A CRITICAL REVIEW OF PRIMARY FLOW ELEMENTS USED IN THE PAPER INDUSTRY

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ABSTRACT

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Flow measurement is very important in the paper industry. Accurate flow measurement increases process efficiency, while not always requiring costly equipment and installation. Conditions of processes that depend on flow are controlled by information obtained from flow measurements. In addition, such information provides operator guidance and is often employed in determining quantities of materials used and processed as well as for inventory and cost controls. The selection of a primary flow element for an individual application, from the many types available, depends on a multitude of factors. However, once clearly understood, the principles of flow measurement may be conveniently applied to solve the particular problem at hand. A large number of flow measuring devices is available, offering users opportunities to make their specifications according to specific service conditions.

This study concentrates on flow measuring methods and applications for the most commonly used types of primary flow elements, or flowmeters, in the paper industry today. Their advantages and their disadvantages will be presented along with comparisons on major selection criteria such as accuracy, flow range, rangeability, cost, applicability and installation requirements. Guidelines to determining the type of primary flow elements best suited for a particular installation are presented in Chapter VII.

To illustrate the use of the equations, tables and figures given in this report, several example calculations in the paper industry applications have been included.

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NOMENCLATURE

A	area in any units consistent with the rest of the equation
B	magnetic field strength
C	coefficient of discharge
C_1	a constant equal to $(Vs/f_1)\ 2 \cos \theta$
C_g	gas density factor
C_{ld}	liquid density factor
C_m	a constant
C_n	a constant
C_o	capacity factor
C_{pb}	base pressure factor
C_{tb}	base temperature factor
C_{tf}	gas flowing - temperature factor
C_s	steam density factor
D	inside pipe diameter, inches
d	diameter of bore of primary device, inches
Er	reference voltage
Es	voltage generated in a conductor
f	frequency, cycles per second
f_d	downstream frequency
f_u	upstream frequency
Δf	difference between downstream and upstream frequencies
f_1	transmitted frequency
f_2	received frequency
g	acceleration of gravity, ft/sec^2

H	head on weir flow measurement
H_t	total depth of the fluid flowing through the weir
h	differential pressure in feet of flowing fluid
K	number of pulses per gallon
L	distance between ultrasonic transducers
ℓ	length of the weir crest
P	static pressure, psia
Q	volume flow rate, cubic feet per second
Q_g	air or gas flow rate, scfh
Q_l	Liquid flow rate, gph
Q_t	flow rate, gallons per minute
R_D	pipe Reynolds number
t	pulses transit time across the pipe
t_d	pulse travel time - downstream
t_u	pulse travel time - upstream
V	velocity in any units consistent with the rest of the equation
$\forall$	velocity component at the angle of transmission
Vs	velocity of sound in the fluid
W	mass flow rate, pounds per hour
α	angle of a V-notch weir
β	diameter ratio, d/D
ρ	density of flowing fluid, lb mass/cu. ft.
θ	angle between fluid flow an acoustic signal path
μ	absolute viscosity, lb mass/ft. sec.

CHAPTER I

INTRODUCTION

1.1 Flow measurement concept

Process fluid flowing through a pipe in a paper making process represents monetary investment. To keep informed about this investment, accurate measurement of the fluid at all stages of the process is important. The purpose of a measurement is to obtain the true value of a process quantity by comparing it to a standard or reference. A standard is an arbitrarily chosen reference of suitable magnitude which is assumed to be unvarying[1]. The actual value of the measurement is the value of the process quantity, obtained by an instrument, with no systematic or random errors[2].

Measurement is defined as the extraction of signals from physical and chemical systems or processes which represent parameters or variables[3]. Flow is the controlling variable in the fluid processing industries[4]. That is, flow is the variable which, by being modulated, maintains all the other process conditions at the values required to keep the plant producing products of the specified quality at the desired rate. This rate measurement can be accomplished by various types of rate meters which measure fluid quantities without disrupting or stopping normal process flow.

The selection of a flow measuring instrument can be a difficult undertaking unless the user has some basic information as to making a good choice. The choice of a flowmeter is often primarily based on accuracy, reliability, rangeability, cost as well as ease of installation, availability, ease of maintenance, type of signal transmission and need for calibration. These parameters are not necessarily in order of importance but are factors in one way or another in selecting the flowmeter for a particular application. However, any one of these factors may decide the selection of the flowmeter to be used, as will be shown in Chapter VII.

1.2 Classifications of Primary Flow Elements

Primary flow element is that part of a fluid meter which is in contact with the flowing fluid and produces some form of interaction with the fluid. Secondary devices, such as transmitters, indicators or recorders, will not be covered in this study. One must keep in mind, however, that the primary flow elements are practically useless without some form of indication as is provided by the secondary device.

Primary flow elements or flowmeters can be divided into two major categories. These are: rate flowmeters and totalizing or quantity flowmeters.

Rate flowmeters are defined as those flowmeters through which the fluid passes in a continuous stream, rather than in isolated quantities. They are sometimes called inferential meters because the quantity of flow is not determined by counting, but is inferred from the interactions of the flowing fluid and the primary flow element by means of known physical laws and empirical relations. Rate flowmeter performance depends on properties such as fluid inertia and kinetic energy in the case of differential pressure flowmeters, in addition to mass or volume.

Quantity or totalizing flowmeters consist of the weighing devices which are divided into weighers and tilting traps, and volumetric devices which are further divided into several types.

After mentioning the two major categories of flowmeters, one possible grouping of the various types of flow metering methods considered in this study could be as follows:

- Head or Differential pressure flowmeters
- Area flowmeters
- Positive displacement flowmeters
- Volumetric flowmeters based on velocity principle
- Head area systems or open channel flowmeters

The more recent innovations in flow measurement supplement, but do not replace, the original differential pressure or head type flowmeters. There are certain applications in which a specific type is more advantageous than others.

CHAPTER II

DIFFERENTIAL PRESSURE FLOWMETERS

2.0.1 General Principles

The differential pressure method belongs among the most important flow measuring methods used in the paper industry. It is based on the continuity law and the Bernoulli's theorem.

According to the law of continuity, the rate of flow in a pipe is the same at all points. When the cross section of the pipe is reduced at one point, the flow velocity is increased at that point.

According to Bernoulli's theorem the sum of kinetic energy (due to velocity) and potential energy (due to position and pressure) is constant at any point in a pipe through which a liquid is flowing. Consequently, an increase in velocity causes a reduction of the static head. The resulting differential pressure h is a measure for the rate of flow Q.

Figure 1 illustrates a differential pressure device, also called a head producer, installed in the pipe at the point of measurement, restricting the flow to a certain cross section, and used as a sensor in flow measurement based on the differential pressure principle.

2.0.2 Basic relations

The basic equations used in studying the flow through differential pressure flowmeters are, as mentioned above, the equation of continuity and the energy equation. For use in the equations the values of pressure, velocity, kinematic viscosity and specific weight are arithmetical mean values obtained by averaging over a particular cross-section. It is also conventional to assume that the pipe section is horizontal so that the effect of gravity is the same at all sections, and that the flow is steady and the density is constant.

In general, the user of a differential pressure flowmeter is interested in knowing the rate of flow in terms of volume per unit time. By applying the continuity equation and the energy equation the volume rate of flow becomes [7]:

$$Q = VA = C\sqrt{h} \qquad (2.1)$$

where h is the differential pressure, and C is the factor controlled by several variables. Some of these variables are the shape of the restriction, the beta ratio (ratio of the restriction throat to the diameter of the pipe), the density of the flowing fluid and the locations of the pressure taps.

This equation (2.1) illustrates that the differential pressure produced across a restriction is proportional to the square of the flow.

More complete derivations of the basic flow equations, based on the continuity law and Bernoulli's theorem, have been developed by various authors, and the development given by ASME [5] and Spink [6] are probably the most complete.

2.0.3 Characteristics of the Differential Pressure producers

If restrictions are used whose properties are well known, so that the equation (2.1) can be evaluated by calculation, the measuring result (differential pressure) yields absolute flow results without the need for reference measurements. Therefore, it is possible to check a flow measuring system without regard to the instrument manufacturer.

The non-linear relationship developed between the flow rate and the measurement signal (differential pressure) can introduce problems, particularly if the range of flow variation is large. For example, an orifice plate that develops a differential pressure of 100 inches of water at 100 percent rated flow will develop a differential pressure of 25 inches of water at 50 percent and only 1 inch at 10 percent of rated flow, as can be seen from Figure 1c.

Fluid flowing in a pipeline will be subjected to resistance due to friction and viscosity. If the average velocity of the flow is very low, the fluid will flow in parallel lines along the pipe walls, and the flow is said to be laminar or viscous. If the velocity is increased beyond a certain critical value when eddies start to form, the laminar flow pattern is changed and the flow becomes turbulent. The pattern of flow can be determined by evaluating the Reynolds number (R_D). This dimensionless number takes into account the pipe diameter, density, velocity, and the absolute (dynamic) viscosity:

$$R_D = \frac{\rho V D}{\mu} \qquad (2.2)$$

This equation indicates that as the diameter of pipe, D, increases, the Reynolds number becomes larger and the effect of viscosity is decreased. Consequently, large primary flow elements are less subject to viscosity effects than small ones.

An orifice plate can be used successfully with Reynolds numbers as low as 500, while a Venturi tube is only unaffected by Reynolds numbers above 200 000. Venturis can be used at lower Reynolds numbers but with a correction factor.

The differential pressure or head producers are restrictions of sturdy design and can be applied to wide temperature and pressure ranges when a pure phase (a liquid, vapour or gas, containing no solid particles) is involved.

2.0.4 Selection criteria

In the selection of the differential pressure primary flow element, the occurring pressure loss plays an important role (see Figure 1.b). The Venturi tube features a lower pressure loss than a Flow Nozzle or an orifice plate, as shown in Figure 9, and the energy costs are lower. Due to difficult manufacturing involved in Venturi, their price is higher so that cost has to be considered in each case. A Flow Nozzle or an Orifice plate are easier to manufacture and their prices are much lower, which are good reasons for their recommendations. In any case, a study should be made for every application before deciding which one of the primary flow elements is to be used.

2.1 ORIFICE PLATE

The orifice plate, originally developed for use on gas by T. Weymouth of the American Gas Association, is a simple, inexpensive, and accurate flow measuring device. It is suitable for measuring of water, steam, gas and other fluids flow. It is used where small dimensions and a high degree of accuracy are important and where pressure loss does not play an important part. The main application of the orifice plate, in the paper industry, is for the measurement of steam, uncontaminated gases and clean water flows.

The orifice plate, usually installed in the pipe line between flanges, reduces the free cross-section of the pipe and thereby produces an increase in flow velocity and a corresponding decrease in pressure at that point. The flow pattern shows an effective decrease in cross section beyond the orifice plate, with a maximum velocity and minimum pressure at the vena contracta. This vena contracta location depends on the beta ratio and the Reynolds number.

Orifice plates can be divided into various classes depending upon their orientations, their shapes and their designs. The shape of the edge of the orifice plate can be referred to as sharp-edged, rounded or beveled. The most popular shape, of those shown in Figure 2., is the concentric circular orifice, but there are many others. Some of these are eccentric orifices, segmental orifices, and square edge orifices.

The most often used, in the paper industry, is the concentric type orifice, but for fluids with suspended solids the segmental type orifice is applied.

2.1.1 Concentric orifice

Concentric type orifice plate has a hole (orifice) centered in the plate and is installed with the hole concentric to the inside diameter of the pipe. The upstream side of the hole must be sharp. The downstream side is sometimes beveled depending on the beta ratio and the pipe line size.

The thin plate concentric orifice, one of the most widely used primary flow elements in the paper industry, is suitable for measurement of any steady flow of clean, homogeneous fluid which is in the normal turbulent flow region with pipe Reynolds number 500 or greater. This covers in general, liquids having a viscosity lower than 300 Saybolt Universal Units at 15°C and most of the gases and vapours. Accurate coefficients are available for pipe line sizes from 2 to 14 inches and Reynolds numbers from 500 to 10^7.

In the paper industry, the sharp edge concentric orifices are used, as mentioned above, on clean, non-viscous fluids, where the cost of pumping (energy) is not a large item or is insignificant. Orifices are usually not used on dirty fluids, slurries, wet steam, or vapour bearing liquid flowing in horizontal lines. Condensate may tend to form a puddle at the bottom of a horizontal line ahead of the orifice plate and change the approach velocity pattern when wet gases or saturated steam are measured. Liquid flow, likewise, may contain small quantities of gas or vapour bubbles which tend to collect at the top of the line to cause erratic flow measurement. This condition is alleviated by drilling a small hole nearly flush with the inside diameter of the pipe, at the bottom when condensate is carried in a gas or vapour stream, or at the top when a liquid carries gas bubbles.

The pressure differential is sensed through precisely located connections (known as taps, Figure 3) which are determined by accuracy and installation requirements. Radius or D and 0.5D taps usually are preferred in the paper industry. Flange taps have centers one inch upstream and one inch downstream of the orifice plate faces. These taps are drilled right through the flanges. Vena-contracta taps have the upstream center in the range of 0.5 to 2 pipe diameters from the orifice plate surface. The downstream tap center is at the average location of the vena-contracta. Vena-contracta taps are used mainly with large pipe sizes. Corner taps are located as near to the orifice plate as possible, but they are very rarely used.

In measurement of liquid and steam flow, the orifice taps should be made on the side of the pipe and, in measurements of gas flows, the taps should be located on the top of the pipe.

Orifice plates are made of different materials, but in the paper industry because of a corosive atmosphere, the 304 or 316 stainless steel orifice plates are usually used.

The procedures for computing orifice sizes and flow through orifices are given in various publications[5, 6, 7, 8]. The particular equations to be used depend on personal preference and available sources of coefficient data. The basic equation for the actual rate of flow through an orifice is

$$Q = VA = C\sqrt{h} \qquad (2.1) \text{ Rep.}$$

The value of the discharge coefficient C is controlled by several variables. Some of these variables, as mentioned already in 2.0.2, are the pressure taps' locations and the beta ratio. For a given concentric orifice these are known. Thus to insure proper selection of C from references [6, 7, 9, 10, 11], one must find what the conditions were under which the orifice was tested. Since C and beta are both ratios, their numerical values will be independent of the system of units in which the various quantities are measured. The dependence of the discharge coefficient on the Reynolds number and the pressure tap locations has been described by Halmi [12].

Examples of orifices used on severe pulsating flow and pressure conditions that often prevail in piping systems, have been given in several papers [13, 14, 15].

The advantages of the orifice plate, such as: simplicity, low cost, vast amount of coefficient data, ease of capacity changes made by switching plate sizes, ease of duplicating, ease of maintenance, applicability to wide range of temperatures and pressures; usually outweigh the disadvantages, such as: relatively high unrecoverable pressure drop (shown in Figure 9), length of straight approach piping required for accuracy (Figure 5), subject to inaccuracies as upstream edge wears, low rangeability 3:1, and unsuitability for slurry applications.

2.2 VENTURI TUBE

The Venturi tube in the paper industry, shown in Figure 6, is mainly used for measurements of air and gas flows. It has been used for steam flows and for fluids containing suspended solid particles. But because of its high cost the Venturi tube on steam flow measurement is today replaced more by a vortex meter; and on fluid flow measurement the magnetic flowmeter replaces the Venturi tube.

The Venturi tube combines into a single unit a short constricted portion or throat between two tapered sections and it is usually installed between flanges or welded in the pipe line. Its purpose is to accelerate the fluid and temporarily lower its static pressure. The design of Venturi tubes most used today is essentially the same as the one conceived in 1887 by the inventor Clements Herschel [16]. The original attraction of the Venturi tube was its relatively low permanent pressure loss, from 10 to 16 percent, as shown in Figure 9 for a long cone venturi. Since then, many other differential pressure devices have been developed which have even lower permanent pressure loss, such as Dall flow tube.

Venturi tube flow coefficients are relatively stable over a wide range of Reynolds numbers above 200 000. That means it is beneficial to select sizes and flow ranges so that this line of Reynolds number would always be exceeded.

The accuracy for a calibrated Venturi system, including a secondary device such as a transmitter, is typically around ± 1 percent of full scale over a 4:1 range. Flow capacities may go up to practically any maximum.

Venturi tube pressure recovery is much better than for an orifice or a flow nozzle. It has a high capacity, does not need to be flow calibrated, and resists wear due to abrasion because of its smooth profile.

Principal disadvantages of the venturi tube are high cost, low rangeability, requires considerable room for installation, sensitive to Reynolds numbers below 200 000, and it produces lower differential than an orifice plate for the same flow and throat size.

2.3 FLOW NOZZLE

A flow nozzle is rarely used in the pulp and paper industry. When it is used, the primary application is for the measurements of steam and water flows where the velocity of the fluid is too great to permit the use of an orifice plate.

The principle of flow measurement is the same as for the orifice, i.e., it is a restriction which creates a pressure differential proportional to the square root of the velocity and thus to the square of the rate of flow. The functional difference between the two is capacity; a flow nozzle permits measurement of about 60 percent more flow than an orifice having the same beta ratio and producing the same pressure differential.

The coefficients of discharge for nozzles are higher than for orifices. While this indicates that flow through a nozzle more closely approximates ideal flow as expressed by the formulae, it does not indicate greater accuracy of measurement. The accuracy with which the rate of flow through either primary element can be measured, depends on the accuracy of the coefficient of discharge applied in calculating its inside diameter for specific flow conditions, and, on the manufacturer's ability to duplicate the tested units within close tolerances.

