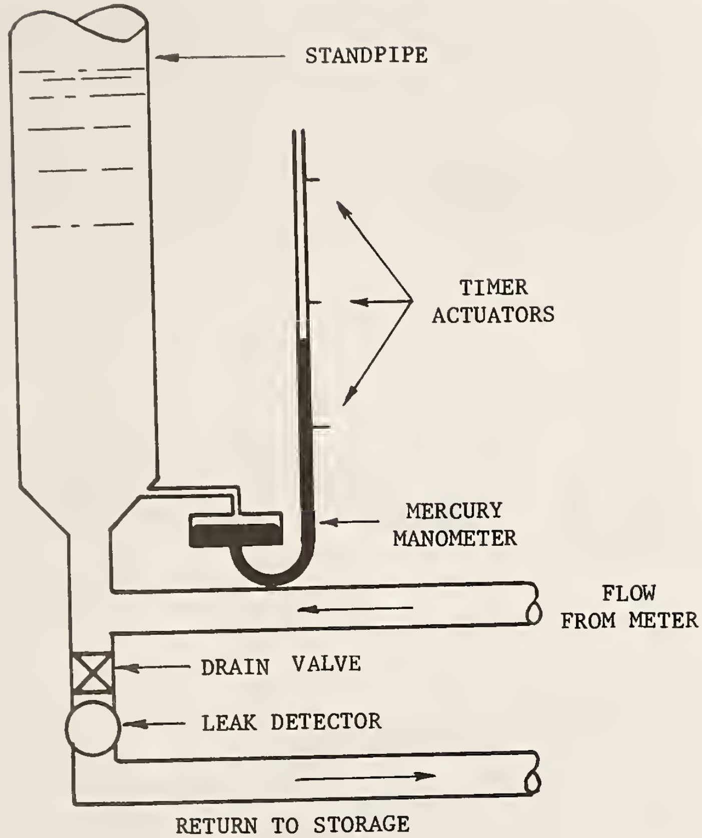


Fig. 11 Dynamic weighing calibrator.

For accurate calibrations using this type of apparatus several factors must be considered:

1. The thermal expansion of the standpipe cross-sectional area.
2. The density of the manometer liquid.
3. Complete drainage of the cylinder walls before starting the weigh time determination; particularly important with high-viscosity liquids.
4. Air pressure within the cylinder or manometer column must not change during the timing interval.
5. Air or vapor in the connecting line between cylinder and manometer must be eliminated.
6. Dynamic considerations require that the pressure measuring device has completed its acceleration and attained a constant velocity prior to starting the timing interval.

6.3. Volumetric Calibration Systems

There are a great variety of volumetric calibration systems; however, all of them employ either the standpipe or ballistic methods. Although the many calibrators utilizing the standpipe method vary in details, the essential features of all of them are included in the schematic diagram of Fig. 12.

These systems consist essentially of a supply tank, flowmeter test section, flow control system, calibrated receiver (standpipe) and instrumentation. Some are completely self-contained and include liquid storage, pumps, filters and heat exchangers for temperature control. The standpipe is equipped with liquid level sensors at levels bracketing accurately known volumes.

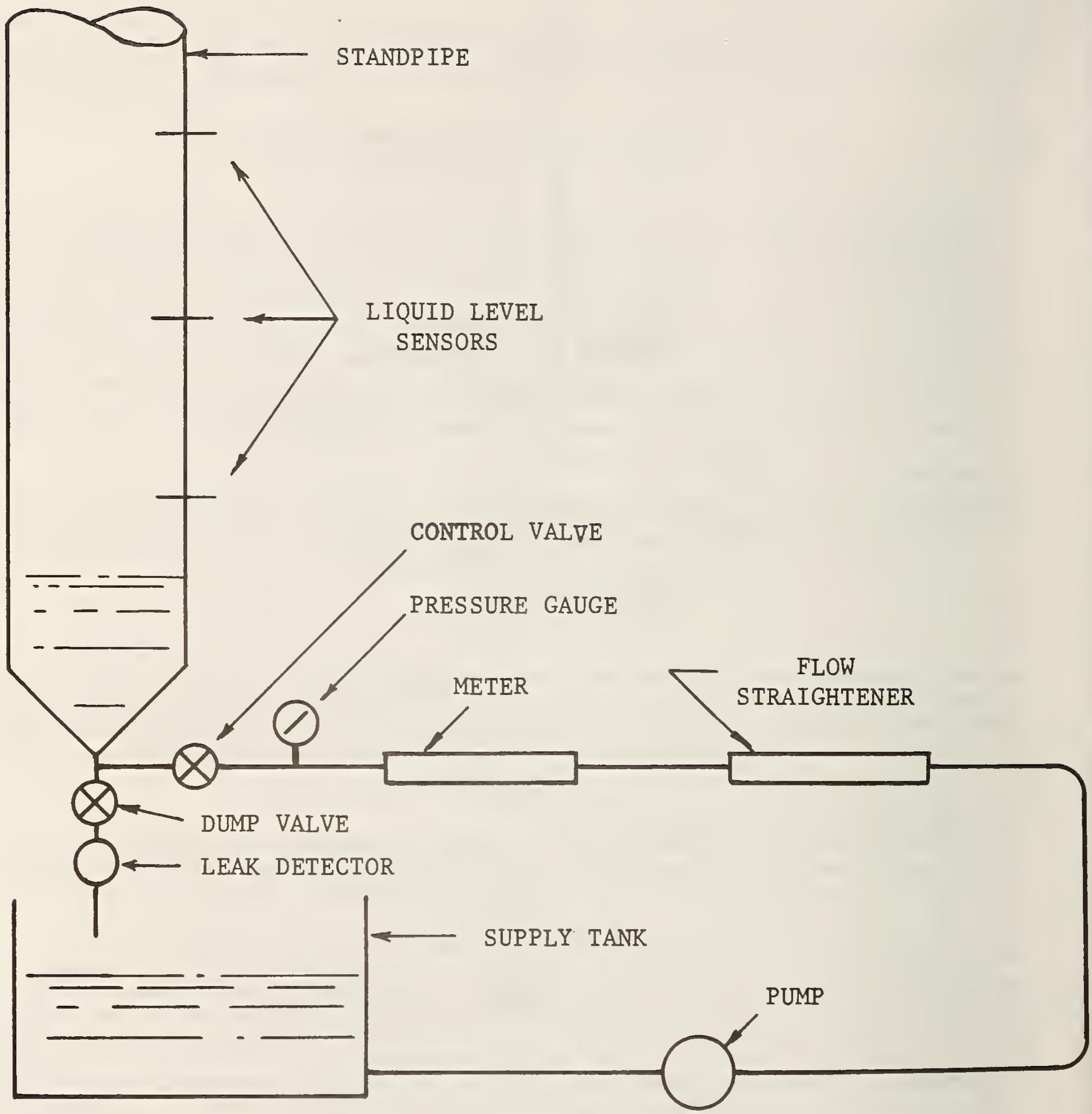


Fig. 12 Standpipe calibrator.

Calibrations with this system are made in the following manner. With the dump valve open and the standpipe drained, the pump is started and a flow through the meter is adjusted with the flow control valve. After a condition of equilibrium in flow and temperature has been established the dump valve is closed. The liquid rises in the standpipe, starts a timer at the first liquid level sensor and stops the timer at the upper sensor. During this timing interval the output of the flowmeter under calibration is observed and recorded. In the case of turbine-type flowmeters the liquid level sensors also gate the counter which is used to count the pulses during the calibration interval. Other required measurements are the temperature of the liquid both in the standpipe and flowing through the meter, a density determination of the liquid and a viscosity measurement.

The "ballistic" or "piston" calibrator is the other common form of volumetric calibrator. One variation of this form is shown in Fig. 13.

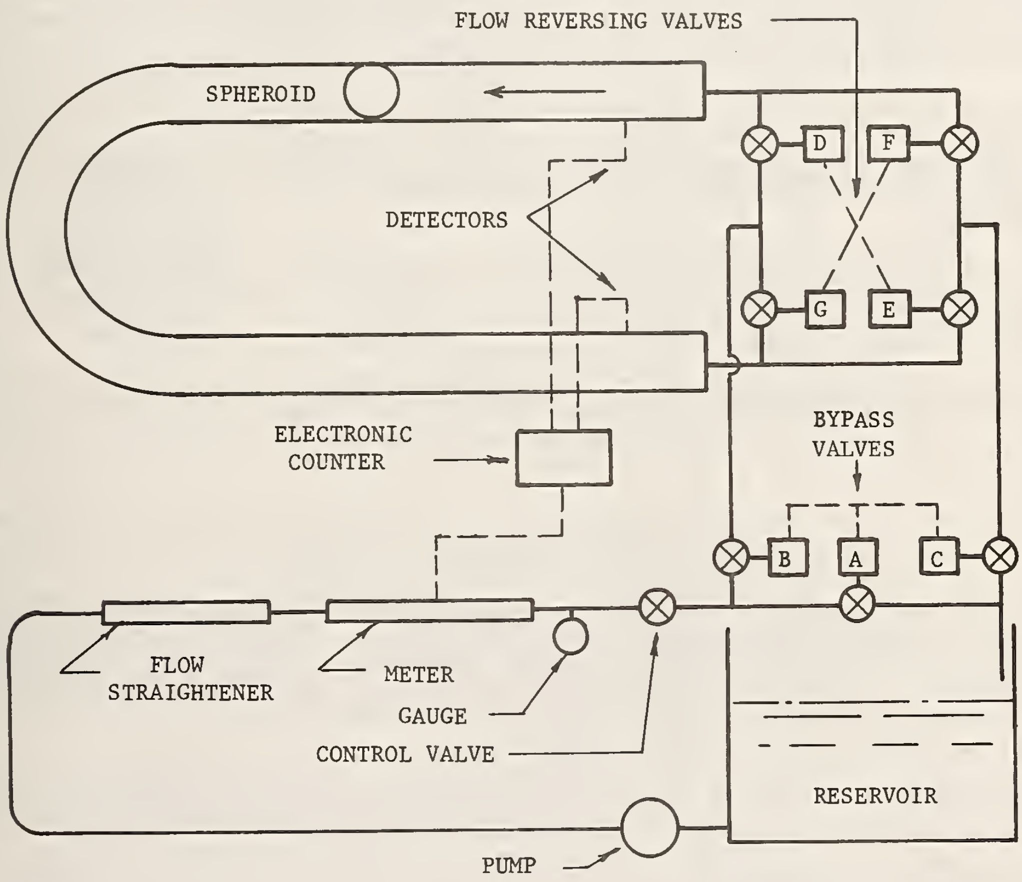


Fig. 13 Ballistic calibrator.

It consists of a liquid reservoir, pump, flowmeter test section, control valves and a calibrated prover section. The prover is either a straight tube or a U-tube of essentially constant inside diameter equipped with a piston or ball. Pistons are generally used in provers with straight tubes while liquid filled elastomer spheroids are used in the U-tubes. In either case there must be no leakage past the piston or ball. Detectors are located near the ends of the prover tube to detect the passage of the piston. The volume of the tube between the two detectors is accurately calibrated, usually with calibrated containers. The passage of the piston or ball across the detectors gates electronic timers and/or counters.

Calibrations of meters in this system are performed in the following manner. The entire system must be filled with liquid; all air and vapor must be eliminated from prover and all piping and valves. With the valves to the prover closed, the desired flow is established through the meter to the reservoir through the bypass valve A; at this time valves B and C are closed. After an equilibrium condition is attained and with valves D and E open with F and G closed, A is closed while simultaneously opening B and C. Thus, the flow is directed into the prover driving the ball, in the indicated direction, which actuates the timer or counter as it passes the two location detectors. A complete proving requires an additional travel in the opposite direction by reversing valves D, E, F and G.

This system is particularly suitable for calibration of meters with high vapor pressure liquids because it is a closed constant volume system. It also lends itself well to the calibration of turbine type flowmeters which because of their high speed of response can tolerate a somewhat nonuniform flow during the calibration interval. For meters having a lower response rate (variable area and head types) constant flow and meter output must be reached before triggering the first detector.

These calibrators must be monitored frequently to ensure against leakage past the piston or ball during the proving interval. Any such leakage will result in more flow through the prover than indicated. This monitoring can be done by recalibrating the prover volume. A more convenient method consists of frequent provings with a reference turbine meter.

In general the measurements required during calibrations include temperature, density and viscosity of the liquid flowing through the meter. The temperature of the prover is required to determine its volume.

In the case of calibrations of turbine flowmeters the total count of pulses between the two detectors is required. For volume rate of flow, density measurements will not be required unless there is a difference between the densities of the liquid in the flowmeter and prover.

A variation of the ballistic calibrator is a type in which the piston is driven by some means other than the flowing liquid. Some are driven with precision screw threads and a variable speed motor while others are driven by compressed gas. In either case the piston travel is tracked with some form of shaft encoder which generates a train of electrical pulses which can be counted on electronic counters. Thus, each pulse is equivalent to the passage of a discrete volume of liquid. Apparatus of this type is well-suited for the calibration of turbine-type flowmeters. Calibrations can be made quickly and conveniently with small volumes of liquid. Where calibrations are required with several liquids of diverse properties this is a decided advantage.

Calibrations of turbine meters with these calibrators can be performed in several ways. Generally, the counter recording the turbine flowmeter pulses is gated by two sensors actuated by the passage of the piston. The spacing of the sensors brackets an accurately known volume. Thus meter factor K is

$$K = \frac{\text{Total pulses}}{\text{Volume, gallons}} \tag{39}$$

One manufacturer uses the period (the time between two successive pulses) or multiple periods of the flowmeter to gate the pulse counter receiving the pulse train generated by the piston. Since each pulse represents a discrete volume of liquid, the total count will be proportional to the volume per pulse of the meter or the reciprocal of K.

6.4. Meter Installation

Variations in the piping layout of flowmeter installations can have a large effect on the accuracy of flow measurement. The rate of flow derived from the outputs of orifice, nozzle, Venturi and turbine flowmeters may be in error if the piping arrangements tend to produce distorted flow conditions. Helical swirls, vortices and skewed velocity distributions in the flow entering flowmeters have been found to degrade the accuracy of flow measurements. Upstream elbows, tees, valves, projecting gaskets, misalignment and projecting burrs on pressure taps can cause appreciable errors.

For best results the liquid should approach the flowmeter with a fully developed velocity profile (usually turbulent) and free of swirls or vortices. This condition can be achieved through the use of adequate lengths of straight pipe both upstream and downstream from the flowmeter. Eight diagrams depicting different piping installations are shown in [1] with the recommended straight lengths of pipe in terms of number of diameters, L/D. For most installations 20 diameters upstream and 5 diameters downstream are adequate to hold errors due to piping configurations to less than ± 0.5 percent. The upstream length can be reduced when straightening vanes are used. In this case 10 diameters between the straightener and meter is adequate. A typical straightener is shown in Fig. 14. A length of two diameters is required upstream of the straightener which normally has a length of 2D; thus, the overall length of the straightener section is 14D.

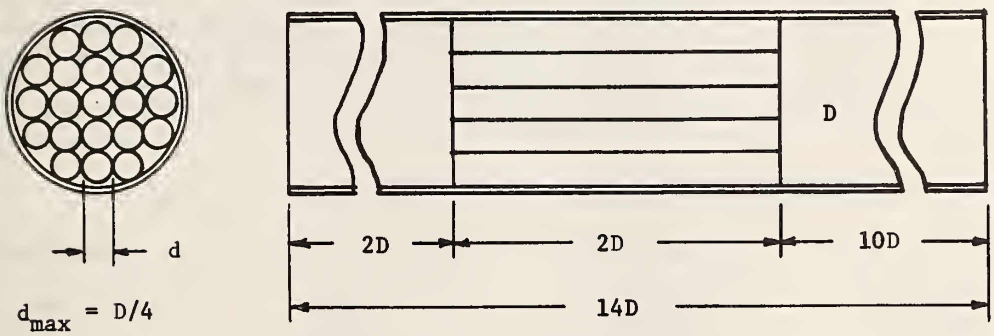


Fig. 14 Typical flow straightener.

Additional lengths of straight pipe either with or without straightening vanes should be provided whenever possible. The control valve should always be located downstream from the flowmeter. If an upstream shut-off valve is required it should be a full ported gate or ball valve so as not to disturb the flow when full open.

When a calibration is required for a flowmeter installed with straight lengths less than these minimums it should be calibrated with its own or duplicated piping including upstream and downstream elbows, tees, valves, etc.

Appendix C of [9] also states that 20 diameters of meter-bore piping upstream and 5 diameters downstream of the meter provides effective straightening in many installations. Shown also are five meter installations with the recommended lengths of straight pipe between the meter and upstream disturbance. The recommendations are summarized in Table 9.

Table 9. Recommended Minimum Lengths of Straight Pipe

Upstream disturbance	Pipe length L/D
Concentric reducer	15
Sweeping elbow	20
Two sweeping elbows in the same plane	25
Two sweeping elbows in planes at right angles	40
Valve partially open	50

This table clearly shows the reason to avoid upstream valves and compound elbows.