A typical flow nozzle is essentially a short cylinder flared at the inlet end to provide a converging entrance to the throat, or measuring portion. Two main types, with many variations, are commercially available: the long-radius nozzle developed by the ASME [5, 17], and the International Standards Association nozzle type as shown in Figure 7.

The advantages of flow nozzles are: they are more rugged than orifice plates and can be used for high velocity flow measurement; their capacity is much greater than for an orifice of the same diameter under the same flow conditions; head recoveries are slightly better than for orifice plates; produce higher-differentials than Venturi tubes; are easily installed between flanges (see Figure 4); are less susceptible to abrasive wear than the orifice plates.

The basic disadvantages are: low rangeability 3:1 or 4:1; they are more expensive than orifice plates; more difficult to fabricate than orifice plate.

2.4 DALL TUBE

To overcome the limitation of high unrecoverable pressure drop in differential pressure flow elements the Dall tube can be used. The Dall tube (Figure 8) is a primary flow element invented in England by H.E. Dall about 1950. The Dall tube has a specially designed shape so that the fluid can flow smoothly through the tube at a much higher velocity without the turbulence associated with an orifice plate. The tube is approximately two diameters long. The static pressure tap is in a line size section which is followed by a sharp shoulder and a steep conical entrance to a short cylindrical section which has an annular slot, followed by a 15 degree conical discharge throat terminating with a shoulder.

The Dall tube is not used very often in the paper industry because of considerable higher cost than an orifice plate, but it can be used for measurements of gas and water flows when savings in energy justify the initial higher cost. Figure 9. compares pressure loss through several common types of differential producing flow elements, and shows the important savings in pressure loss that are achieved with the Dall tube. At large diameter ratios the Dall tube loses as little as 3 percent of the differential and in general its head loss is only from about 2.5 percent to 7 percent of the measured differential, as compared to the 10 to 15 percent for the same flow in the case of a long cone venturi.

The relationship between flow and differential pressure is similar to that of other head type flow meters. The discharge coefficients are meager and are subject to change with viscosity variations. The manufacturer provides data on the effect of the Reynolds number on a discharge coefficient. Calibration curves are usually provided by the manufacturer and the accuracy of flow measurement depends on the accuracy of these curves.

The practical flow calculation formula used in industry for a Dall tube is the conventional formula for differential pressure producers.

The advantages of a Dall tube are: lowest pressure loss of all the differential producers (except the elbow meter); high differentials; installation is less critical in regard to approach piping than for Venturis, nozzles or orifice plates; less costly than Venturi tubes.

The disadvantages of Dall tubes include: sensitivity to viscosity and density variations below Reynolds number of 500 000, making the tube unsuitable for low flows or viscous fluids; unsuitability for fluids containing suspended solids; low rangeability of 4:1 as for other head type flow elements; very expensive.

2.5 PITOT TUBE

The pitot tube (shown in Figure 12) is well known but has limited applications in the paper industry. It measures velocity at one point in a pipe line with the assumption that the other points in the cross section are known and therefore, the average fluid velocity in the pipe is known. This assumption is highly questionable as velocity profile varies with

Reynolds number, especially if the pipe wall roughness is significant or if there is any flow disturbance such as valve, elbow or other fitting within fifty diameters upstream of the measuring point, it has been determined that pitot inserted into a pipe at approximately one third of the pipe radius from the pipe wall will give an average velocity reading.

One manufacturer [19] uses a "distributed pitot", or Annubar, which is a more accurate method, taking a complete traverse across the pipe in various planes. The Annubar probe senses a total pressure (impact and static pressure) through the four velocity ports and a low pressure through the downstream port. For accurate measurement, the design of the Annubar probe requires that the flow sensing ports be located at specific points in the flow stream. When the Annubar is manufactured, the location of the ports is based on the inside diameter and wall thickness of the pipe. If the Annubar is used in a line with different inside diameter or wall thickness, than for which it was manufactured, the ports will not be properly located, causing an incorrect flow measurement.

The Annubar flow sensor is an averaging head type device. The location of the sensing ports have been mathematically determined using fully developed turbulent flow characteristics. This implies that the flow velocity profile is symmetrical across the pipe in all directions. The averaging functions of the Annubar will not take place if the flow profile is not symmetrical. This will cause a change in the flow coefficient from the published information.

The basic Annubar flow equation is the same as for the differential pressure producers, given in Equation 2.1,

$$Q = C\sqrt{h} \qquad (2.1)\ \text{Rep.}$$

The numerical values of the coefficient C are published [19] and can be substituted into the above equation.

The Annubar, properly installed, provides an average velocity reading with an accuracy of ±2 percent of full scale.

The reasons for limited applications of the Pitot tube in the paper industry are the narrow range of flow rates and the fact that they are easily fouled by any foreign material in the flowing fluid.

2.6 ELBOW METER

The Elbow flowmeter (Figure 13) operates on a momentum principle. Centrifugal force developed by fluid flowing around a 90° elbow in a pipe is used to give an indication of the flowrate. The pressure acting on the inner and outer surfaces of the bend rises on the outside and drops on the inside of the bend. By placing pressure taps on the inner and outer circumferential walls of the bend the pressure differential, which varies with the flow rate, can be obtained. The pressure taps are usually located at 45° around the bend. The advantage of this location is that the flow rate can be measured in either direction. However, on vertical installations with liquid flows, the upward direction is preferred to eliminate entrapment of air or vapours. The elbow meter in this type of installation should have at least 25 diameters of straight downstream piping [6] in each direction, otherwise 10 diameters of straight downstream piping is sufficient for unidirectional flow.

It is also possible to place the pressure taps at the 22.5°, instead of 45°, from the inlet to the bend which has been found to give a more consistent and reliable reading, as well as being less affected by the approach piping configurations.

The elbow meter applications, in the paper industry, are limited to lubricating oil and sometimes cooling water flow measurements. Depending on requirements for the specific application, the accuracy of ±5% can be achieved.

The advantages of the elbow meter are: its low cost; ease of installation; and relatively low permanent pressure drop (which is the same as a standard pipe elbow). The major limitations are: the low differential pressure; high inaccuracy; questionable stability and reliability; and the fact that it is affected by density changes of the fluid..

2.7 DIFFERENTIAL PRESSURE PRIMARY ELEMENTS CALCULATIONS

Flow element calculations are usually made to determine one of the following unknowns:

a) The throat diameter of the primary device
b) The rate of flow

The following equations are used in sizing the primary flow elements (orifice, nozzle, Venturi or Dall tube)[7] :

Liquid flow $$Q_l = D^2 C_{ld} C_o \sqrt{h} \quad , \quad \text{gph} \tag{2.3}$$

Air or Gas flow $$Q_g = D^2 C_g C_{tf} C_{pb} C_{tb} C_o \sqrt{Ph} \quad , \quad \text{scfh} \tag{2.4}$$

Steam flow $$W = D^2 C_s C_o \sqrt{Ph} \quad , \quad \text{lb/hr} \tag{2.5}$$

Where h: manometer range, inches of water
D: inside pipe diameter, inches
P: static pressure, psia
C_{ld}: liquid density factor (from Table 2)
C_o: capacity factor (function of beta ratio and discharge coefficient)
C_g: gas density factor (from Table 3)
C_{tf}: gas flowing - temperature factor

C_{pb}: base pressure factor
C_{tb}: base temperature factor
C_s: steam density factor (from Table 1)

Usually gas flow rates are stated at standard conditions , also called base conditions of pressure and temperature, 14.7 psia and 60°F. If base conditions other than 14.7 psia and 60°F are required, then the following factors should be included in equation (2.4):

$$C_{pb} = \frac{14.7}{P_b} \quad (2.6)$$

where P_b is required base pressure, psi

$$C_{tb} = \frac{460+T}{520} \quad (2.7)$$

where T is required base temperature, °F

$$C_{tf} = \frac{520}{460+T} \quad (2.8)$$

2.8 ILLUSTRATIVE EXAMPLES

The following examples are sample calculations taken from the actual design of a Kraft Pulp Mill project in Canada.

2.8.1 How to find the Throat Diameter of the Primary Device

To find throat diameter:

First: Solve the appropriate equation for C_o.
Second: On Figure 10 read beta ratio opposite the intersection of C_o with the appropriate curve.
Third: Multiply internal diameter of the pipe by beta ratio.

Example A

It is required to find bore diameter of a flow nozzle used in steam flow measurement.

Given flow conditions - Steam: 400 psig, 200°F S.H.

Pipe Size: 12" Schedule 80

Max. Flow: 180 000 lb/h

Normal Flow: 140 000 lb/h

Min. Flow: 10 000 lb/h

D/P cell used: 200 inch water column

Determine: Nozzle size

Solution: Using equation 2.5

$$W = D^2 C_s C_o \sqrt{hP} \text{ , lb/hr}$$

where $W =$ 180 000 lb/hr

$D =$ 11.376" (from piping handbook)

$C_s =$ 0.0425 (from table 1)

$h =$ 200"

$P =$ 400 + 14.7 psia

$$C_o = \frac{180\,000}{(11.376)^2 (0.0425) \sqrt{(200)(414.7)}}$$

$$C_o = 113.64 \ \frac{\text{lb}^{1/2}}{\text{h} \times \text{ft}}$$

From figure 10 for $C_o = 113.64$ $\beta = 0.57$

$d = D\beta = (11.376)(0.57)$

$d = 6.484$ inches

Example B

Determine orifice size and vena contracta tap location in gas flow measurement application.

Given -		
	Flow rate:	48 000 scfh
	Natural gas:	Spec. gravity 0.6
	Pipe size:	6" Schedule 40
	Temperature:	60°F
	Pressure:	5 psig
	Manometer:	10" mercury
	Base temp.:	60°F
	Base press.:	14.7 psia

Solution: Using equation 2.4 $Q_g = D^2 C_g C_{tf} C_{pb} C_{tb} C_o \sqrt{hP}$, scfh

where $Q_g = 48\ 000$ scfh

$h = 10''$

$P = 5 + 14.7 = 19.7$ psia

$D = 6.065''$ (from piping handbook)

$C_g = 1.29$ (from table 3)

$$C_{pb} = \frac{14.7}{14.7} = 1$$

$$C_{tb} = \frac{460+60}{520} = 1$$

$$C_{tf} = \frac{520}{460 + 60} = 1$$

$$Co = \frac{48\ 000}{(1.29)\ (6.065)^2\ (1)\ (1)\ (1) \sqrt{(10)\ (19.7)}} = 72.07 \quad \frac{ft^{3/2}}{h \times lb^{1/2}}$$

From figure 10 for $C_o = 72.07$ $\beta = 0.62$

$d = (6.065)\ (0.62)$

d = 3.760 inches

Pressure tap locations:

Upstream: 1D = 6"

Downstream: From figure 11 for $\beta = 0.62 \longrightarrow 0.53D$

0.53D = (0.53) (6.065) = 3.2 inches

2.8.2 How to find Flow Rate

To find the rate of flow:

First: On figure 10, determine C_o opposite the intersection of beta ratio with appropriate curve.

Second: Use C_o in appropriate equation and solve for flow rate.

Example A

A flow of kerosene is being sent through a 3 inch pipe. What is the flow rate in gallons per hour if the process conditions are as follows:

Fluid: kerosene, Sp. gr. 0.8

Pipe size: 3" Schedule 40

Temperature: 80°F

Pressure: 100 psig

Orifice size: d = 1.565 $\beta = d/D = 1.565/3.068 = 0.51$

Flange taps

Mercury manometer: 50"

Solution:

Usine Equation 2.3

$Q_l = D^2 C_{ld} C_o \sqrt{h}$, gph

where: D = 3.068 (from piping handbook)

h = 50" mercury

Now, for $\beta = 0.51$ from Figure 10 → $C_o = 57.5$

From Table 2, for sp. gr. of 0.8 and flowing temp. 80°F → $C_{ld} = 1.085$

$Q_l = (3.068)^2 (1.085)(57.5)\sqrt{50}$

$\underline{Q_l = 4152 \text{ gph}}$

CHAPTER III

AREA FLOWMETER

Area type flow measurement is so called because conditions are maintained whereby flow rate and area exposed to the flowing fluid are held in direct relationship. As the flow rate is increased, the exposed area is increased. The most frequently used type of area flowmeters is the Rotameter.

3.1 ROTAMETER

A rotameter is a simple, economical and accurate flow measuring instrument. This type of meter (Figure 14) consists of a tapered tube mounted vertically in the fluid stream with its larger diameter at the top. Within the tube is a float which is free to move up and down. Fluid flows through the tube from bottom to top. As it does, the float rises until the area between it and the tube wall is just large enough to pass the amount of flowing fluid. When the applied upward force equals the gravitational force acting on the float, the float attains bouyant equilibrium. Any vertical position of the float thus represents a specific flow rate. The height of the float in the tube can be read off a scale which may be graduated in inches, percent, or directly in flow rate.

In the paper industry, Rotameters are used for measuring of water flows and steam flows mainly in lines below 2 inches diameter and for purging applications. The tube is made of a wide variety of materials, including glass, plastic and metal. Glass tubes provide a simple, direct method of visually reading flow rates. Opaque materials require a secondary element, such as a magnetic follower on the float to provide indication or recording, as shown in Figure 14 (b).

Despite its simplicity, the Rotameter offers an accuracy rivaling other flow meter types. Most industrial grade Rotameters have a standard accuracy of ±2 percent of full scale [20].

Just as important as performance is the ease with which the Rotameter adapts to a piping system. Because the Rotameter is highly insensitive to the effects of turbulence, there is no need for metering runs of straight pipe in the upstream piping.

Rotameters have a very efficient self-cleaning action, which is very convenient for shutdowns on tough applications such as paper pulp and slurries. The mirror smooth inner surface and the fluid stream attaining its highest velocity at the annulus between the float and the tube make the Rotameter highly resistant to the adhesion of foreign particles.

Operation of the Rotameter is governed by the basic flow equation that was used for differential pressure producing devices, that is:

$$Q = C\sqrt{h} \qquad \text{(2.1) Rep.}$$

The difference between Rotameter and differential pressure producing flow elements is obvious. The float position is the output of the rotameter and can be made essentially linear with flow rate by making the tube area vary linearly with the vertical distance. Measuring a varying head, as in differential producers, gives a reading which changes as the square of the flow rate, i.e. nonlinearly.

CHAPTER IV

POSITIVE DISPLACEMENT FLOWMETERS

Positive displacement or quantity flowmeters measure the fluid that passes through the meter, in successive and more or less completely isolated quantities, by alternately filling and emptying the compartments or cavities of fixed volume. This process of filling and emptying is usually translated, by mechanical means, into rotary motion which operates a counter to register the total quantity that passed through the flowmeter.

There are many types of Positive Displacement flowmeters available on the market today, however the two that are most often used in the paper industry for flow measurement of fuel oil and water quantities are the Oval gear and Nutating Disk meters.

4.1 OVAL GEAR FLOWMETER

The oval gear type of positive displacement flowmeters continuously and accurately measures the quantity of oil flow passing through it, by using a slight pressure difference to rotate a pair of precision machined oval-shaped gears. When these two gears, here used as metering elements, are intermeshed (as shown in Figure 15.a) they seal the inlet from the outlet flow, thereby trapping a quantity of oil in the crescent-shaped gap illustrated as dots above gear A. Gear B does not rotate because its torque is cancelled. Gear A, however, receives torque from the pressure difference, and drives gear B as shown in Figure 15 (b). When gear A rotates to the position shown in Figure 15 (c), it loses its torque and gear B obtains a torque. This rotation continues at an almost constant rate without any dead points. Because the amount of clearance between the pair of oval gears and the measuring chamber wall is minimal, the Oval gear flowmeter is almost unaffected by changes in density and viscosity of the fluid to be measured.

Each oval gear flowmeter is individually calibrated for the service specified. The curves in Figure 15 (e) show the variations to be expected when using a single meter for various fluids[21]. The accuracy versus percent of flow depicts variations in performance in relationship to the lightest viscosity shown through the heaviest. The pressure drop versus percent of maximum flow shows the pressure drop of a typical flowmeter when measuring liquids of various viscosities.

The oval gear flowmeter is calibrated in the factory thus eliminating the requirement of an on site calibration prior to metering. Brooks [21] claims an accuracy of ±0.5% over the calibrated flow range, or ±2% full scale, and repeatability better than ±0.25% full scale.

Oval gear flowmeter is very accurate and has good repeatability providing that it is adequately installed and maintained. Because of the gears with close tolerances, the strainer should be installed upstream from the flowmeter for solid particles not to come into contact with the gears. Therefore the moving parts with close tolerances limit the effective use of oval gear flowmeter to clean liquids, and necessitate regular maintenance.

4.2 NUTATING DISK

The nutating disk type is one of the oldest positive displacement meters. Through one side of the disk a vertical diaphragm acts as the division between the meter intake and the meter discharge. At the back of the disc an antifriction bearing roller, supported in the disk, takes the thrust. This roller runs in a slot cut in the inside of the measuring chamber and therefore holds the disk in proper alignment.

Figure 16 (a) shows a cross-section through a nutating disk meter. In this position the disk divides its chamber into an intake compartment under the right-hand side of the disk, looking at the intake, and into a discharge compartment above the disk on the discharge side.

If the discharge side of the meter is open, pressure will drop above the disk. The higher pressure of the incoming water under the back side of the disk will lift its right-hand side and move it to the position 180° opposite. In doing this, the space above the disk has now become the intake compartment and the space below the disk the discharge. Excess intake pressure above the disk pushes it down and in the next half cycle of operation will cause it to again take the position shown in Figure 16 (a). From this it is seen that the difference in pressure on the intake and discharge of the meter causes the disc to wobble or nutate. In so doing water is trapped, first on one side then on the other side of the disk and is forced out by the difference in pressure between the intake and discharge side of the meter. If only a small amount of water is taken from the discharge side the disk moves slowly, and if a large amount of water flows the disk moves faster. When the discharge is closed the disk comes to a rest.