6.5. Illustrative examples:

A. Calibration of a turbine-type flowmeter with a gravimetric dynamic calibrator.

Consider a turbine flowmeter Model ANC8-4 installed on a dynamic gravimetric calibrator. The meter is installed horizontally with the meter pickoff coil pointing upward. The meter assembly consists of an upstream 5-inch length of tubing. The pickoff coil was connected to a frequency meter and a totalizing counter gated by the dynamic weigh beam. The following measurements were made:

1. An observed specific gravity of a sample of the liquid at 70°F was 0.76505.
2. Temperature of the flowing liquid was 80°F.
3. Mass of liquid collected was 25 lbm.
4. Frequency of meter was 1400 hertz.
5. Total count of pulses during collection of 25 lbm was 113233. Find "K factor" (pulses per gallon).

a. From the observed specific gravity at 70°F the Specific Gravity 60/60°F is found to be 0.7693 from Table 23 page 239 [3]. Since the calibrator weighs in air, the weight in air of a hydrocarbon having a Specific Gravity 60/60°F of 0.7693 is found to be 6.4046 lb/gal from Table 26 page 494 [3]. To find the weight in air at 80°F multiply 6.4046 by the volume reduction factor of 0.9888 for 80°F found in Table 24 page 426 [3].

$$6.4046 \times .9888 = 6.3329 \text{ lb/gal}$$

b. Thus the number of gallons collected is

$$25/6.3329 = 3.9476 \text{ gallons}$$

c. And

$$K = \frac{113233 \text{ pulses}}{3.9476 \text{ gallons}} = 28684 \text{ pulses/gallon}$$

At the National Bureau of Standards the usual calibration of turbine flowmeters consists of experiments at five frequencies. The reported values are the arithmetic means of ten separate observations at each of these frequencies. They are taken in groups of five successive runs on each of two different days. Also a statement of accuracy is usually given, such as:

Reported Calibration Values

Pulses/Second	Pulses/Gallon
120	28801
350	28791
700	28703
950	28716
1400	28684

These reported values have an estimated overall uncertainty of ± 0.13 percent based on a standard error of 0.01 percent and an allowance of ± 0.1 percent for possible systematic error.

B. Calibration of two turbine flowmeters in series with a dynamic gravimetric calibrator.

Two turbine flowmeters can be calibrated simultaneously by counting the total pulses generated by each during discharge of a weighed quantity of liquid converted to gallons.

Consider two turbine flowmeters Model ANC 8-4, Serial numbers 1A and 1B. As received for calibration the assembly consisted of a 5-inch length of tubing containing straightening vanes, meter 1A, two 5-inch lengths of tubing with the second containing straightening vanes, meter 1B, and a 5-inch length of exit tubing. The assembly, mounted horizontally with the meter pickoff coils pointing upward, was connected to the calibrating bench with an additional 5-inch length of straight tubing downstream from straightening vanes. The fluid was the same as that used in Example A. The following measurements were made:

1. Temperature of the liquid flowing through the meters was 80°F.
2. Mass of liquid collected was 8 lbm.
3. Frequencies: Meter 1A 720 hertz, Meter 1B 700 hertz.
4. Total count: Meter 1A 37239, Meter 1B 36258.

The weight per gallon in air is the same as in Example A because the same liquid is used and metered at the same temperature; thus the liquid weighs 6.3329 lbs per gallon in air at 80°F. Since 8 lbm was collected the volume collected was 8/6.3329 = 1.2632 gallons.

Thus

for Meter 1A K = 37239/1.2632 = 29480
for Meter 1B K = 36258/1.2632 = 28703

Again the results for the arithmetic mean of ten separate observations are listed below:

Meter 1A		Meter 1B	
Pulses/Second	Pulses/Gallon	Pulses/Second	Pulses/Gallon
120	29539	120	28801
360	29477	350	28791
720	29480	700	28703
960	29467	950	28716
1440	29490	1400	28684

Once these flowmeters are calibrated either of the meters can be used as a transfer standard to calibrate other meters having approximately the same flow range. Before such a meter is used as a transfer standard the locations of the two flowmeters should be interchanged to determine the effect, if any, of the upstream flow pattern on its K factor. If the change due to reversal is less than 0.1 percent either of the meters can be used as a transfer standard. If the change is greater, additional straight tubing and/or straightening vanes should be inserted ahead of the upstream meter and between the two meters.

C. Calibration of a turbine flowmeter with a second calibrated turbine flowmeter.

Assume the downstream meter 1B in Example B is the calibrated meter and has a K factor of 28791 pulses/gallon at a frequency of 350 hertz. The pickoff coils are connected to frequency meters and preset counters. The liquid hydrocarbon is the same as in previous examples. The flow through the meters was adjusted so that the frequency of meter 1B was 350 hertz. The following measurements were made:

	Meter No. 1A	Meter No. 1B
Frequency, hertz	360	350
Total pulses, 100 seconds	35877	35042
K factor		28791

Find the K factor for meter 1A

$$K_{1A} = K_{1B} \frac{\text{Total pulses 1A}}{\text{Total pulses 1B}}$$

$$K_{1A} = 28791 \times \frac{35877}{35042} = 29477 \text{ pulses/gallon}$$

Since the calibration is in terms of volume and since the same liquid at the same temperature is flowing through both meters a determination of the density of the liquid is not required. However, if there is an appreciable change in temperature of the liquid between the two meters allowance for the change in density will be required.

In the last Example C let the temperature of the liquid flowing through Meter 1A be 80°F and 85°F through Meter 1B. Let the frequencies and total count for the two meters be the same as in Example C. We know the total count for 100 seconds and the K factor of Meter 1B from which we can find the volume flowing through 1B in 100 seconds as follows:

$$\frac{35042 \text{ total count}}{28791 \text{ pulses/gallon}} = 1.2171 \text{ gallons}$$

Since the liquid flowing through 1A is cooler and more dense the volume flowing through it in 100 seconds is found by use of Table 24 page 426 [3] where the factor for reducing volume is 0.9888 and 0.9860 at 80 and 85°F, respectively, for a liquid hydrocarbon having a specific gravity 60/60°F of 0.7693.

Thus the volume flowing through 1A is

$$1.2171 \times \frac{0.9860}{0.9888} = 1.2137 \text{ gallons}$$

and

$$K_{1A} = \frac{35877 \text{ total count}}{1.2137 \text{ gallons}} = 29560 \text{ pulses/gallon}$$

It should be noted that the tabulated frequencies are nominal and should not be used in the calculations.

7. Types of Flowmeters

7.1. Introduction

Practical commercial liquid flowmeters making use of a wide variety of physical principles are available. Differential pressure types such as orifice, nozzle, Venturi and laminar meters depend on the conversion of potential energy to kinetic energy of the liquid. Positive displacement meters such as quantity and turbine-type flowmeters are driven by the liquid. In the electromagnetic flowmeter the basic principle is similar to that of an electric generator. The ultrasonic flowmeter depends upon the speed of sound in the liquid. Thermal meters make use of change of enthalpy in the flowing liquid.

7.2. Differential Pressure Type Meters

There are perhaps more meters of the differential pressure type in present use than all other liquid flowmeters combined. The theory and equations common to orifice, nozzle and Venturi meters were discussed in Chapter 4.

7.2.1. Orifice Meters

Of the differential pressure type flowmeters, the orifice is the most widely used. The principle advantages of the orifice flowmeter are low cost, easy installation and replacement, and fairly well established coefficients of discharge.

On the debit side, the orifice has a high nonrecoverable head loss. Many different configurations of orifices such as the quadrant edge, double bevel, conical inlet, eccentric and segmental described in [1] are used; however, this discussion will be confined to thin plate concentric orifice flowmeters.

The orifice plate is usually made of Monel, stainless steel or other nonrusting steel alloy. The thickness of the plate for low temperature liquid flows should not exceed those shown in Table 10.

Table 10. Maximum Thickness for Thin Plate Orifices

Pipe Size, Inches	Orifice Thickness, Inches
Up to 3	3/32 ± 1/32
4 to 6	5/32 ± 1/32
7 to 8	1/4 ± 1/16
10 and over	3/8 ± 1/8

The orifice hole should be concentric with the pipe. The width of the cylindrical edge of the orifice hole should be between 0.01 and 0.02 times the diameter of the pipe. If the thickness of the plate exceeds this limit the orifice outlet edge should be beveled at an angle of 30 to 45 degrees from the pipe axis. The inlet edge of the orifice should be square and sharp, free from burrs or rounding. The orifice diameter should be measured in four meridian planes at 45 degrees. The diameter ratio β should not be less than 0.25 or more than 0.70.

A typical installation of a thin plate orifice with pressure connections is shown in Fig. 15. Pressure taps are located and defined as follows:

1. Flange Taps. The centers of the pressure holes are one inch upstream and one inch downstream from the upstream (inlet) and downstream (outlet) faces of the orifice plate.
2. Taps at D and D/2. The center of the upstream pressure tap is located one pipe diameter upstream of the inlet face of the orifice plate. The center of the downstream tap is one-half pipe diameter downstream from the inlet face of the orifice plate.
3. Vena Contracta Taps. The center of the upstream pressure tap is usually located one pipe diameter upstream from the upstream face of the orifice plate. The downstream tap is located at the place of minimum pressure. This location is shown in Figure 1-5-5 of [1].
4. Corner Taps. The pressure holes are located in the corners formed by the pipe walls and orifice plate. Corner taps are generally used for the smaller meter tubes where either the flange tap or D/2 tap would place the downstream tap in a varying pressure recovery region.

Flow through thin plate orifice flowmeters can be calculated with Equations 27 and 28 and the coefficient of discharge. It is always preferable to determine this coefficient through calibration when the orifice is installed in the pipe section in which it is to be used. When this is not possible the coefficients can be obtained from Tables II-III-2, II-III-3 and II-III-4 reference [1] for flange taps, taps at D and D/2 and vena contracta taps, respectively.

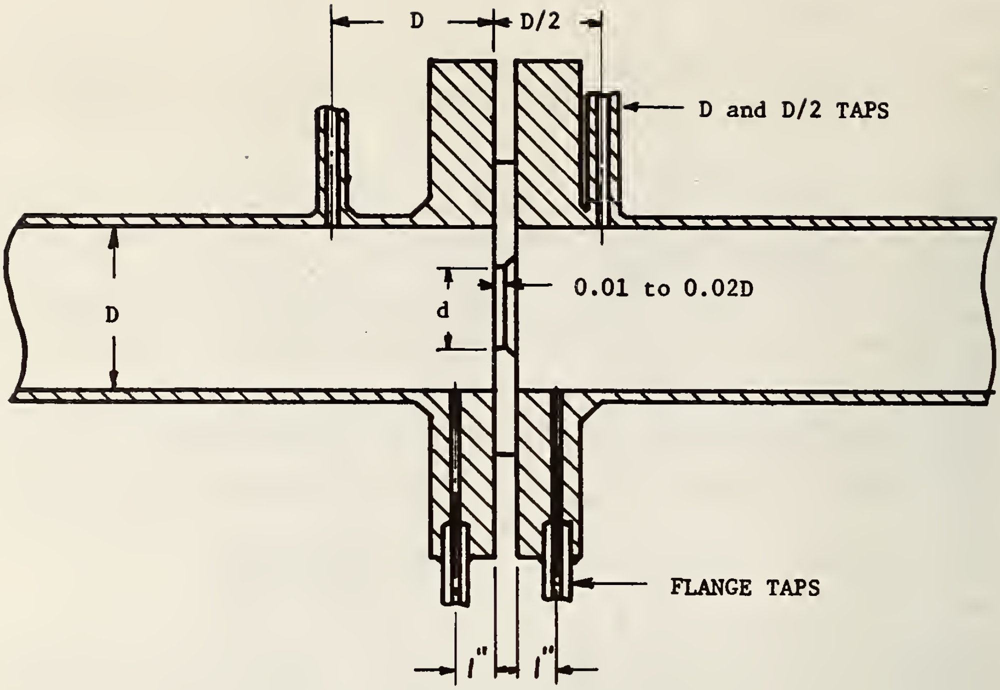


Fig. 15 Thin plate orifice meter.

7.2.2. Flow Nozzles

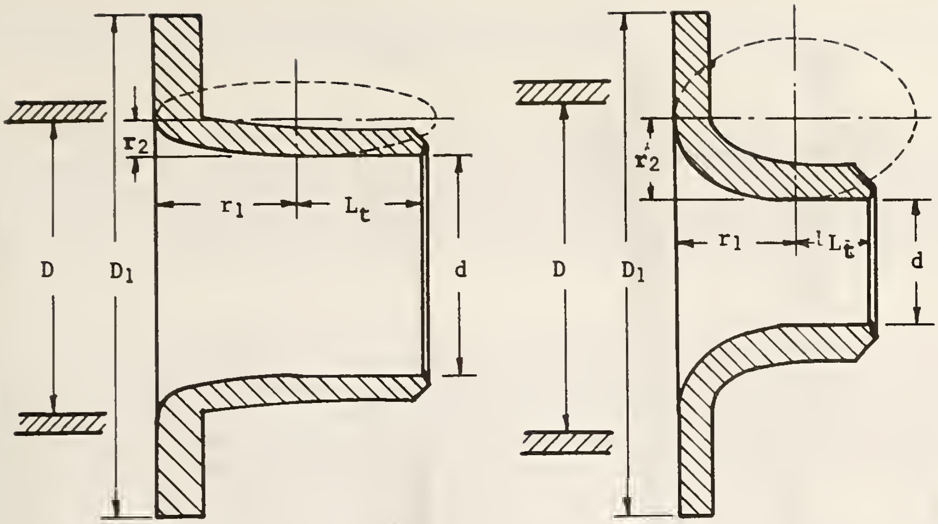
Flow nozzles are more costly than orifice flowmeters but cost less than equivalent Venturi meters. For the same flow they have about the same head loss as orifice meters. The principle advantage of the nozzle over the orifice is its higher coefficient of discharge and one that is less subject to change due to erosion. The coefficients of discharge of orifice flowmeters have been found to increase appreciably due to rounding of the upstream edge.

Flow nozzles are made of aluminum, brasses, bronzes and stainless steel. All of these are satisfactory for liquids free of corroding or abrasive substances. Stainless steel should be used for high temperature, corrosive and abrasive environments.

Flow nozzles having a wide variety of configurations have been manufactured, calibrated and are in use. This discussion will be confined to the "long radius" or elliptical inlet nozzle as recommended by the ASME, not because it is inherently a better nozzle but because more reliable information on discharge coefficient versus Reynolds number is available for this configuration.

The curvature of the inlet to the nozzle throat is the quadrant of an ellipse. The proportions of the ellipse with respect to pipe and throat diameters are shown in Fig. 16. The low β nozzle is recommended for diameter ratios d/D below 0.50 and the high β nozzle for β between 0.45 and 0.80. There is a small range of β between 0.45 and 0.50 where either can be used. All important dimensions for both low and high β nozzles are shown in Fig. 16.

These flow nozzles are used in continuous pipe lines, at the end of a pipe line discharging to the atmosphere, or at the outlet of a plenum chamber. The inlet pressure tap is located one pipe diameter upstream from the inlet plane of the nozzle when the nozzle is installed in a continuous pipe line or at the open end of a pipe section. When the nozzle is installed at the exit of a plenum chamber, the inlet pressure is the pressure in the plenum chamber.



High β Nozzle $\beta \geqq 0.45$
$r_1 = 1/2D$
$r_2 = 1/2(D-d)$
$L_t \leqq 0.6D$ or $\leqq 1/3D$

Low β Nozzle $\beta \leqq 0.5$
$r_1 = d$
$5/8d \leqq r_2 \leqq 2/3d$
$0.6d \leqq L_t \leqq 3/4d$

Fig. 16 ASME long-radius flow nozzles.

With high β nozzles the outlet pressure connection is located D/2 downstream from the entrance plane of the nozzle. For a low β nozzle the pressure tap (either pipe wall or throat) is located 1.5d downstream from the entrance plane of the nozzle. When a nozzle is installed at the outlet end of a pipe section or the outlet of a plenum chamber, the outlet pressure is measured with a barometer located near the nozzle outlet. For liquid flow this measurement is usually not required. The differential pressure drop across the nozzle is then the upstream pressure measured against atmospheric pressure.