The nutating disk flowmeters are used, in the paper industry, only for measurements of water flows in small quantities.

The accuracy of nutating disk liquid meters is normally expressed as a percentage variation over the full recommended flow range (not as a percent of full flow value) [22] and ±1% can be attained. The performance curve, Figure 16 (b) can be shifted vertically in relation to the 100 percent line in order to place the curve at mid point of actual flow range. This is accomplished by changing the ratio between calibration gears.

CHAPTER V

VOLUMETRIC FLOWMETERS - VELOCITY PRINCIPLE

A volumetric flowmeter, based on velocity principle, can be defined as a device in which the reaction of the primary flow element is proportional to the fluid flowing through it. It might have a primary element containing some device, such as a wheel in a turbine, kept in continual rotation by the fluid stream. The velocity type meter does not break the stream into nominally discrete segments. By means of a secondary element the meter measures the total distance of travel of the fluid past the primary device. Knowing the cross-section of flow, the distance can be converted to units of total volume that went through.

5.1 TURBINE METER

The turbine meter, used in the paper industry on gas flow measurements, is a velocity measuring device. The gas enters the meter (Figure 17) and is constricted, by a flow deflector, into a smaller annular passage [23]. This annular passage increases the velocity of the gas. In passing through the meter the gas imparts an angular velocity to the rotor proportional to the linear velocity of the gas in the meter. As the gas velocity is directly proportional to the volume flow rate it follows that the speed of rotation of the rotor is also directly proportional to the volume flow rate. Therefore, by accurate measurement of the rotor speed the volume flow rate can be obtained.

In most designs the angular velocity of the turbine meter rotor is sensed through the meter housing by a magnetic pick-up. Permanently installed magnets turning with the rotor produce a magnetic field which passes through a coil. As each magnet passes the coil, it produces a separate and distinct voltage pulse. The frequency of these pulses is linearly proportional to the angular velocity of the rotor and thus to the flow rate. Each pulse also is incrementally proportional to a small unit of volume. The amplitude of the pulses from the pick-up coil varies in rough proportion to rotor velocity but is not considered in the measurement process. Flow rate and total flow data are transmitted by frequency and by counting the pulses. Since the gas passing through the rotor represents a discrete unit of volume, each electrical pulse also represents a discrete unit of volume. It is this positive ratio of electrical pulses proportional to units of volume that gives the turbine flowmeter its high accuracy of ± 0.5 percent of reading [4, 24, 25].

The capacity of the turbine meter is determined by factors such as gas velocity, rotor speed, and pressure drop. The gas velocity becomes a controlling factor due to the aerodynamic characteristics of the rotor blades and also the need to avoid the possibility of obtaining sonic velocity within the meter.

The bearings used in the turbine meter have a given life expectancy under a given load and at a specific speed. As the speed of the rotor is varied the speed of the bearings varies. Although the turbine meter is capable of turning at more than three times its maximum speed without immediate damage, its life can be substantially reduced if this speed is maintained for longer periods of time.

The variable thrust load on the rotor shaft and bearings is intensified with rising pressure loss resulting from an increase in line pressure or specific gravity. Therefore, holding the pressure loss to a minimum increases the life span of the meter.

The minimum capacity of the turbine meter is limited by meter accuracy. This minimum flow accuracy is determined by gas density, bearing friction and the aerodynamic characteristics of the rotor.

The rangeability is the most important characteristic of the turbine flowmeter. It is defined as the ratio of the maximum meter capacity to the minimum capacity for a stated set of operating conditions and during which the meter retains its specified accuracy. Foxboro [26] claims rangeability of up to 20 to 1, while Daniel [27] claims as high as 196 to 1 on their 8 and 12 inches gas turbine meters.

Since the turbine meter is a velocity meter it is particularly sensitive to any spiraling that may be caused by upstream piping configuration. The streamline character of the diffusor section ahead of the rotor has a tendency to minimize this effect, depending on the particular design of the manufacturer. Being therefore impossible to give specific rules for all types of turbine meters, it is suggested that the manufacturer's recommendation be followed in specifying the piping system requirements.

Foxboro [26] provides a characteristic curve (shown in Figure 18) with each turbine flowmeter. This curve, of pulses per gallon versus gallons per minute, results from a minimum of ten calibration points taken through the linear range of the flowmeter. From the calibration data, an average K factor is assigned. The equation used to calculate this factor is

$$K = \frac{60\ f}{Q_t} \tag{5.1}$$

where K is in pulses per gallon, f is in cycles per second, and Q_t is the flow in gallons per minute. As can be seen from Figure 18, turbine flowmeters have an output signal linear with flow over a specified range.

Disadvantages of turbine meter are: anything that affects the propeller causes an error such as poor flow profile or foreign material sticking on it and slight off-center alignment or angular offset from pipe axis; obstructs flow in pipe; requires periodic maintenance.

5.2 MAGNETIC FLOWMETER

At the present time, the magnetic flowmeter is one of the most important flow measuring devices used in the paper industry. It has become one of the most efficient means to measure flows of slurries of a dirty or viscous nature. Particularly, it has become the standard device for the accurate measurements of fibrous pulp and stock and other fluids which are difficult to measure in bleaching, recausticizing, stock preparation, washing, evaporators, and digesters areas.

5.2.1 Principle of operation

Operation of the magnetic flowmeter is based on the discovery by Faraday [28] that currents are induced in a conductor which is in motion through a magnetic field. Although the principle is simple and was established so long ago, 1831, it was not until the 1950's that a truly commercial flowmeter became available.

Figure 19 illustrates the basic operating principle of a magnetic flowmeter. The metering fluid is the conductor with a transverse length D equivalent to the inside diameter of the flowmeter. The fluid conductor moves with a velocity V directed along the axis of the flowmeter through a magnetic field B. A voltage Es is induced within this fluid which is mutually perpendicular to the direction of the fluid velocity and the flux linkages of the magnetic field; i.e., in the axial direction of the meter electrodes. This electrode voltage is proportional to the volumetric flow rate. Mathematically, this may be expressed as

$$Es = \frac{BDV}{C_m} \tag{5.2.1}$$

where Es is the voltage generated in a conductor, B is the magnetic field strength, D is the flowmeter inside diameter, V is the fluid velocity, and C_m is the dimensionless constant.

The fluid velocity

$$V = \frac{Q}{A} = \frac{4Q}{\pi D^2} \tag{5.2.2}$$

Substituted into equation (5.2.1) gives

$$Es = \frac{BD}{C_m}\frac{4Q}{\pi D^2} \qquad (5.2.3)$$

from where

$$Q = \frac{C_m D}{4}\left(\frac{Es}{B}\right) \qquad (5.2.4)$$

Since the magnetic flux density B is proportional to a reference voltage Er, and since C_m, and D are constants, we can say that

$$Q = C_n \frac{Es}{Er} \qquad (5.2.5)$$

where C_n is another dimensionless constant. This equation (5.2.5) shows that the volumetric flow rate is directly proportional to the induced voltage as measured by the magnetic flowmeter.

5.2.2 Operating Characteristics

Generally, any fluid which will conduct an electric current can be measured by the magnetic flowmeter. An absolute minimum conductivity of 0.1 micromhos per centimeter is necessary.

Above the minimum fluid conductivity requirements, the meter is unaffected by conductivity changes, but the effect of the fluid operating temperature upon the fluid conductivity should be considered. Insofar as most fluids exhibit a positive temperature coefficient of conductivity,it is possible for certain marginal fluids to become sufficiently nonconductive at lower temperatures so as to hamper accurate metering, whereas, the same fluid at higher or normal temperatures may be metered with optimum results. The possibility of an adverse temperature conductivity characteristic should be investigated before attempting to meter such a fluid.

Other fluid variables such as viscosity, density and fluid pressure have no direct influence on metering accuracy. Fluid density has no effect on volumetric flow rate since only the area of the meter pipe and liquid velocity are required to determine the rate of flow.

Since the magnetic flowmeter senses velocity as analogous to volumetric flow rate it is always absolutely essential that the meter be completely filled at all times for accurate results. Where there is a possibility of operation with a partially filled horizontal pipeline, it is recommended that the magnetic flowmeter be installed in a vertical section of that pipe such that fluid flow moves upward.

The magnetic flowmeter will measure the total amount of material passing in the fluid stream. The meter will not, for instance, differentiate between the amount of liquid and the amount of entrained gases, or, in the case of a slurry, it will not differentiate the amount of liquid from solids. If the liquid to mixant ratio is of importance, then separate measurements of the concentration of the desired medium must be made and appropriate correction factors must be applied to the magnetic flowmeter output. The Table 4, illustrates various metering and fluid conditions which may be encountered and provides a qualitative analysis of the effects of these conditions upon the meter signal output [29].

Nomographs in Figure 20, give approximate magnetic flowmeter capacities based on fluid velocities of from 1 to 30 feet per second [29]. Minimum full scale flow velocity is 1 foot per second, giving a volumetric flowrate of about 0.32 gallons per minute using a meter with 0.1 inch bore.

5.2.3 Applications and properties

Certain fluids tend to coat the inside of the meter (liner and electrodes) with electrically insulating deposits. Any appreciable coating on the electrodes results in loss of signal and inaccuracy. In such cases, a meter with some sort of electrode cleaning should be specified. Electrical, mechanical, and ultrasonic methods are available and the ultrasonic one is the most popular one with excellent results.

A wide variety of liners and electrodes are available from all manufacturers. Electrode materials such as 316 stainless steel, Hastelloy C, Tantalum, Titanium, Carpenter 20, and Platinum are available. There is no reason why any stable metal could not be used, however, before selection, reference to suitable corrosion tables or manufacturer's data should be made.

Lining materials such as Teflon, Kynar, Polyurethane, Neoprene, and Natural Rubber are common and available in most sized flowmeters.

Correct sizing for a particular type magnetic flowmeter is just as important as choosing the proper liner and electrodes. For non-abrasive slurries with suspended solids, for example, the velocity of the flowing fluid should be 7 feet per second or greater at normal flow rates. At lower velocities, the solids tend to settle out and adhere to the pipe wall and electrodes. This has two effects: first, as the solids build up, the inside diameter of the pipe decreases causing a span error; secondly, the electrodes become coated and depending on the conductivity of the coating, an error may develop.

Reducing the meter size to achieve higher fluid velocities will result in enough mixing action to maintain a uniform slurry throughout the pipe, and help eliminate the above problems.

Magnetic flowmeters have many advantages including: high accuracy of ±0.5 percent of full scale; no obstruction to the fluid flow; pressure loss is no greater than through an equivalent length of pipe; output is linear with respect to flowrate; measures flow in either direction; not sensitive to flow profile or Reynolds number; and not sensitive to pressure, temperature, density or viscosity. In addition, the ultrasonic cleaning has virtually eliminated electrode fouling.

5.2.4 Illustrative Example

Note: This is an actual design specification performed for a Pulp Mill Project.

In the Recausticizing plant flow of green liquor to Slaker should be controlled. Magnetic flowmeter will be used as the primary device. The following are process conditions:

Fluid:	Green Liquor
Temperature:	200°F
Pressure:	40 psig
Max. flow:	900 USgpm
Flow velocity:	11 ft/sec.

It is required to determine the magnetic flowmeter size.

Solution:

Using the Magnetic Flowmeter Capacity Nomograph of Figure 20, Appendix I, for flow rate of 900 gpm and flow velocity of 11 fps the closest size is 6 inches.

Now, according to manufacturer's recommendations, all the components of the magnetic flowmeter can be specified using suppliers catalogue. In the above case the specification can be as follows:

Tube size:	6"
Tube material:	304SS
Electrode material:	Hastelloy C
Tube lining material:	Teflon

5.3 ULTRASONIC FLOWMETERS

5.3.1 Basic Principles

The use of sound waves for measurement signal generation has been known since the 1930's but it has only been applied practically to flow measurement since the early 1960's. Many technical papers have devoted considerable amount of attention to the ultrasonic flowmeters [30, 31, 32, 33, 34, 35].

The ultrasonic flowmeters can be broadly divided into two groups. Those which use some variant on the method of determining transit time across a flow path, often in two directions, with resultant processing that gives a flow dependent output that is substantially independent of the absolute sonic velocity; and those which detect flow by other means such as Doppler, beam deflection, correlation techniques or ultrasonic detection of vortices.

In this report I will consider only two flowmeters, one based on the difference in frequencies, and the other based on the Doppler effect. They are applied in the pulp and paper industry to measurements of Wash and Waste Water flows, Pulp Stock, Coating Colours, and Pigment slurries flows.

5.3.2 The Frequency difference flowmeter

In the simplest arrangement two acoustic transducers are mounted in diametric opposition across the pipe with the axial line of the transducers inclined to the direction of flow by an angle Θ, as shown in Figure 21.

Flow is measured by transmitting a high frequency acoustic signal across the pipe, through the fluid, alternately in both the upstream and downstream direction. In no flow conditions the acoustic pulses will have a time of transit across the pipe which is determined by the distance between the transducers, L, and the velocity of sound in the fluid Vs.

$$t = \frac{L}{Vs} \tag{5.3.2.1}$$

As the fluid velocity, V, increases, the velocity component at the angle of. transmission, Vθ, aids the acoustic pulse when in the direction of flow and deters it in the other direction. The travel times downstream, t_d, and upstream, t_u, can be expressed as:

$$t_d = \frac{L}{Vs + V\theta} \tag{5.3.2.2}$$

and

$$t_u = \frac{L}{Vs - V\theta} \tag{5.3.2.3}$$

In the principal form of the frequency difference method, the received pulse in each path is used to trigger another pulse signal, thus generating a train of pulses in each path whose period equals the acoustic travel time. These repeated frequencies can be expressed as:

$$f_d = \frac{1}{t_d} = \frac{Vs + V\theta}{L} \tag{5,3.2.4}$$

$$f_u = \frac{1}{t_u} = \frac{Vs - V\theta}{L} \tag{5.3.2.5}$$

Now, if the two frequencies are subtracted, then the frequency difference is:

$$\Delta f = f_d - f_u = \frac{2\,V\theta}{L} \tag{5.3.2.6}$$

Since the average fluid velocity is:

$$V = \frac{V_\theta}{\cos\Theta} \qquad (5.3.2.7)$$

then the frequency difference can be expressed as:

$$\Delta f = \frac{2\,V\cos\Theta}{L} \qquad (5.3.2.8)$$

From this equation it follows that, since cosΘ and L are both constants, once a pipe's dimensions are established the frequency difference, Δf, is proportional to the average fluid velocity, V. Therefore, the frequency difference, Δf, is not affected by any process parameter other than fluid velocity.

The volume flow rate is now found by multiplying the fluid velocity, V, with the cross sectional area of the pipe.

Because the frequency difference is proportional to velocity, V, with no dependence on velocity of sound in fluid, as shown in equation (5.3.2.6), and because Δf is an easily measured quantity, this method has considerable appeal. One disadvantage is that in practical cases the frequency difference is small, and the long counting interval needed for a given resolution results in slow response time.

5.3.3 The Doppler effect flowmeter

The Doppler effect, the basis of the Doppler flow measuring method, is the apparent change in the frequency of sound due to relative motion between source and observer. This change in frequency is directly proportional to the relative velocity of a moving source and a stationary detector.

The measurement of fluid flow in a pipe is achieved by using the Doppler frequency shift of ultrasonic signal reflected from discontinuities in the flowing fluid. The discontinuities can be suspended solids, air bubbles or interfaces caused by turbulent eddies in the flowing stream.

The sensor is mounted on the outside of the pipe and an ultrasonic beam from a piezoelectric crystal is transmitted, through the pipe, into the fluid at an angle to the flow. Reflected signals are received by a second piezoelectric crystal in the same sensor and the transmitted and reflected signals are compared in an electronic circuit. The frequency shift is proportional to flow velocity.

Figure 22 shows the method of operation of the Doppler flowmeter. By the electrical excitation of a piezoelectric crystal (transmitter) the ultrasonic beam, f_1, is generated and transmitted at an angle Θ to the flowing fluid. Particles in the fluid reflect the sound back to the receiver, with a Doppler shifted frequency, f_2, which can be expressed as

$$f_2 = f_1 \pm 2\,V\cos\Theta\frac{f_1}{Vs} \qquad (5.3.3.1)$$

The ± sign denotes the flow direction. The velocity of the fluid is obtained from the above equation, giving

$$V = (f_2 - f_1)\frac{Vs}{f_1}2\cos\Theta \qquad (5.3.3.2)$$

Providing that frequency f_1, angle Θ, and velocity of sound in fluid remain constant

$$V = C_1\,(f_2 - f_1) \qquad (5.3.3.3)$$

which shows that the frequency shift is proportional to the flow velocity.

The Doppler flowmeters are being used successfully in the paper industry for the measurement of water flows and as a flowswitch on pump protection detecting if there is a blockage or if the pump is running dry.

A flow range of up to 0 to 15 meters per second is obtainable, with a repeatability of ±1% of full scale [36]. On small pipe sizes, below 2 inches, a linearity of ±2 percent is achievable above a pipe Reynolds number of 100 000. Below that Reynolds number, flowmeter becomes nonlinear [32] . The accuracy between 5 and 10 percent can be achieved. While the low accuracy is a serious shortcoming, the Doppler flowmeter is the only other meter to perform with any success in the area of the two-phase fluids measurement besides the magnetic flowmeter.

The main disadvantage of the Doppler flowmeters is that they require sufficient suspended particles or bubbles for reflection of the sound. This means that they will not operate on clean liquids. In addition, they are not usually satisfactory on slurry flows with velocity below 0.5 ft per second.

5.4 VORTEX FLOWMETERS

5.4.1 Operating principles

Operation of the vortex-shedding flowmeters is based on a natural phenomenon that takes place when a fluid stream flows around a blunt object. The flow being unable to follow the object on its downstream side, because of a viscosity related effect, separates from the surface of the object creating a continuous series of vortices downstream. The vortices are shed from one side of the object (vortex shedder), and then from the other side in a regular train, as shown in Figure 23.

When the vortex shedder, shaped in a different manner by different companies [37, 38, 39] , is placed in a pipeline, it forms a primary flow element that generates pulse signals over wide flow ranges at a frequency proportional to the volumetric flow rate. The number of pulses per gallon or cubic foot is determined only by the dimensions of the flow element and the velocity (or pipe diameter). It does not depend on fluid gravity, viscosity, pressure or temperature.

5.4.2 Design Characteristics

The Foxboro [37] vortex generating element was designed for detecting vortex shedding inside the wake where the dominant vortex frequency exists. Viewed from the inlet, the vortex generating element looks as a simple rectangular plate. The cross section of the vortex generator appears as a flat plate with a centered tail, as shown in Figure 24. Vortex shedding generates an alternating differential pressure across the sensor located within the tail. The sensor, a piezoelectric differential pressure detector, is completely sealed from the process fluid and located on the vortex generating element. Research by Foxboro resulted in a vortex element shape that is essentially a flat plate. However, the geometry of the end of the tail type section is considered a significant factor in the control of stable vortex shedding. In addition because the tail is behind the flat plate, the plate also acts as a shield to prevent damage to the sensor from the impacting of any solid particles carried by the flow stream.

The Neptune/Eastech V/C-3000 Vortex Cell Flowmeters shape of the vortex generator is a modified delta with its base facing upstream (as shown in Figure 26). The ratio of frequency to flowrate is governed by the ratio of base width to pipe diameter. Because of the vortex shedding alternately from either side of the body, the flow pattern is periodically assymmetrical causing the stagnation streamline to oscillate about the centerline of the vortex generator. The sensors which detect the vortex shedding frequency can thus be located on the side face where the signal to noise ratio is much higher than in the highly turbulent wake. Sensing is therefore of flow rather than pressure. The sensor (Figure 25) is a nickel disc enclosed in a chamber over the flow element. Openings on either side of the flow element lead into the chamber, and as the vortices alternately pass the openings, there is an up and down flow generated in the chamber which causes the disc to oscillate along the axis of the flow element. The motion of the disc is detected by a magnetic pick-up which provides an input to the preamplifier in the form of a series of voltage pulses at a frequency directly proportional to the flow rate.

The Yokogawa [38] uses a piezoelectric sensor element that is embedded inside the vortex shedding body, located outside the pipeline. A special glass is used to provide a secure, long life bond between the sensing element and the vortex shedder, and to hermetically seal the element. When vortices are shedding, the shedder is stressed alternately in opposite directions. The direction of the stress alternates as the vortex shedding frequency. The piezoelectric element converts the stress into an electric pulse signal. The sensor is suitable for use over a wide range of temperatures. It is simple, robust and maintenance free. There are no moving parts and no sensor ports exposed to process fluid.

The Yokogawa vortex shedder is similar in shape as one designed by Neptune/Eastech.

5.4.3 Applications and properties

There are numerous applications in the paper industry where the Vortex flowmeters can be used for accurate flow rate measurement of condensate and steam. Until the present time, the orifice plate has been used almost exclusively for these applications. Because of the very wide rangeability of the Vortex flowmeter on steam, minimum 10 to 1, one flowmeter can be used for the entire flow range expected. The accuracy, from all manufacturers, is about ±1 percent of actual flow rate. For example, steam flow to pulp digesters varies from full flow conditions at the beginning to very low flows as cooking progresses. Only the Vortex flowmeter with the rangeability of 10 to 1 or greater can be expected to accurately measure flow through the entire range.

The Vortex flowmeter is superior to the orifice plate in terms of rangeability, accuracy, independent from variations in fluid properties, linearity, and calibration stability. In comparison with the turbine type meter, it offers the outstanding feature of no moving critical parts, hence no wear problems and no damage due to over speeding, as well as independence of calibration factor from variations in fluid properties such as viscosity.

All types of vortex flowmeters require about 20 diameters of straight piping upstream of the meter and an obstruction. Downstream 3 to 5 diameters is usually acceptable.

CHAPTER VI

HEAD AREA FLOWMETERS

6.1. Introduction

The flow of liquids in open channels and conduits, or in channels and conduits in which there is a free surface, is usually measured by head area flowmeters. In these flowmeters, the area of the stream is a function of head. In the pulp and paper industry the head area flowmeters are used to measure flow of water, chemical wastes and sewage sludge in the water treatment and effluent treatment areas.

Two of the most commonly used types, of head area primary flow elements are Weirs and Parshall flumes. They both produce a contraction of the flow stream which causes the upstream level to back up to a greater or lesser degree. Flow rate is determined by measuring the upstream level and converting it into rate of flow terms. These devices measure volumetric flow regardless of the fluid density.

6.2 WEIRS

The weir is one of the simplest and most accurate devices for measuring the flow in open channels. It consists of a partition or bulkhead of timber, concrete, sheet metal or of other material, having in its top edge an opening of fixed dimensions through which a stream can flow, Figure 27.

Of the various types of weirs, the three most commonly used are the rectangular, Cipolletti, and V-notch, as illustrated in Figure 28.

The type and size of weir selected will depend upon the total flow which it is necessary to measure, the head available, on local conditions with reference to space, accessibility, etc. In general, V-notch or rectangular weirs are preferred.

When the maximum and minimum flow rates are known, the size and type of weir can be selected from a graph obtained from the manufacturer, as shown in Figure 29a [40].

V-notch weirs are especially recommended for metering of low flows, less than 1 cubic foot per second, and are suitable for measuring slowly changing flows up to 10 cubic feet per second. The flow rate is a 5/2 power function of head. The selection of various notch angles, 30°, 60° or 90°, is made by considering the maximum flow rate and the maximum available head.

The Rectangular weir is capable of high capacity metering and is simple and inexpensive to construct. To assure complete contraction of the nappe, the side and bottom clearance dimensions of the notch must equal or exceed those shown in Figure 28. This shape is not as good as the Cipolletti weir because the flow is contracted on the side as it goes over the weir. This effectively narrows the width of the weir and limits the accuracy.

The Cipolletti weir, Figure 28, is similar to the rectangular weir except for sloping sides, 1 horizontal to 4 vertical, of the notch. This design has the advantage of a simplified discharge formula which is more convenient to work with than that of the rectangular weir. The flow rate varies as the 3/2 power of head.

In order to obtain more accurate measurements, the following requirements should be observed when designing a weir installation:

- The approach channel, upstream from the weir plate, should be straight, unobstructed and with minimum length 20 times the maximum head on the weir.

- Velocity of approach should not exceed 0.3 feet per second.

- Weirs should have a side clearance of at least 2 times the maximum head, between edge of weir notch and side of upstream approach channel, as shown on Figure 28.

- Maximum head, preferably, should not exceed 2 feet, and the minimum head should not be less than 0.2 feet for rectangular or Cipolletti weirs.

- Weir should be designed to use the maximum head practical, up to 2 feet, since metering accuracy improves as the head increases.

6.3 PARSHALL FLUMES

Although weirs are easy to construct and convenient to use, they are not always suitable. The required loss of head for free flow measurement is often not available on flat grades. A Parshall flume will prove a more accurate and dependable device for these applications.

The Parshall flume consists of a converging upstream section, a downward sloping throat and an upward sloping, diverging downstream section, as shown in Figure 30. The discharge through the flume is considered free flow when the elevation of the water surface downstream from the throat is not high enough to cause the flow to be retarded by the effect of the back-water. However, when the surface elevation of the water downstream is sufficiently high to affect the rate of flow, the critical point of submergence has been reached and the condition of submerged flow exists. At first the flow is only slightly reduced, but as the degree of the submergence increases, a greater reduction in the discharge results.

The rate of flow is determined by the head of the water in the stilling well, Ha, when the discharge is free flow, and in both the Ha and Hb wells for submerged flows.

Knowing the maximum and minimum flows that will be handled through the flume, select a value for throat section width, L, from Figure 29 (b), in the range of head, H, desired.

The Figure 29 (b) gives the width, L, of the throat section from 3 inches to 50 feet, and the head, H, to be expected at minimum and maximum flow values. Flow values are listed as million gallons per day, gallons per minute or cubic feet per second.

6.4 Relationship between Discharge and Head

The various equations relating discharge and head for standard open channel devices and the methods of obtaining these expressions are derived in many excellent technical publications[6, 41, 42, 43]. It would serve little purpose to repeat them here. It may, however, be of interest to notice that the expressions for Parshall flume and weirs, though derived in entirely different ways, are all of similar form to the expressionns for closed conduit differential pressure producing devices.

To illustrate this, let us refer to Figure 28. The length of the crest of the rectangular weir is denoted by l and the depth of flow over the crest by H_t, which is equal to Hmax + 2H. Denoting the rate of flow in volume units per unit time under head H_t by Q, then the velocity, V, of flow a distance H below the surface will be equal to

$$V = \sqrt{2gH} \tag{6.4.1}$$

If the thickness of an element at this depth is dH, the discharge through this element will be

$$dQ = l \cdot \sqrt{2gH} \quad dH$$

The total discharge is

$$Q = l \cdot \sqrt{2\,g} \int_0^{H_t} H^{1/2} \, dH$$

$$Q = 2/3 \cdot l \cdot \sqrt{2g} \; H^{3/2} \tag{6.4.2}$$

In the same manner, for the V-notch weir with the angle of V-notch , the length of the crest is

$$l = 2\,(H_t - H)\,\tan\frac{\alpha}{2}$$

so that

$$dQ = 2\tan\frac{\alpha}{2}\sqrt{2\,g\,H}\,(H_t - H)\,dH$$

and the total discharge,

$$Q = 2\tan\frac{\alpha}{2}\sqrt{2g}\int_0^{H_t}(H_t - H)\,H^{1/2}\,dH$$

$$\therefore\ Q = 8/15\,\tan\frac{\alpha}{2}\,\sqrt{2g}\,H^{5/2} \qquad (6.4.3)$$

A Parshall flume is compared with a rectangular weir in much the same manner as a venturi is with an orifice plate. It is designed to reduce loss. Its flow is related to measured head in a way similar to that of the rectangular weir, although the power term is not exactly 3/2 as derived in equation 6.4.2. In fact, the power term is slightly different with each size flume, ranging between 1.52 and 1.6, [6].

The actual power term used for triangular weirs is 2.44 for the 60° angle and 2.475 for the 90° angle, instead of 5/2 as derived in the equation 6.4.3 above.

6.5 Application Recommendation

The recommended type of sewer measuring device, in the pulp and paper industry, is the Parshall flume. The Parshall flume is used rather than the various types of weirs because it is silt-free, gives a better accuracy and has a much lower head loss.

Tables 5 and 6 list the various dimensions for Foxboro [40] Parshall flumes, for widths L from 3 inches to 50 feet.

6.6 Illustrative Example

Note: The following example is taken from an actual design performed for a Pulp Mill Project.

In the Bleach plant, sewer flow is to be recorded. It is required to specify the flume to be used, for the following process conditions:

Max. flow:	4400 USgpm (10 cfs)
Channel width:	5 feet
Liquid surface:	1 foot above the bed

Note: The degree of submergence for the moderate sized flume, may approach 70% before the free-flow rate of discharge is affected. The usual practice is to set the flume operate at 60% [40].

Solution:

The first step is to select the flume size.

From Table 5, Appendix II, for 10 Sec.-ft flow the 2-foot flume is selected to start with.

From Figure 29(b), Appendix I, it is found that for a discharge of 4400 gpm through a 2-foot flume, the upper head, H_a is approximately 1.17 feet.

The degree of submergence (which is the ratio of the lower head, H_b as measured in the throat, to the upper head, H_a as measured in the conveying section) will be used as criterion in establishing the elevation of the crest of the structure.

$$\frac{H_b}{H_a} = \frac{H_b}{1.17} = 60\%$$

$$H_b = 0.702 \text{ ft}$$

Since the water surface elevation right below the flume will remain constant after the flume is installed, and since the standing wave in the throat of the flume will be the same as the fluid surface in elevation at 60% submergence, the crest elevation may be determined from the fluid surface elevation before flume installation. That is it would be 0.702 ft below the downstream fluid surface and since the depth of the fluid is 1 foot, it would be placed at 0.3 ft above the bed of the channel. This setting gives a flow of 4400 gpm for a submergence of 60%. The overall head loss is approximately 0.5 ft.

Now, if a 1.5 ft flume had been selected, the H_a gauge reading would be 1.49 ft and at 60% submergence the H_b would be 0.9 ft. For this case the elevation of the crest would be 0.1 ft below the bed of the channel and the loss of head would be approximately 0.8 ft.

From the above, it can be concluded that as the size of the flume increases, the crest elevation for a common discharge and degree of submergence becomes higher and the head loss becomes smaller.

CHAPTER VII

SELECTION OF PRIMARY FLOW ELEMENTS

Determining which type of primary flow elements, described in this report, should be used at a particular installation depends on fluid characteristics as well as the flowmeter's performance.

For a preliminary selection of flowmeters, the flowchart in Figure 31 can be used. Where steam and gas measurements are involved, the number of flowmeters becomes considerably reduced to a few most often used primary devices. However, when measuring flow of liquids more than one characteristic is taken into consideration.

For a clean conductive liquid one would opt for the use of a magnetic flowmeter or an orifice plate, or any additional choice that would perform as well as the two mentioned. In the case of a clean but nonconductive liquid, one would never use a magnetic flowmeter since a conductivity is necesssary. The alternative would be either a turbine flowmeter or again an orifice plate.

Regarding a liquid with suspended solid particles, a magnetic flowmeter, ultrasonic flowmeter or Venturi tube is most often used.

Once the preliminary selection has been made Table 8 can be consulted to choose a flowmeter for the particular application area. Regarding pulp stock or slurry applications, a magnetic flowmeter is most appropriate since it does not obstruct the flow and since it is not sensitive to pressure, temperature, density or viscosity. For vapours containing liquids, a Vortex shedding flowmeter would be the most advantageous one since experience shows that no performance degradation occurs after considerable in-line use which is not the case with an orifice plate.

Table 7 shows additional important factors in flowmeter selection, such as: range of maximum flow, maximum pressures and temperatures, permanent pressure loss, accuracy, rangeability, installation requirements, viscosity and the relative cost.

A supplier's most common designation for accuracy is the percentage of flow rate. Rangeability is also important. That is, the accuracy of the flowmeter selected should be relatively linear over the range of flows being measured.

Pressure loss, although not related to accuracy, is another determinant. In the industry it is becoming more important to reduce permanent pressure losses caused by pressure drop across the flowmeter. When pressure loss increases, a larger pump is needed to maintain the desired flow rate. This in turn, increases the cost of transmitting fluids from one point to another.

When considering relative cost of different flowmeters for a particular application not only the initial price should be considered but also the cost of installation, operating cost and maintenance. In addition this cost comparison should take into account the effects of accuracy, rangeability and permanent pressure loss on the process efficiency and final product quality.

Therefore, as can be seen from the above, the application and selection of a flowmeter is always a compromise between performance and accuracy versus costs.

CHAPTER VIII

CONCLUSIONS

The principal objective of this study was to review and evaluate methods and devices used, at the present time, for measurements of flow in the pulp and paper industry. It has been shown that all these methods and devices are a result of the various factors and practical requirements for each installation. To aid in the flowmeter selection, Figure 31 and Table 7 are included which itemize the various factors previously discussed that are considered very important. As already mentioned some flowmeters do have properties that make them especiallly suitable for a particular application and yet inadequate for other tasks. Table 8 shows application areas for the flowmeters reviewed. In addition, Table 9 gives manufacturing sources for the most important flow measuring devices available on the Canadian market and used in the paper industry today.

New techniques (such as magnetic, ultrasonic and vortex flowmeters) that were introduced as flow measuring devices in the pulp and paper industry have been discussed in great detail because, in my opinion, they will be the devices most widely used in the future. Even though some are still in the development stages, they have already shown excellent results.

In this energy-conscious age, the future for these new flow measuring devices is especially bright because of their ability to measure flow using minimal amounts of energy while giving accurate readings. Magnetic, ultrasonic and vortex flowmeters create either a very low (vortex flowmeters) or non-existing pressure loss (magnetic and ultrasonic flowmeters). Because of the absence of moving parts there is no mechanical failure and therefore minimum maintenance costs.

Another advantage to these relatively new flow measuring devices is the fact that each one of them may be hooked up to a microprocessor. A microprocessor-based system can take into account many variables (such as temperature, pressure and density) and handle complex calculations easily and quickly. Design tendencies in all new devices used for flow measurement will be for use with microprocessors.

The use of Figures and Tables contained in the Appendices in the solution of practical problems was illustrated with several paper industry application examples in Chapters II, V, and VI.