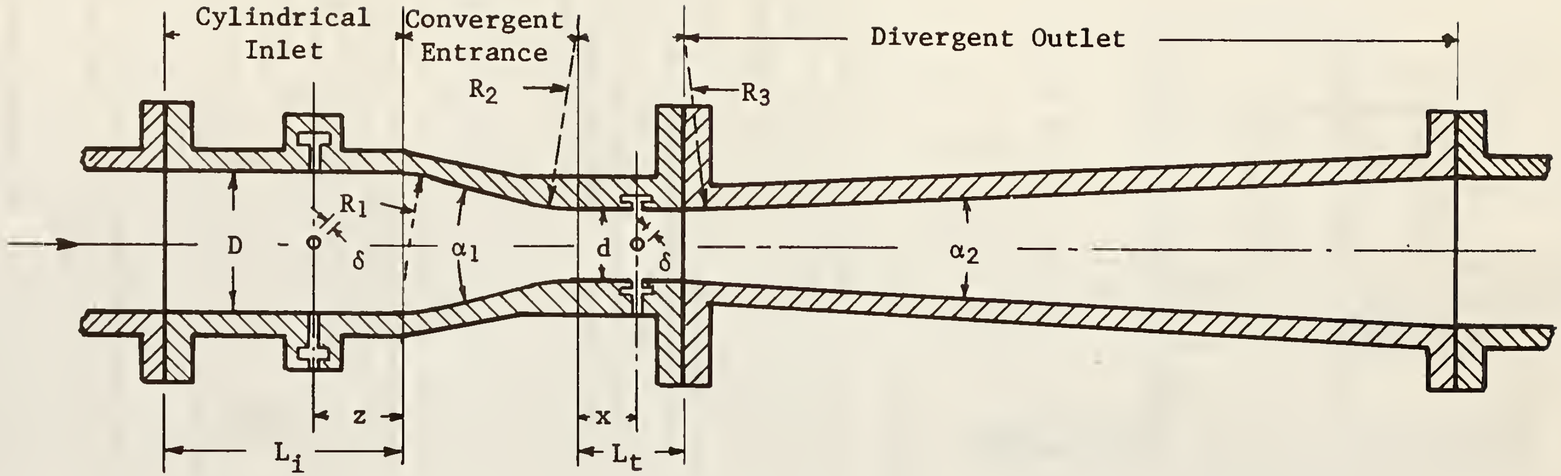
Flow through these nozzles can be calculated from Equations 27 and 28 and the coefficients of discharge listed in Table II-III-5 reference [1]. As in the case of orifice meters it is preferable whenever possible to determine the nozzle coefficient through calibration of the nozzle when installed in the pipe section in which it is to be used.

7.2.3. Venturi Flowmeters

The Venturi tube flowmeter is the most costly and the largest of the differential pressure meters. Its principle advantage is its low overall pressure loss. The efficient conversion of velocity head to pressure head in the conical expansion section is responsible for its low pressure loss. The classical (Herschel) Venturi tube flowmeter is shown in Fig. 17. A number of modifications of the Venturi are available. Some involve a combination of a nozzle inlet with the conical expansion (the Nozzle-Venturi). Others employ modifications in or near the throat section to obtain a high differential pressure with as low an overall pressure loss as possible. All of these modified Venturis require calibration as the relation between coefficient of discharge and Reynolds number is not well known.

The classical Venturi shown in Fig. 17 consists of a cylindrical inlet, a convergent conical section, a cylindrical throat and a divergent conical discharge section. The dimensional proportions as recommended in [1] are tabulated in Fig. 17.

These tubes are usually made of cast iron or cast steel in the smaller sizes. In the very large sizes some are fabricated of welded sheet steel. The throat section may



$L_i \leq D$ or $L_i \leq (D/4+10'')$

$z \leq D/2 \pm D/4$ for $4'' \leq D \leq 6''$

$D/4 \leq z \leq D/2$ for $6'' \leq D \leq 32''$

$L_t \geq d/3$

$y \geq d/6$

$5/32'' \leq \delta \leq 25/64''$ and

$\delta < 0.1D$ or $0.13d$

$R_1 = 1.375\ D \pm 20\%$

$R_2 = 3.625\ d \pm 0.125d$

$5d \leq R_3 \leq 15d$

$\alpha_1 = 21° \pm 1°$

$7° \leq \alpha_2 \leq 8°$ or $7° \leq \alpha_2 \leq 15°$

Fig. 17 Classical (Herschel) Venturi.

be lined with bronze or other corrosion-resistant material. The inlet and throat sections contain piezometer rings or annular chambers for measuring static pressures at these points.

As with orifice and nozzle flowmeters the mass or volume rate of flow for the classical Venturi flowmeter can be calculated from Equations 28 or 27. The coefficients of discharge can be obtained from page 64 reference [1] for rough cast, machined and rough welded sheet steel convergent sections with tolerances varying from 0.7 to 1.5 percent. For more accurate flow determinations a calibration of the Venturi meter should be performed.

7.2.4. Laminar Meters

Another form of head meter is one which has a linear relationship between the pressure drop and the flowrate from zero up to some maximum rate, depending on the geometry of the meter and the viscosity of the liquid flowing through it. In its most common form the laminar or linear meter consists of a capillary tube or a bundle of capillary passages. It is not necessary for these passages to be circular or even uniform in cross-section. Both the single tube and bundle form of meters are shown in Fig. 18.

The linear relationship between pressure drop and rate of flow requires that the Reynolds number be below about 2300, the value at which laminar flow begins to become turbulent. In the case of laminar meters the Reynolds number is difficult to determine because the characteristic length is usually not known. It may be measureable in the case of a single tube of circular cross-section but not for a bundle of tubes including irregular areas between them or a large number of thin slit-like passages. For these meters the limit of linearity must be determined by experiment.

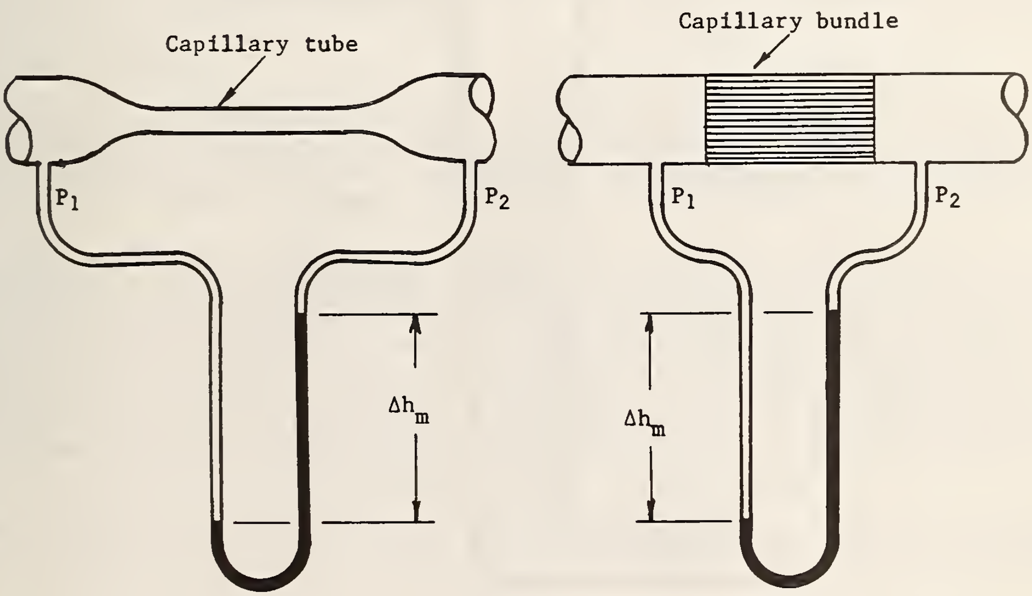


Fig. 18 Laminar flowmeters.

The basic relation for flow through capillary tubes as first shown by Hagen and Poiseuille and now known as the Hagen-Poiseuille law for the units used herein is:

$$Q = C(\frac{\pi g_c}{128}) (\frac{D^4}{L}) (\frac{P1-P2}{\mu}) \quad (42)$$

where C is the coefficient which must be determined by calibration. The effects of inlet and exit losses, and in the case of coiled capillaries, the effects of curvilinear flow are included in C. In meters where D is difficult or impossible to determine, the product of the first three terms may be determined through calibration.

7.3. Variable Area Meters

Another form of meter which can be considered as a head meter is the variable area meter. In these meters the cross-sectional area of the measuring aperture is caused to vary as a function of flowrate while the differential pressure or head producing the flow remains essentially constant. Generally, the variation of area with flowrate in this type of meter is automatic and the position of the area changing element is an indication of flowrate.

The most common meter of this type consists of a tapered tube and float. The tapered tube is vertical with its inside diameter increasing with elevation. The direction of flow is vertical upward through the tube. The float which is free to move vertically responds to the flow until it finds a position where the weight of the float less the buoyant force of the liquid is equal to the upward force produced by the flow of the liquid past the float. A schematic drawing of a typical variable area meter is shown in Fig. 19.