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Appendix I

FIGURES

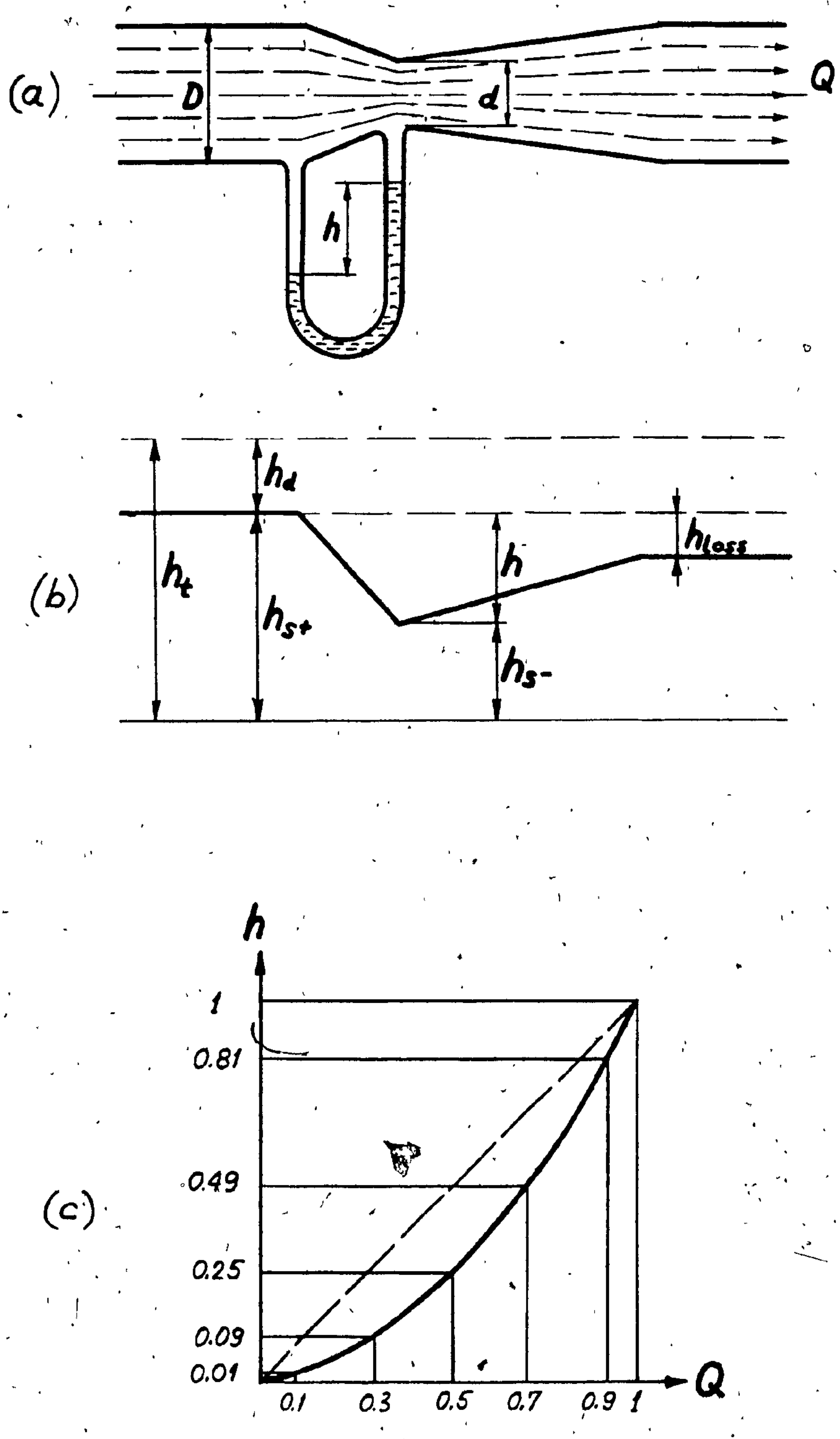


Figure 1. PRESSURE DISTRIBUTION ACROSS A RESTRICTION IN A PIPE

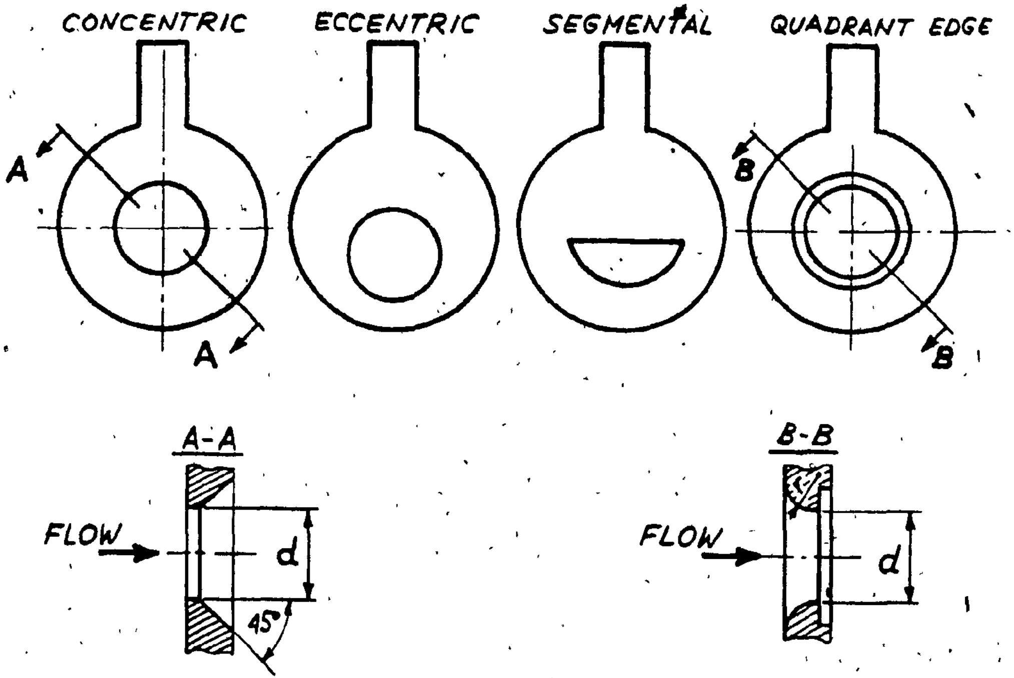


Figure 2. TYPES OF ORIFICE PLATES

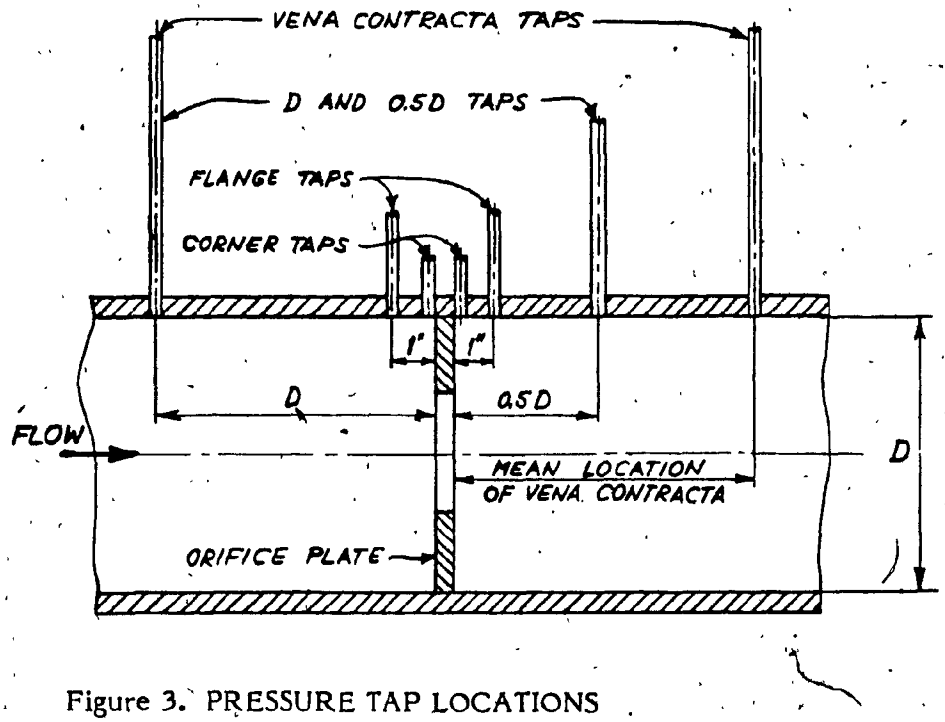
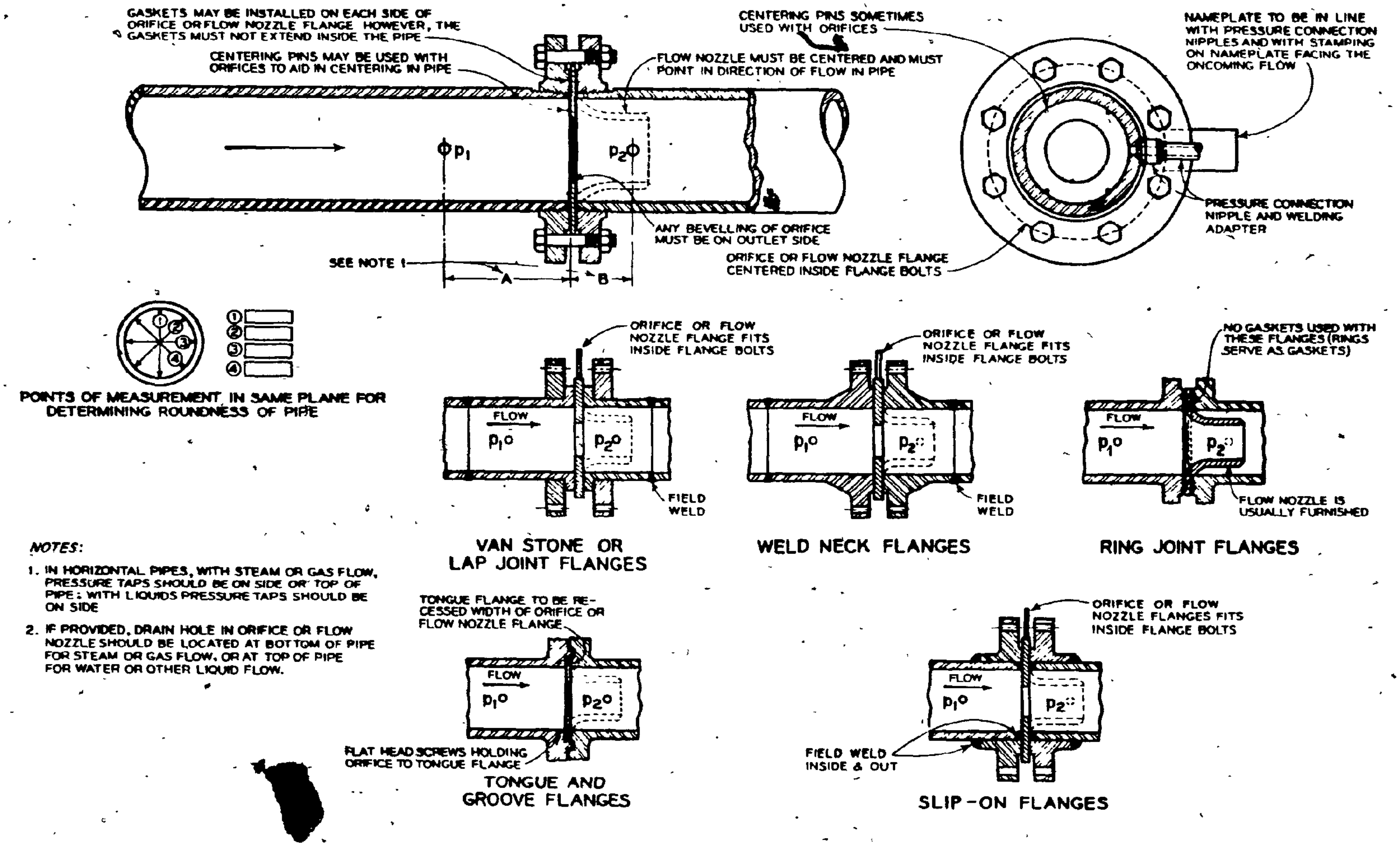


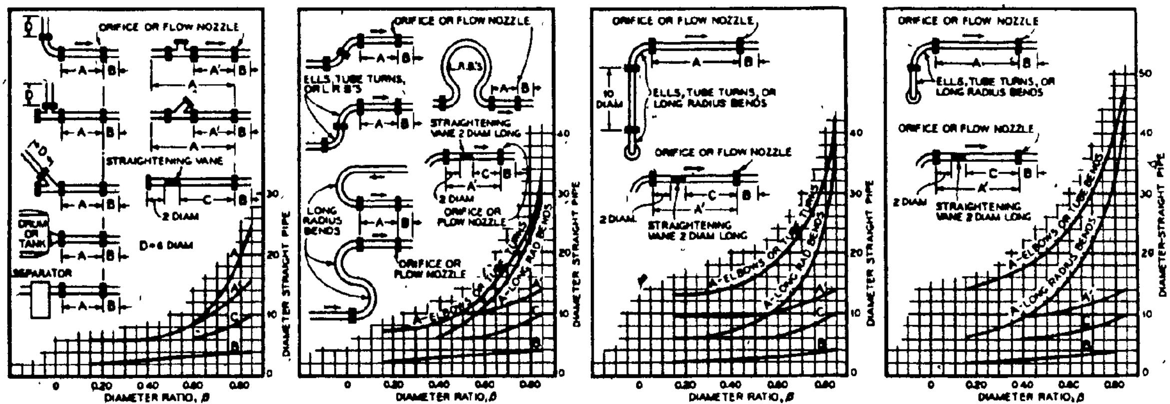
Figure 3. PRESSURE TAP LOCATIONS



NOTES:

1. IN HORIZONTAL PIPES, WITH STEAM OR GAS FLOW, PRESSURE TAPS SHOULD BE ON SIDE OR TOP OF PIPE; WITH LIQUIDS PRESSURE TAPS SHOULD BE ON SIDE
2. IF PROVIDED, DRAIN HOLE IN ORIFICE OR FLOW NOZZLE SHOULD BE LOCATED AT BOTTOM OF PIPE FOR STEAM OR GAS FLOW, OR AT TOP OF PIPE FOR WATER OR OTHER LIQUID FLOW.

Figure 4. ORIFICE OR FLOW NOZZLE INSTALLATION [5]

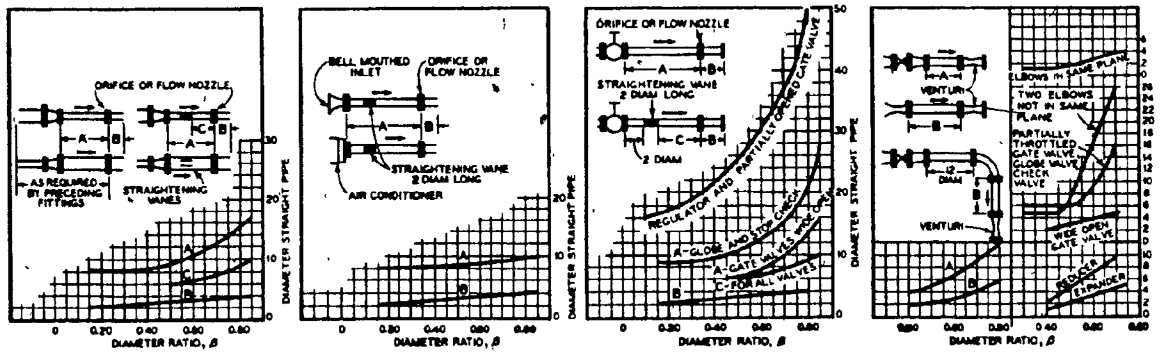


(A) FOR ORIFICES AND FLOW NOZZLES ALL FITTINGS IN SAME PLANE

(B) FOR ORIFICES AND FLOW NOZZLES ALL FITTINGS IN SAME PLANE

(C) FOR ORIFICES AND FLOW NOZZLES FITTINGS IN DIFFERENT PLANES

(D) FOR ORIFICES AND FLOW NOZZLES FITTINGS IN DIFFERENT PLANES



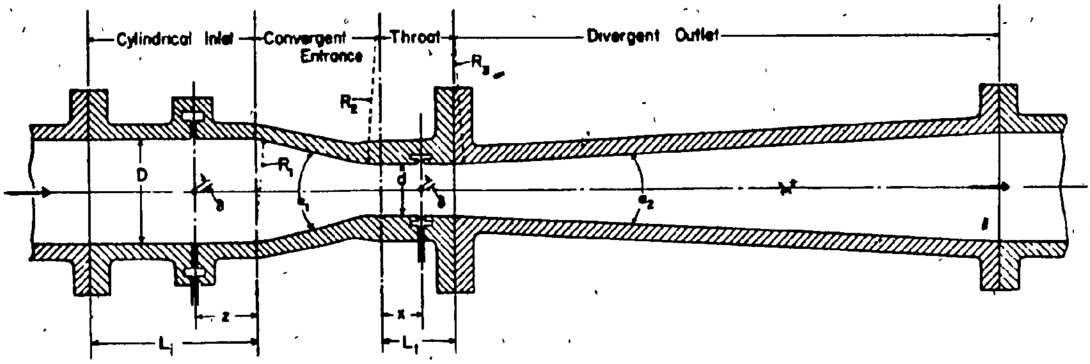
(E) FOR ORIFICES AND FLOW NOZZLES WITH REDUCERS AND EXPANDERS

(F) FOR ORIFICES AND FLOW NOZZLES IN ATMOSPHERIC INTAKE

(G) VALVES AND REGULATORS

(H) FOR VENTURI TUBES

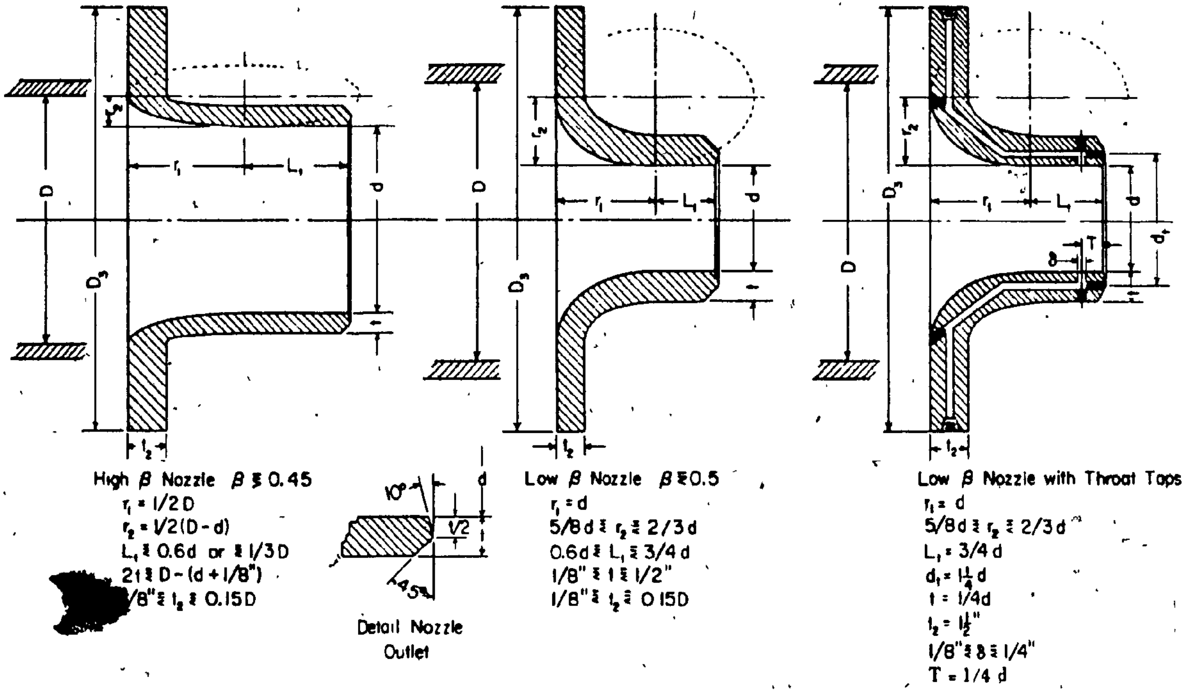
Figure 5. PIPING REQUIREMENTS FOR PRIMARY ELEMENTS INSTALLATION [5]



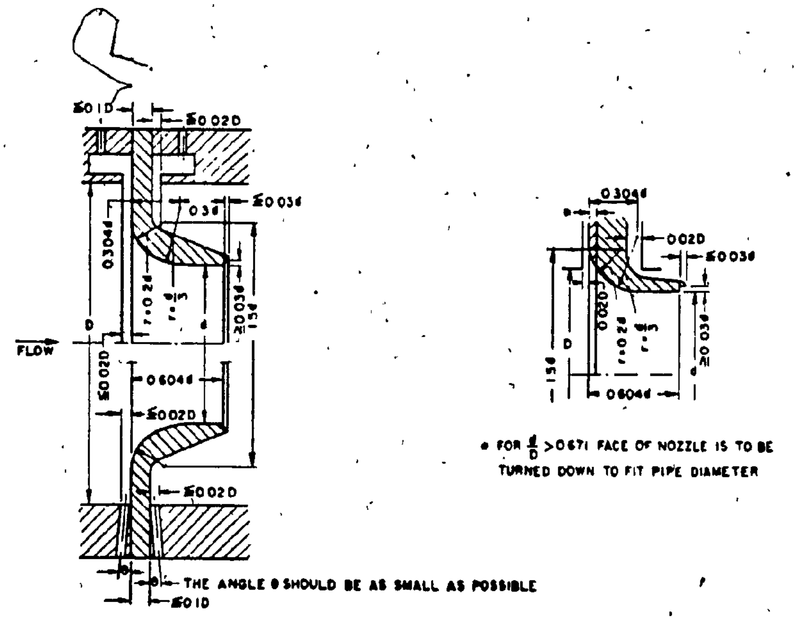
$L_i \lesseqgtr D$ or $L_i \lesseqgtr (D/4 + 10'')$
$z \lesseqgtr D/2 \pm D/4$ for $4'' \lesseqgtr D \lesseqgtr 6''$
$D/4 \lesseqgtr z \lesseqgtr D/2$ for $6'' \lesseqgtr D \lesseqgtr 32''$
$L_1 \lesseqgtr d/3$
$y \lesseqgtr d/6$
$5/32'' \lesseqgtr \delta \lesseqgtr 25/64''$ and
$\delta < 0.1\,D$ or $0.13\,d$

$R_1 = 1.375\,D \pm 20\%$
$R_2 = 3.625\,d \pm 0.125\,d$
$5d \lesseqgtr R_3 \lesseqgtr 15d$
$e_1 = 21° \pm 1°$
$7° \lesseqgtr e_2 \lesseqgtr 8°$ or $7° \lesseqgtr e \lesseqgtr 15°$

Figure 6. VENTURI TUBE [5]



a. The ASME Long-Radius Flow Nozzle



b. The ISA Flow Nozzles

Figure 7. FLOW NOZZLES [5]

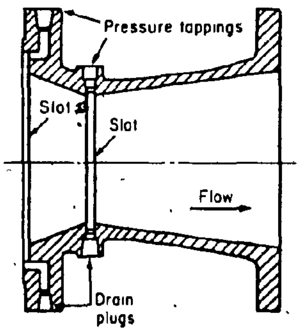


Figure 8. DALL TUBE [18]

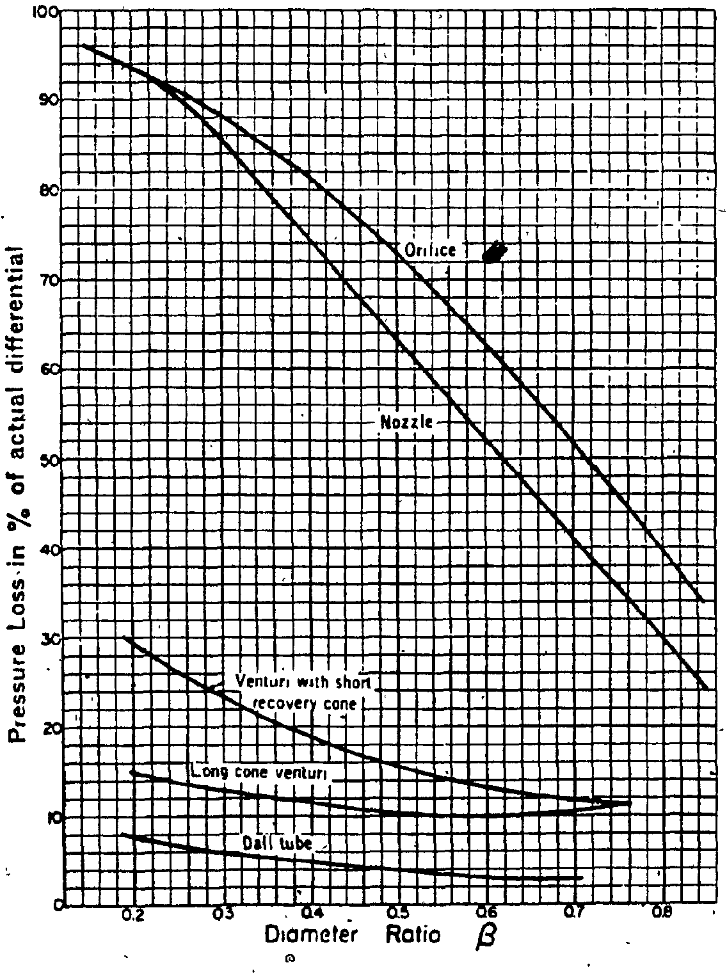


Figure 9. OVERALL PRESSURE LOSS THROUGH PRIMARY ELEMENTS [5]

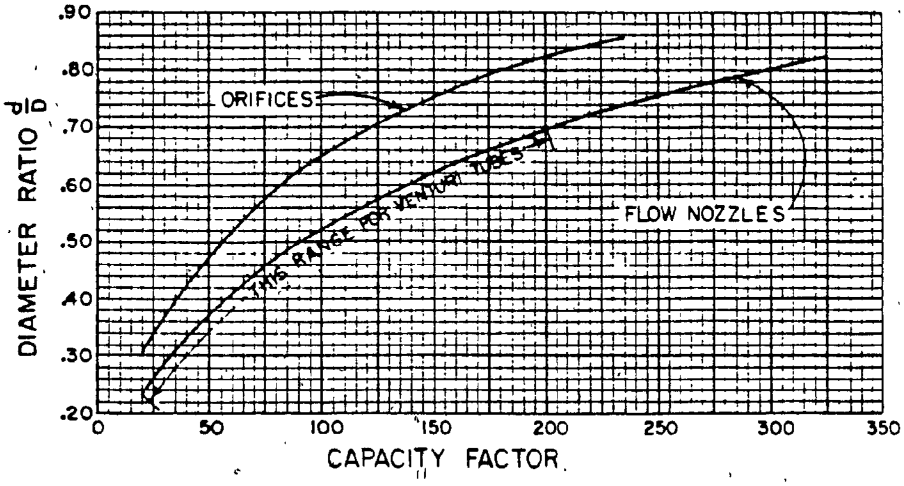


Figure 10. RELATIONSHIP BE CAPACITY FACTOR, C_e , AND BETA RATIO [15]

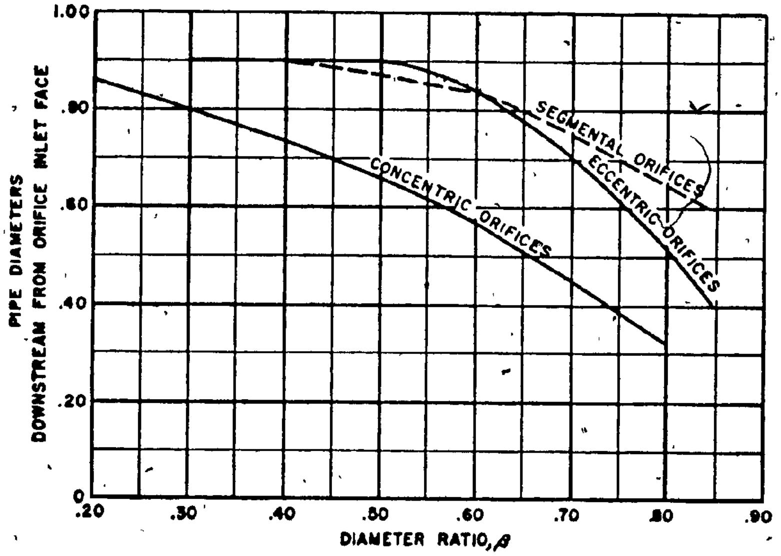
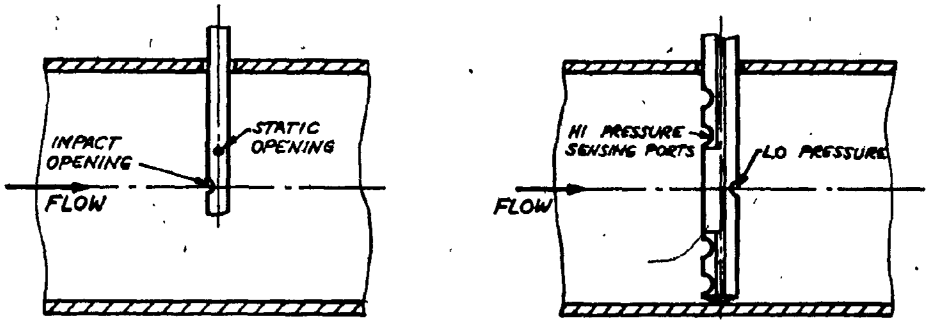


Figure 11. LOCATION OF VENA CONTRACTA [6]



TYPICAL PITOT

DISTRIBUTED PITOT (ANNUBAR) [19]

Figure 12. PITOT TUBE

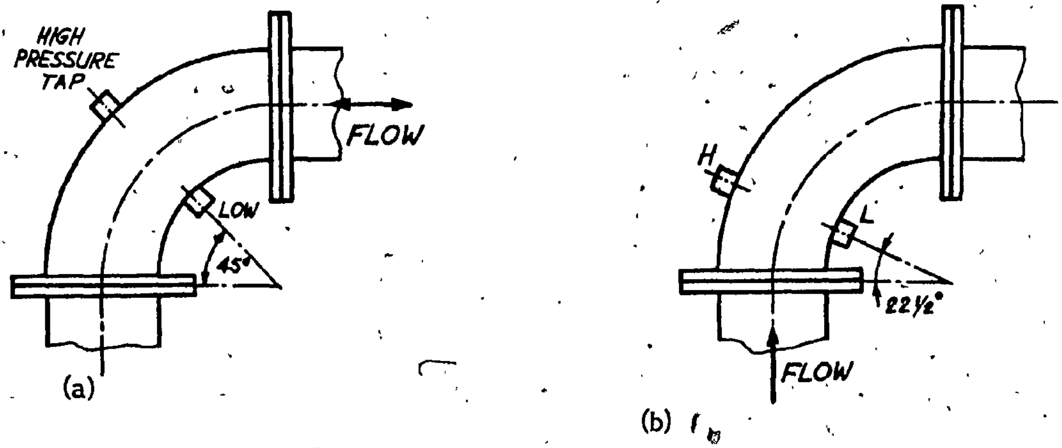
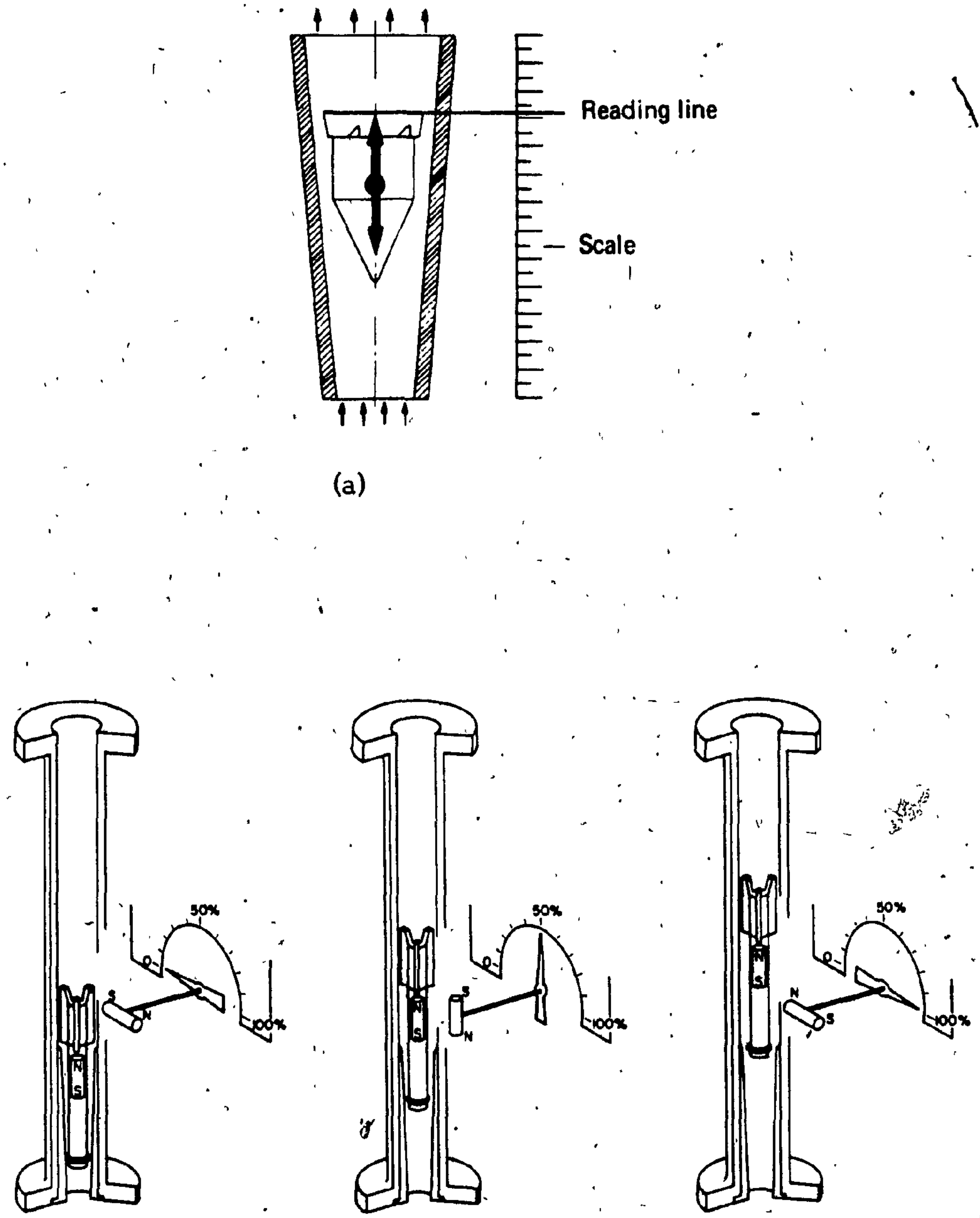