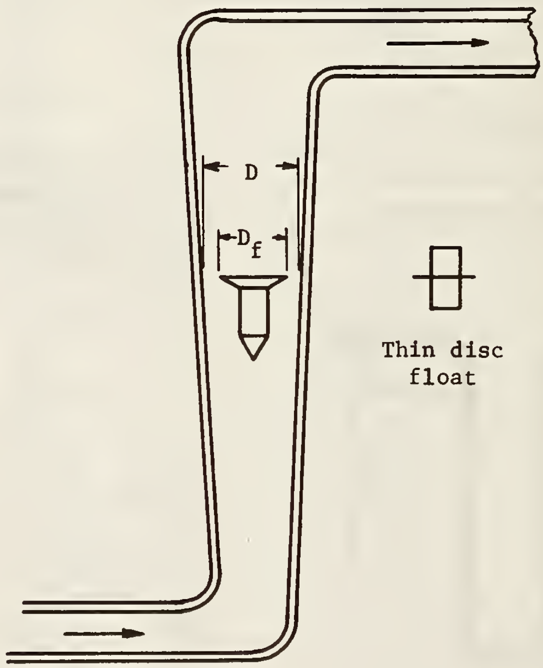


Fig. 19 Variable area flowmeter.

The parameters which determine the characteristics of such a meter are density and shape of the float, variation of the annular area (between float and tube), elevation of the float, and density and viscosity of the flowing liquid. It has been shown that a float with a thin disc, like that shown in Fig. 19, is much more independent of liquid viscosity than cylindrical and spherical floats. The tapered tubes are generally of a constant taper angle and the annular area is kept less than the cross-sectional area of the float so that the flowrate is nearly linear with elevation.

Glass is the most commonly used material for the manufacture of the tapered tubes. The floats are guided either with a central rod or with flutes integral with the glass walls. Other materials are sometimes used for the tubes but these require auxiliary means for the indication of the float position. In that case a magnetic coupling and follower can be used. Remote indication and recording are sometimes effected with the float altering the inductance or capacitance of an electrical circuit.

Equations for the volume and mass rates of flow shown below are derived in [1]:

$$Q = (\alpha^2-1) \left(\frac{2g_c AF}{\rho}\right)^{1/2} \qquad (43)$$

$$m = (\alpha^2-1) \, (2g_c AF\rho)^{1/2} \qquad (44)$$

Where $\alpha = D/D_f$
$A = \pi/4 \, D^2$
F = Buoyed weight of the float, lbf

Of themselves, these equations cannot predict the flow through variable area meters; for that, calibrations of individual meters are required. However, the equations do show the variation of flow with float and liquid densities. For accurate liquid metering over a range of liquid densities and viscosities, Shafer, et al. [10], have shown that calibration at several float positions, with four or five liquids having physical properties covering the required ranges of densities and viscosities, eliminates the necessity for calibration with each liquid of interest.

7.4. Turbine Flowmeters

The turbine-type flowmeter is perhaps the most widely used flowmeter utilizing a generated electrical signal which is proportional to fluid flow. Flowmeters of this type have found considerable application in the aircraft industry because of such advantages as small size, fast response, accuracy, simplicity and adaptability for remote indication.

The turbine flowmeter consists of a flow tube in which is mounted a bladed turbine rotor, supported by one or more bearings, together with means of generating an electrical signal having a frequency proportional to turbine angular velocity. The turbine rotor is designed in an effort to produce speed of rotation directly proportional to volume rate of flow. This has been approached for turbine flowmeters in the larger sizes and for moderate sized meters with liquids of low kinematic viscosities. In an average application a typical turbine flowmeter can be expected to meter volume rate of flow to accuracies of one-half to one percent over flow ranges varying from 3 to 1 up to 20 to 1 and even higher depending upon meter design, size and the viscosity of the liquid.

There are several types of electrical signal-producing devices; some of the principal types are as follows:

a. Inductance system: The routing element of the turbine carries permanent magnets embedded in the hub or blade tips. The magnetic flux from the moving magnets induces a voltage within a pickup coil located close to the magnetic field.
b. Variable reluctance system: A fixed permanent magnet is centered with a pickup coil which is located in close proximity to the rotating turbine rotor. Variation in the magnetic flux results from the passage of each blade of the highly permeable magnetic rotor material.
c. RF type of pickoff: An oscillator applies a high frequency carrier signal to a coil in the pickoff assembly. The rotor blades pass through the field generated

by the coil and modulate the carrier signal by shunting action on the field shape.

d. Photoelectric system: A beam of light is interrupted by blades of the rotor so that a pulsed signal output is developed.

e. Magnetic reed switch system: The contacts of a reed switch are opened and closed by magnets embedded in the rotor or in the rotating part of the turbine meter. The switch action causes a constant input to be interrupted so that a pulsed signal output is produced.

With all of these systems the frequency of the pulses generated becomes a measure of volumetric flowrate and the total number of pulses measures total volume. Either of these measurements requires that turbine flowmeter output frequencies be linear with flowrate; that is, each pulse be equal to the same unit volume of fluid measure, regardless of frequency. Manufacturers of turbine flowmeters have claimed linearity within ± 0.5 percent of flowrate over ranges as great as 75 to 1 for liquids having viscosities of about 1 centistoke. Range of linearity depends primarily on meter size and liquid viscosity. In general, lower flowrates, smaller meter sizes and higher velocities all tend to decrease the range of linear operation.

Turbine meter calibration data can be presented in a number of ways. A plot of frequency versus volumetric flowrate can be used as shown in Fig. 20a. Ideally these data should plot in a straight line passing through zero. However, only the most linear of meters approach the straight line and all meters will show some viscosity dependency. Note that as viscosity increases the frequency output decreases as a result of viscous drag.

A more practical method of showing the data, one which more directly displays the linearity or lack of linearity of the meter is to plot the reciprocal of the slope of the curve shown in Fig. 20a versus frequency. Thus this plot shown in Fig. 20b is a curve of the frequency divided by the volumetric flowrate versus frequency. This parameter is termed the "flow coefficient" or "K factor" and for most aircraft work has the units of cycles or pulses per gallon. The ideal plot of "K" versus frequency is a straight horizontal line.

Another method is a plot of the relation shown by Shafer [11]

$$f/Q = \phi\ (f/\nu)$$

If this relation is correct a plot of f/Q which is the "K factor" versus f/ν (the frequency divided by the kinematic viscosity of the fluid) will give a smooth curve, the shape of which is determined by the function ϕ, throughout the working range of the meter calibrated. The curves in Fig. 20c especially at the low rates of flow show that no single form of the function ϕ describes the performance of a turbine meter. However, curves of this form are useful in describing the effects of flowrate and viscosity upon the performance of turbine meters even though significant deviations are obtained.

There are many methods suitable for the calibration of turbine flowmeters; a more complete discussion of the methods is treated in Chapter 6. A partial listing of these methods include

1. Gravimetric Methods
    a. Static
    b. Dynamic
2. Volumetric Methods
3. Running Start and Stop
4. Standing Start and Stop