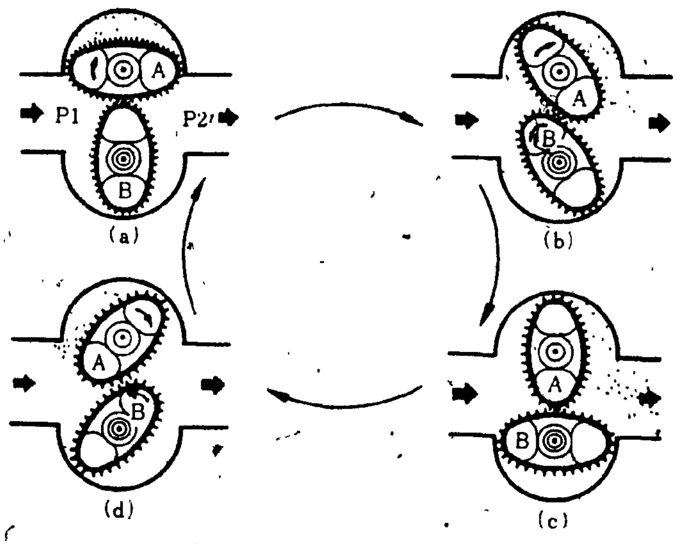
Figure 13. ELBOW METER



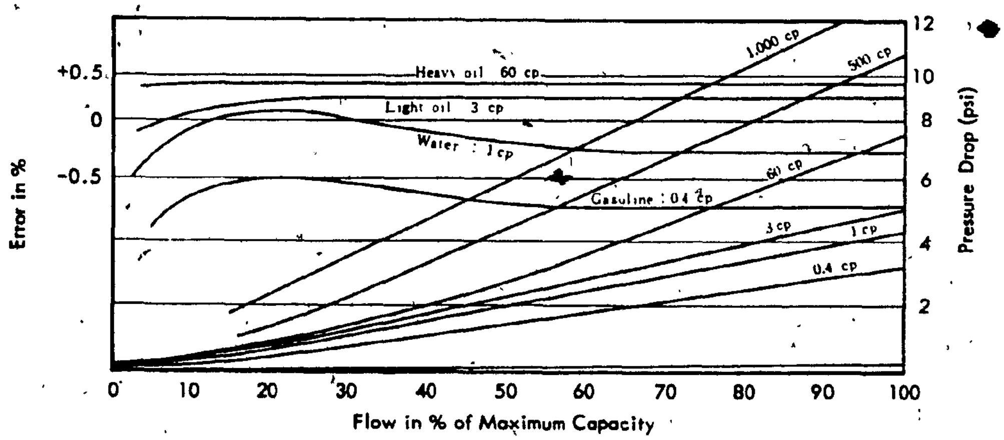
(a)

(b)

Figure 14. ROTAMETER PRINCIPLE OF OPERATION [20]



PRINCIPLE OF OPERATION



ACCURACY AND PRESSURE DROP

Figure 15. OVAL GEAR FLOWMETER [21]

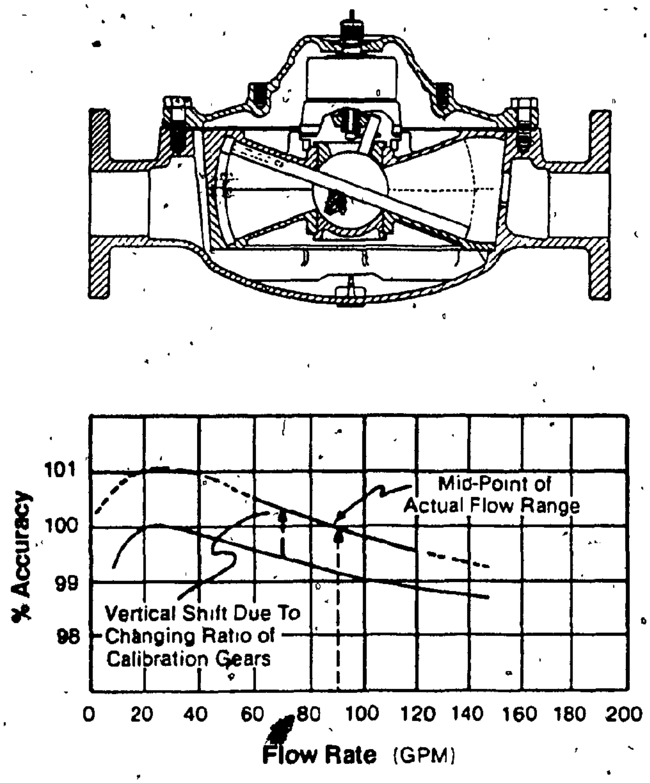


Figure 16. NUTATING DISK FLOWMETER [22]

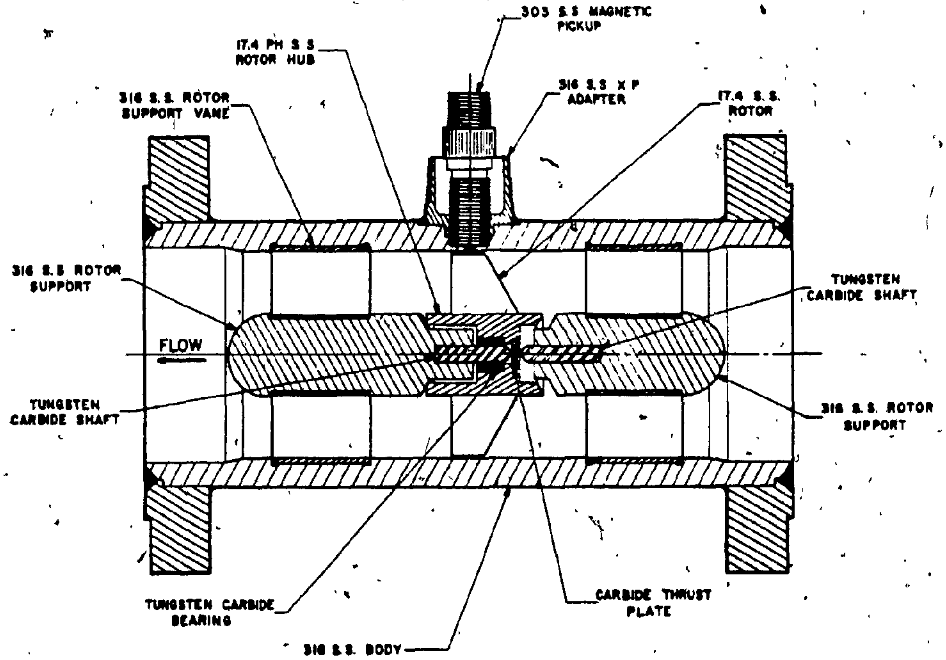


Figure 17. TURBINE FLOWMETER [23]

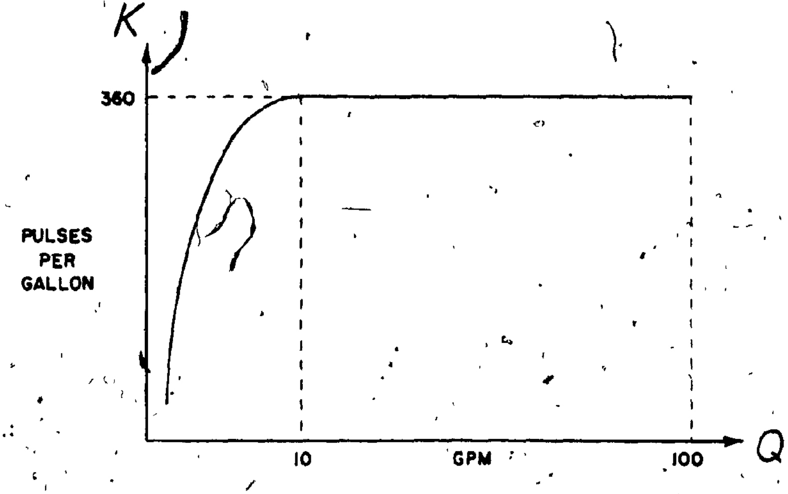


Figure 18. LINEARITY OF A TURBINE METER [26]

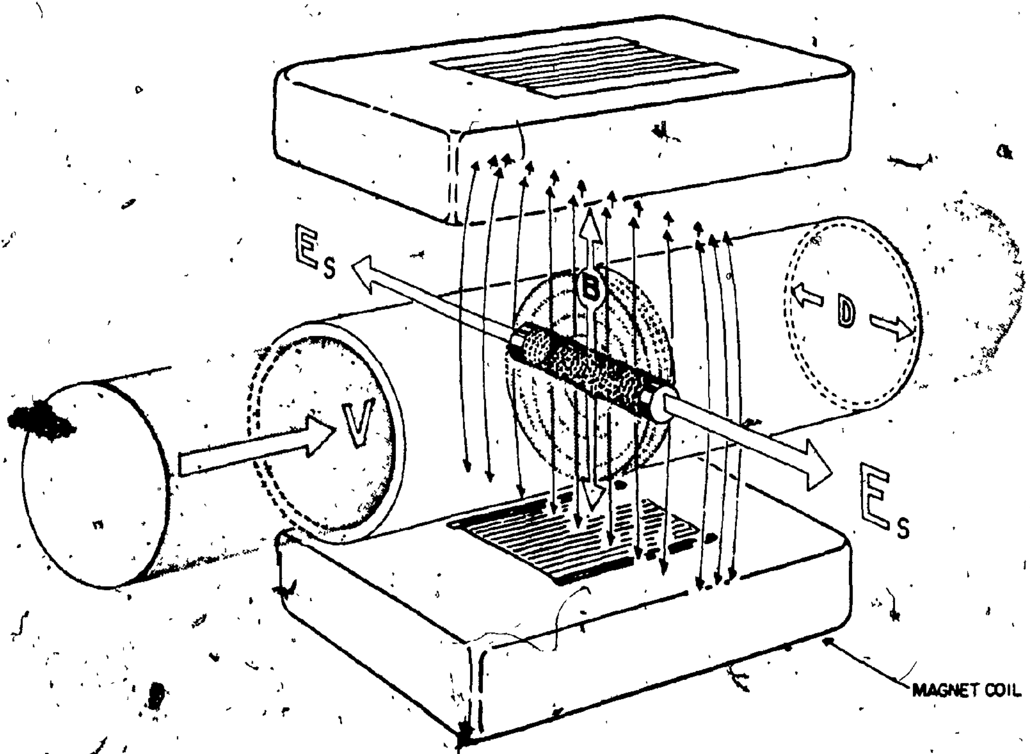


Figure 19. MAGNETIC FLOWMETER OPERATING PRINCIPLE [29]

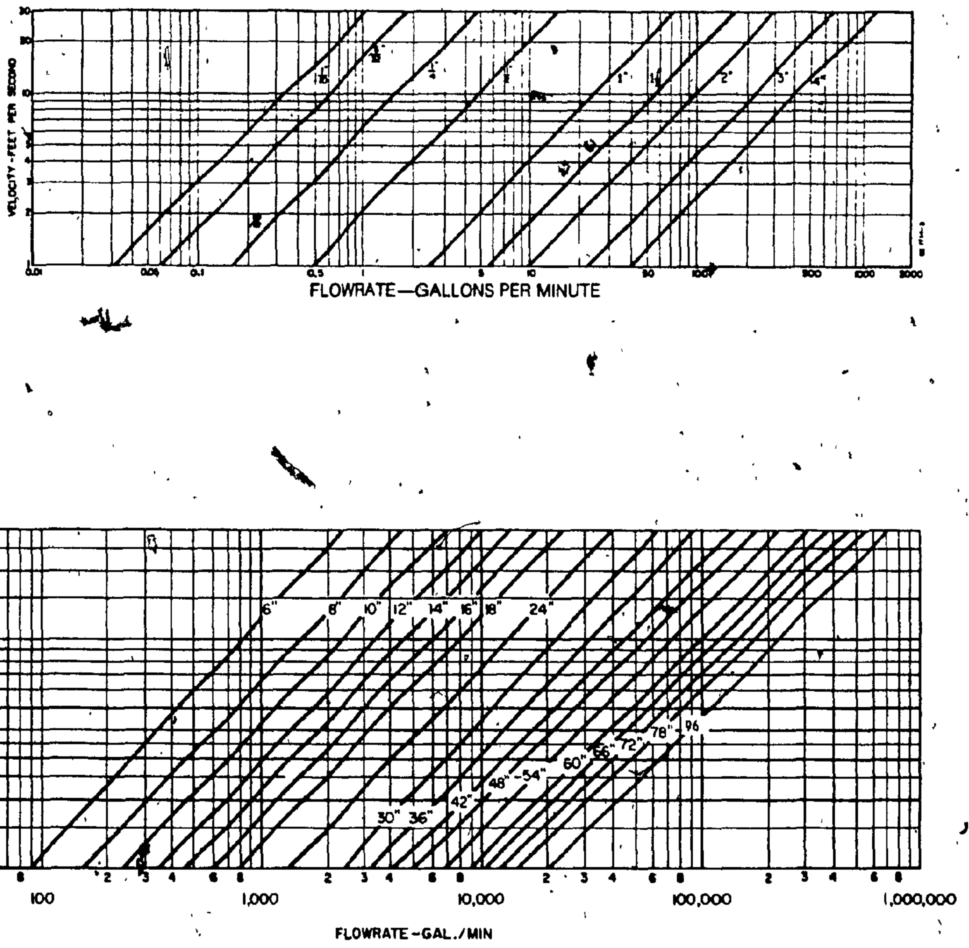


Figure 20. MAGNETIC FLOWMETER CAPACITY NOMOGRAPHS [29]

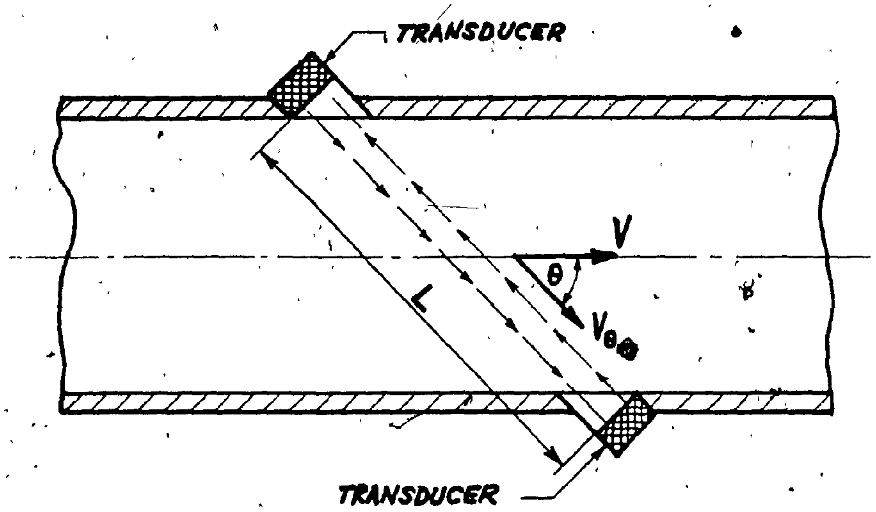


Figure 21. OPERATING PRINCIPLE OF FREQUENCY DIFFERENCE FLOWMETER

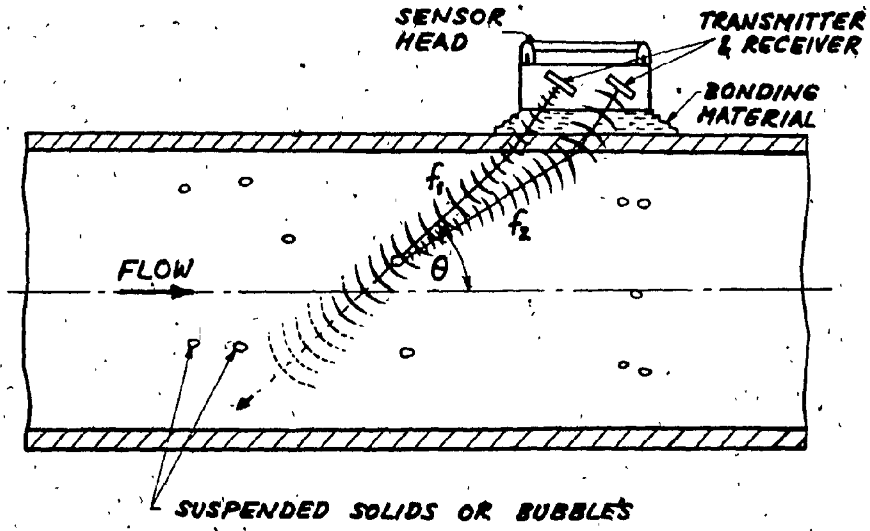


Figure 22. SCHEMATIC DIAGRAM OF DOPPLER FLOWMETER

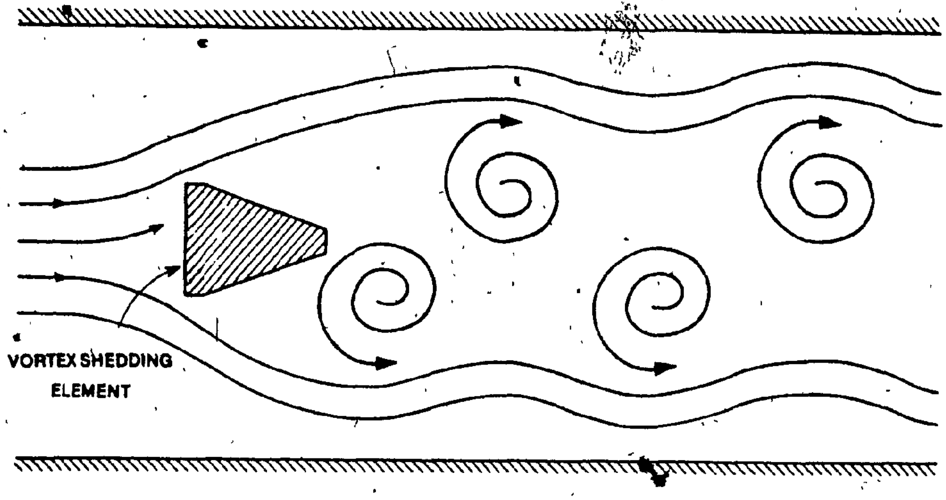


Figure 23. SCHEMATIC OF VORTEX FORMATION

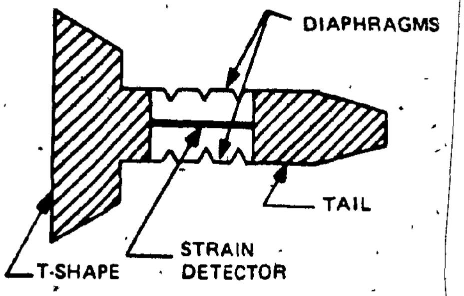


Figure 24. VORTEX ELEMENT AND SENSOR [37]