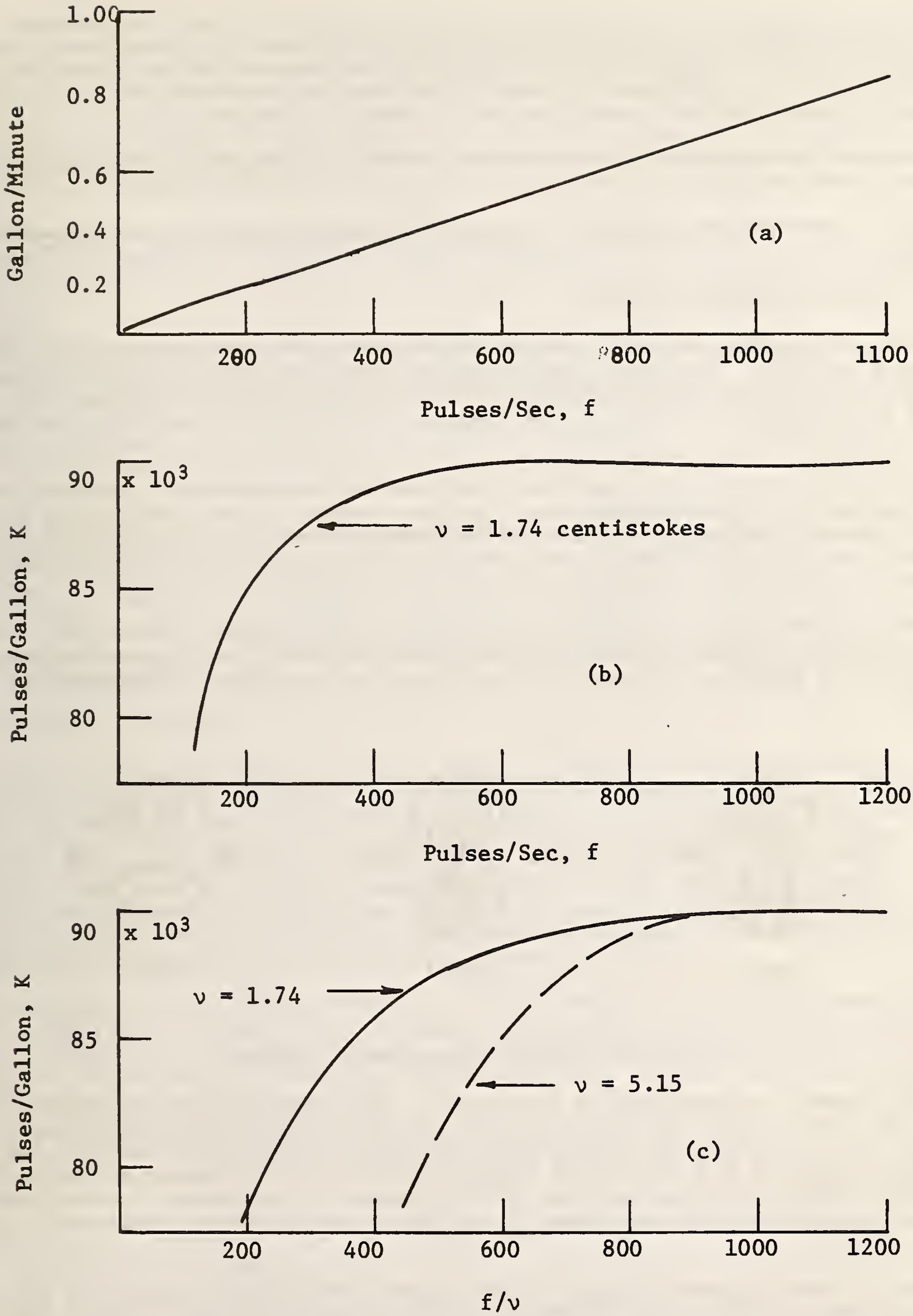


Fig. 20 Turbine flowmeter characteristics.

The fast response of turbine flowmeters makes possible the use of the Standing Start-and-Stop Method of calibration. In this procedure there is no flow through the transducer prior to the beginning and at the end of the calibration run. The procedure requires that at least 95 percent of the total delivery be at the desired flow. In this method solenoid valves are synchronized with an electronic counter.

Turbine flowmeters are also conveniently calibrated with mechanical displacement devices called "ballistic" or "piston" calibrators as described in Section 6.3.

For a more complete treatment of turbine flowmeters [9] and [12] are recommended reading.

7.5. Positive Displacement Meters

Positive displacement meters measure the volume rate of liquid flow by repeatedly filling a container. The total volume of liquid flowing through the meter in a given time is the product of the volume of the container and the number of fillings. The number of fillings is registered by a counter geared to indicate the quantity in gallons, cubic feet or barrels.

Displacement meters of a great many configurations are available. The more common types include the reciprocating piston, ring piston meters, sliding and rotating vane meters, nutating disk meters and gear and lobed impeller meters. The latter are probably the most used and will be briefly discussed to indicate the principle of displacement meters.

These meters measure the liquid flow by using a small pressure differential to rotate the pair of elements. These two elements seal the inlet from the outlet thereby developing the pressure differential. The principle of operation is illustrated in Fig. 21.

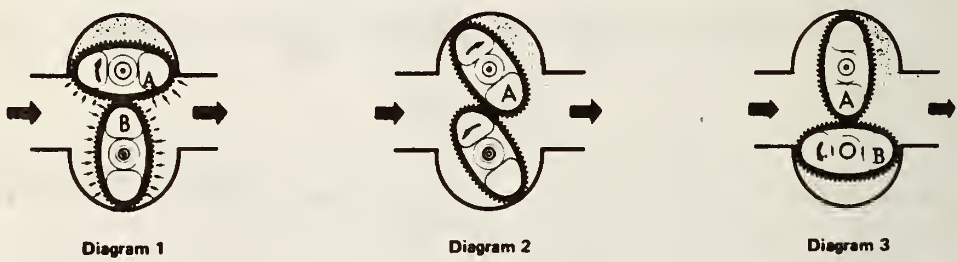


Fig. 21 Positive displacement flowmeter.

When the elements are positioned as in diagram 1, the torque developed on element A due to the differential pressure causes it to rotate and drive element B which has balanced torques. When A reaches the position shown in diagram 3 its torque is balanced; however, the torque developed in B causes B to rotate and drive A. The alternate driving action provides a smooth continuous rotation. If the elements are not geared as shown, they are geared externally with equal gears to keep the rotors in correct relationship to each other.

As the elements rotate they trap liquid in the crescent shaped gaps of the flowmeter. The total quantity of flow for one revolution of the elements is equal to four times the volume of the crescent shaped gap. Thus the volume rate of flow is proportional to the rotational speed of the elements. The clearances between the rotors and the case are very small so that effective capillary sealing between inlet and outlet is maintained. The pressure differential between inlet and outlet is kept small through the use of low friction precision bearings on the rotor shafts. Despite these two features there is some residual leakage (slip) past the rotors. Slip is defined as the difference between the quantity which actually passes through the meter and the quantity displaced by the measuring chambers.

Although it is possible to calculate the volume of the measuring chamber, so as to determine displacement per revolution, this is seldom done. The usual practice to determine the capacity of the meter is by "proving" or calibrating the meter. In proving the meter:

1. The meter should be calibrated with the liquid it is to meter or one having nearly the same properties.
2. The meter should be calibrated over the range of flowrates at which it will be used.
3. The liquid should be free of entrained air and vapor.
4. The meter should be calibrated at about the same temperature and pressure at which it will be used.

These meters can be calibrated in essentially the same manner as turbine-type flowmeters. If the meter is equipped with an electrical signal generating device, a counter, gated with the weigh beam of a dynamic gravimetric calibrator or with the position sensors of a volumetric calibrator, is used to count the total pulses. If the meter contains only a volume register the calibration can be performed by timing the passage of a given registered volume and simultaneously making a flowrate determination with either a gravimetric or volumetric calibrator.

7.6. Magnetic Flowmeters

The basic principle of the magnetic flowmeter is similar to that of an electric generator. According to Faraday's law the passage of an electrical conductor through a magnetic field induces an electromotive force across the conductor in a direction normal to both the magnetic field and the direction of the conductor. In a magnetic flowmeter the conductor is the flowing liquid within a pipe or tube of insulating material. Such a meter is shown schematically in Fig. 22. The direction of liquid flow is into the plane of the paper and normal to the magnetic field produced by the permanent magnet. The induced voltage e is detected with insulated electrodes placed diametrically in the tube and also normal to the magnetic field.

The magnet may be a permanent magnet, a DC electromagnet or an AC electromagnet; consequently, there are both AC and DC magnetic flowmeters. The flow tube must be nonmagnetic material such as glass, plastic, aluminum, brass or stainless steel. Metallic tubes must be lined with an insulating material to prevent the metal tube from short-circuiting the path of the induced emf.

From Faraday's law of induction it can be shown that

$$q = \frac{\pi}{4} \frac{D^2}{\delta} \frac{e}{B} \qquad (45)$$

where q = rate of flow, in^3/s
D = Diameter of tube, inches
δ = Distance between electrodes which may be less than D, inches
e = Induced emf, volts
B = Flux density, $webers/in^2$.

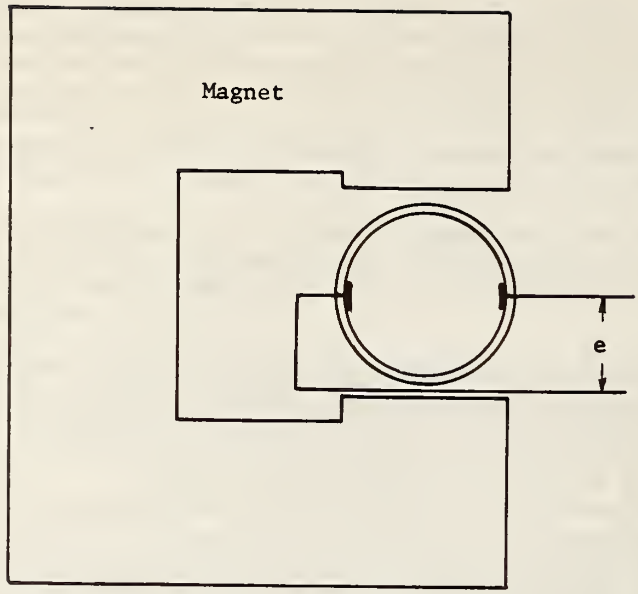


Fig. 22 Electromagnetic flowmeter.

The flux density produced in a DC magnetic flowmeter is constant and the volume rate of flow is proportional to the induced emf. In the case of AC magnetic flowmeters neither the induced emf nor the flux density is constant. However, the volume rate of flow is proportional to e/B, therefore with AC magnetic flowmeters it is necessary to measure this ratio.

Since the magnetic flowmeter is responsive to velocity and therefore a volume rate flowmeter, its indications are essentially independent of liquid density and viscosity. It has been said that these meters are not sensitive to changes in velocity profile or helical flow. Another decided advantage of this type of meter is its unobstructed flow path; therefore, it is not subject to abrasion and has a low overall pressure loss.

A conductivity of 5 micromhos/cm will meet the threshold conductivity for most magnetic flowmeters. This value of conductivity includes a great many industrial liquids. Most petroleum products have conductivities below this limit; hence they cannot be metered in this type of meter.

One manufacturer claims an accuracy of flowrate vs indication of ± 0.5 percent of maximum flow. This of course is after a calibration of the meter.

7.7. Magnetic Resonance Flowmeters

The nuclear magnetic resonance (NMR) flowmeter is another flowmeter utilizing magnetic principles. In this case it is the liquid which becomes magnetized. Most liquids will become slightly magnetized when passed through a magnetic field. Radio frequency energy is then used to amplify (resonate) the magnetic effect and produce strong signals from the weakly magnetized liquids. In order to measure flow, the magnetization is disturbed in small portions of the liquid stream and the passage of these tagged portions are detected downstream. Each detected tag represents a known volume of liquid and is totalized on a counter.

Nuclear magnetic resonance can be stimulated in all nuclei having magnetic dipole moment. For flowmeter applications the hydrogen nucleus (the proton) and the fluorine nucleus have been of the greatest interest for two reasons. First, the magnetic resonance of the proton is stronger than that of any other commonly occurring nucleus. Secondly, the presence of hydrogen and fluorine nuclei in all water-bearing liquids, hydrocarbons and fluorocarbons permits metering of these liquids with meters based on the NMR principle. The flowing liquid need not be conducting as in the case of the electromagnetic flowmeters.

A typical NMR flowmeter shown schematically in Fig. 23 consists of:

1. A ceramic liner in which there are no obstructions to flow.
2. Strong permanent magnets and static field coils to magnetize the liquid (to rearrange the orientation of the dipoles from random to alignment with the magnetic field).
3. A radio frequency field coil (resonator coil) to resonate the magnetization and produce usable signals for flow measurement.
4. Modulator coil to modulate the magnetic vector in a small portion of the flow (to tag the flow).
5. Detector coil which detects the passage of the small tagged modulated portion of flow.

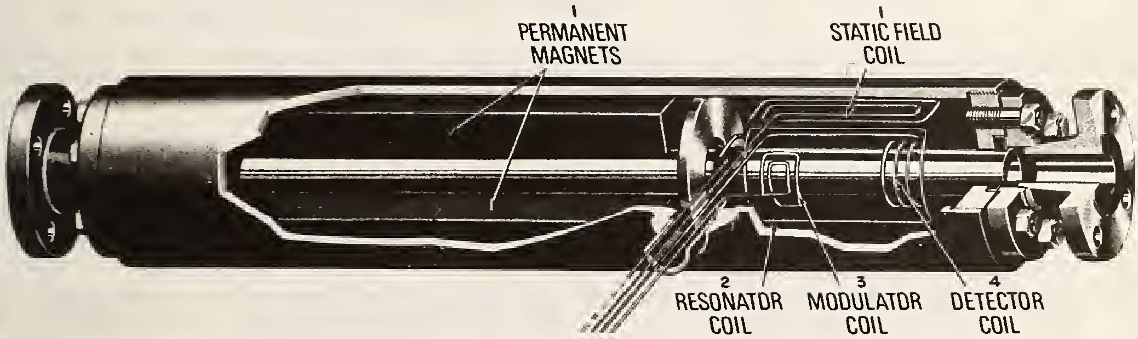


Fig. 23 Nuclear magnetic resonance flowmeter.

Each tag pulse represents the passage of a known discrete volume of liquid. Total volume of flow is obtained from totalizing pulses on a counter. Volume rate of flow can be derived from the frequency of the pulses.

A manufacturer has claimed the same meter factor (pulses per gallon) for different fluids under similar flow conditions.

7.8. Ultrasonic Flowmeters

Several ultrasonic flow measuring devices utilizing the speed of sound in and the velocity of the flowing fluid have been developed. One of these described herein is referred to as a "sing-around velocimeter." Such a device is shown schematically in Fig. 24.

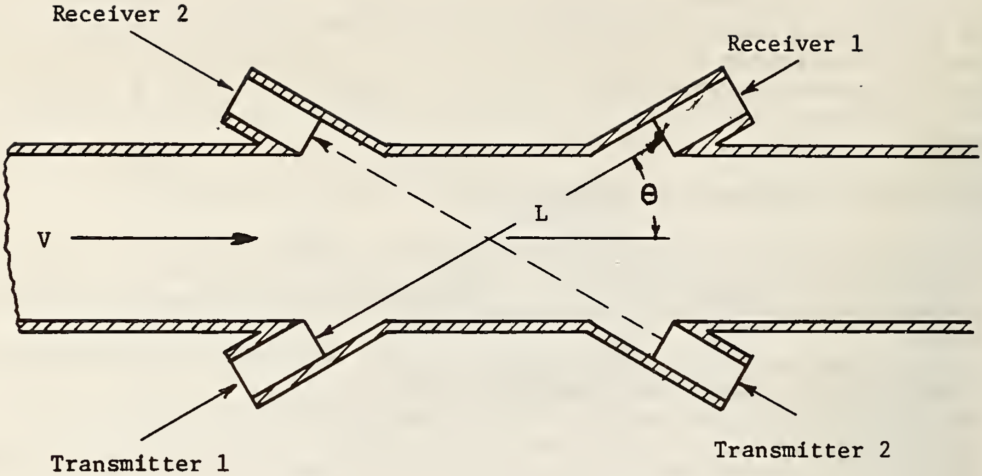


Fig. 24 Ultrasonic flowmeter.

It consists of a straight tube, two identical ultrasonic pulse generators and two identical receivers oriented as shown. The time required for a pulse to travel from transmitter 1 to reveiver 1 is

$$t_1 = \frac{L}{c + V \cos \theta}$$

where L = distance between transmitter and receiver
c = velocity of sound in the liquid
V = velocity of the liquid. And the time t_2 from transmitter 2 to receiver 2 is

$$t_2 = \frac{L}{c - V \cos \theta}$$

thus,

$$\Delta t = t_2 - t_1 = \frac{2LV}{c^2 - V^2 \cos \theta}$$

and when V is very small as compared to c

$$\Delta t = \frac{2LF}{c^2}$$

Thus for a given meter $$V \propto \Delta t c^2 \qquad (46)$$

Similarly it can be shown that $V \propto \Delta f = f_1 - f_2$ where f_1 and f_2 are the frequencies detected on receivers 1 and 2.

The velocity of the liquid can be determined by measurements of either the frequency difference of the two detectors (beat frequency) or the difference in transit time. The instrumentation required for these measurements is beyond the scope of this paper. Suffice it to say such measurements can be routinely made with good accuracy.

The signal output of meters of this type will be a function of the velocity distribution across the duct. As a consequence, these meters will require calibration within the pipe system in which they will be used.

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Figures 8, 10, 17 and 22 are modifications of figures taken from [1]. Figure 21 is taken from Catalog DS-900, Brooks Instrument Division, Emerson Electric Company. Figure 23 is borrowed from Bulletin MRF-125 of the Badger Meter Manufacturing Company.

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16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

These notes are intended to serve as an instruction manual for technicians and engineers engaged in metering liquids and calibrating liquid flowmeters. It is a condensed review of the properties of liquids and the mathematical relations required in this work. References to more complete sources of properties of liquids, theoretical relations and instructions for metering liquids are included. Separate chapters discuss liquids and their properties as they affect flow, the theory of incompressible flow of liquids and the measurements required in the metering of liquids. One chapter describes several different apparatus and their use in the calibration of liquid flowmeters. The last chapter contains brief descriptions of the many types of flowmeters such as differential pressure, positive displacement, electromagnetic and ultrasonic. It also includes a discussion of the physical principles involved in their design and use.

17. KEY WORDS (Alphabetical order, separated by semicolons)

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