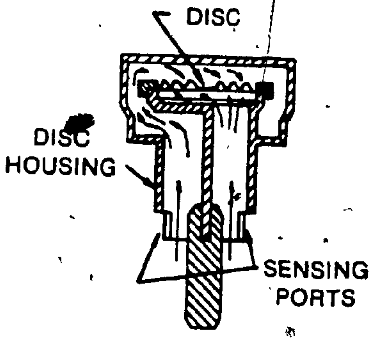


Figure 25. VORTEX SENSOR [39]

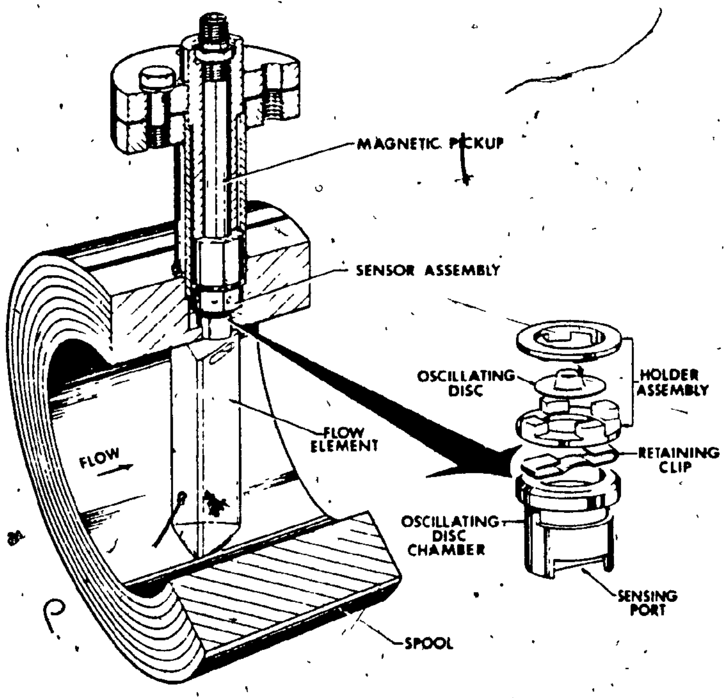


Figure 26. VORTEX FLOWMETER [39]

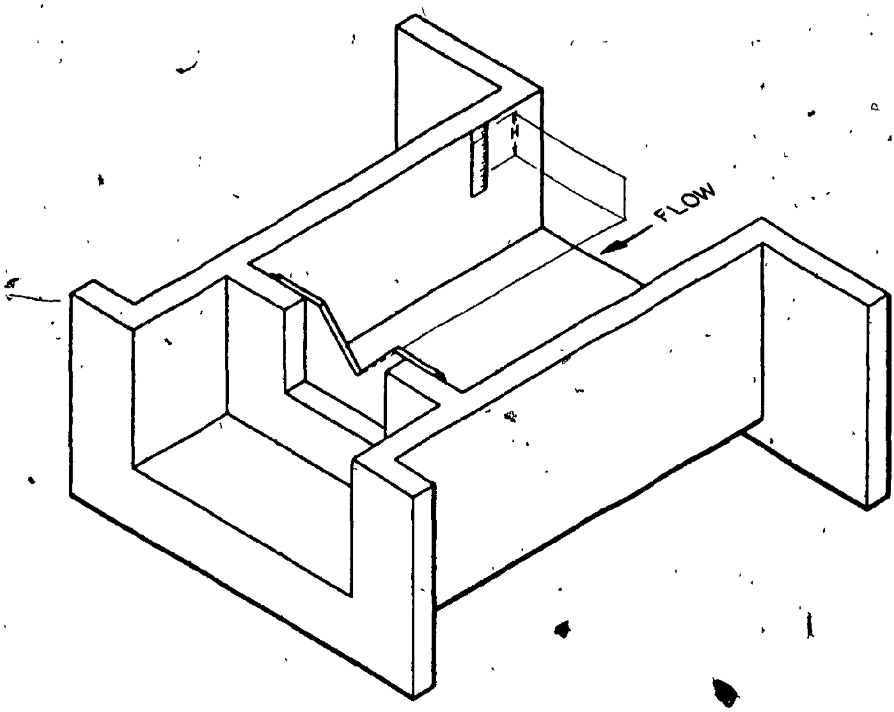
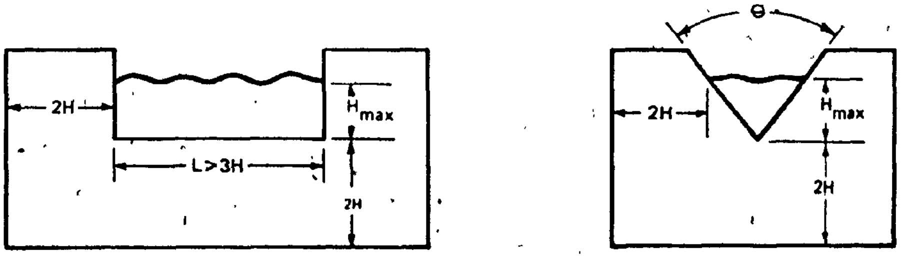
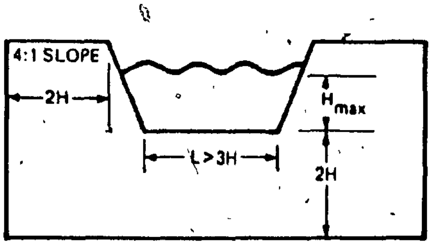


Figure 27. WEIR BOX WITH V-NOTCH WEIR



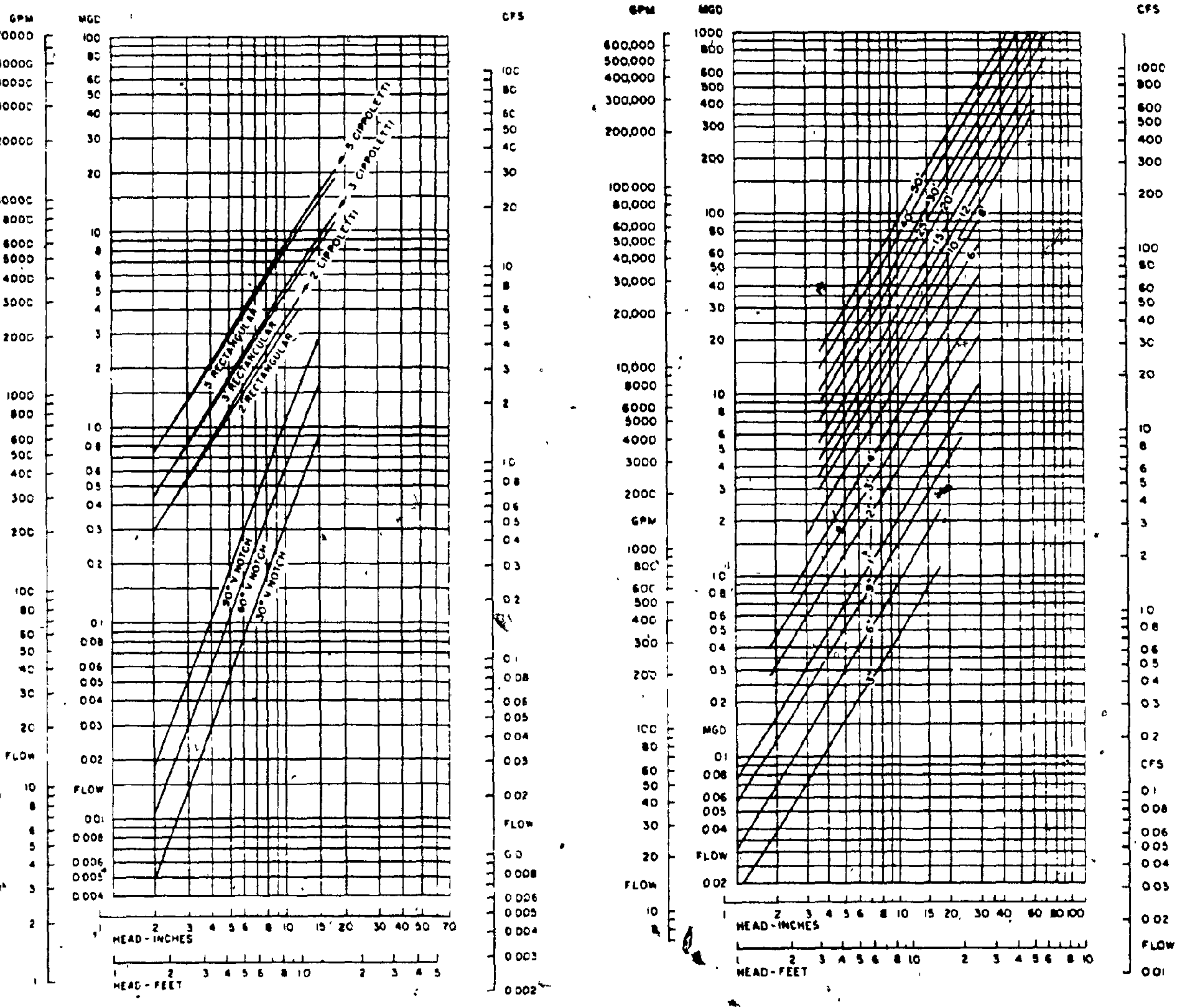
RECTANGULAR WEIR

TRIANGULAR OR
V-NOTCH WEIR



CIPOLLETTI WEIR

Figure 28. COMMON WEIR TYPES



(a)

(b)

Figure 29. GRAPHS FOR SELECTION OF TYPE AND SIZE OF (a) WEIR, (b) PARSHALL FLUME [40]

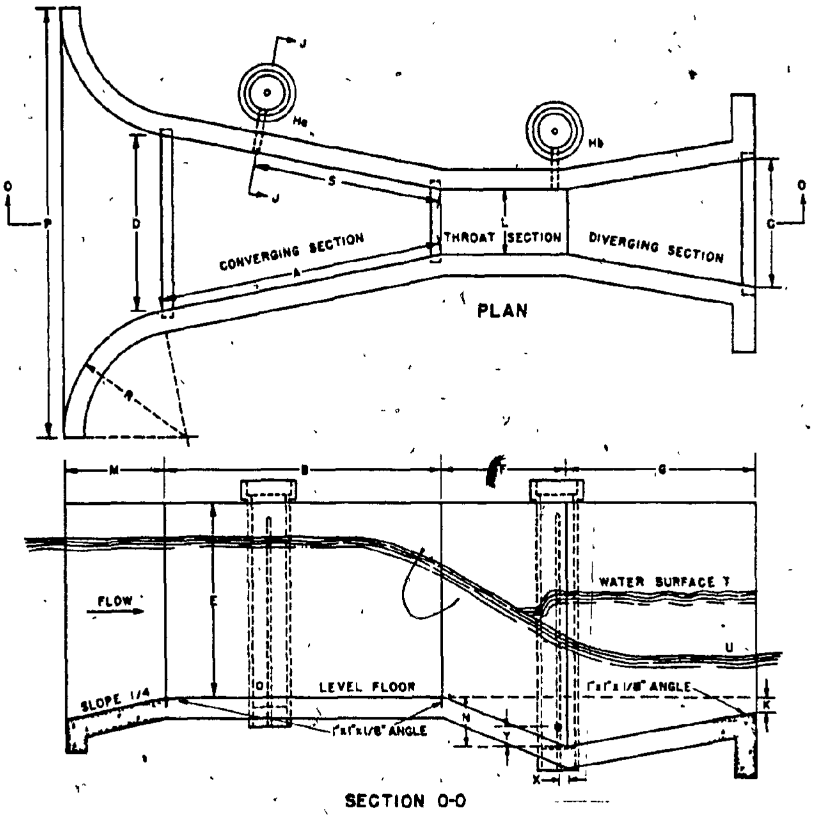
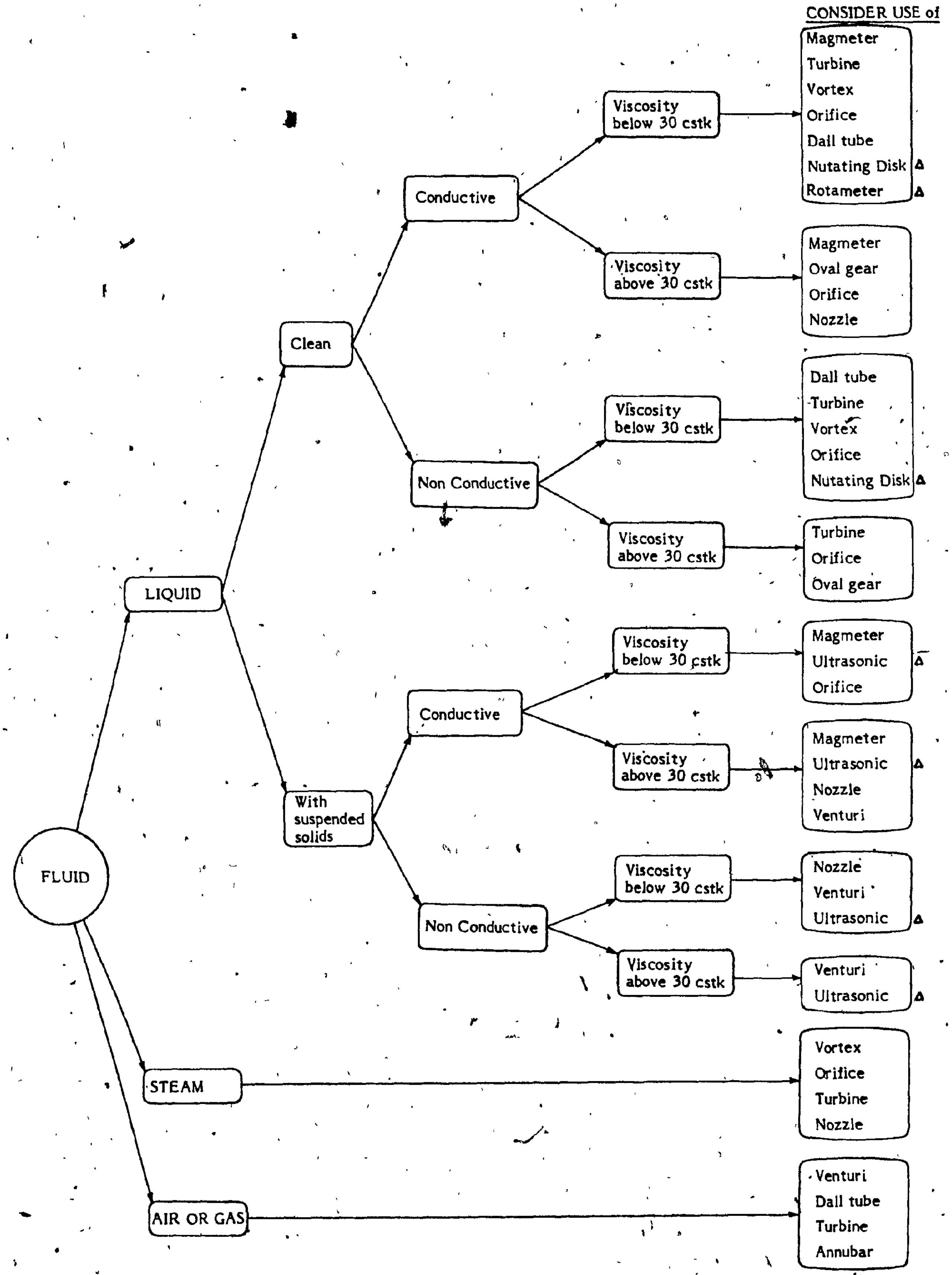


Figure 30. PARSHALL FLUME [40]



Δ Consider for field flow indication.

Figure 31. PRELIMINARY SELECTION OF FLOWMETERS

Appendix II

TABLES

SATURATED STEAM

$\frac{1.0219}{\sqrt{p_f{}^s}}$, For *Mercury-Type* Meters

Pressure, psig	Steam Quality, Per Cent										
	100	99	98	97	96	95	94	93	92	91	90
1	.0514	.0516	.0519	.0522	.0524	.0527	.0530	.0533	.0536	.0539	.0542
5	.0510	.0513	.0515	.0518	.0521	.0523	.0526	.0529	.0532	.0535	.0538
10	.0506	.0509	.0512	.0514	.0517	.0520	.0522	.0525	.0528	.0531	.0534
15	.0503	.0506	.0509	.0511	.0514	.0516	.0519	.0522	.0525	.0528	.0531
20	.0501	.0503	.0506	.0509	.0511	.0514	.0517	.0519	.0522	.0525	.0528
25	.0499	.0501	.0504	.0506	.0509	.0512	.0514	.0517	.0520	.0523	.0526
50	.0491	.0494	.0496	.0499	.0502	.0504	.0507	.0510	.0512	.0515	.0518
75	.0487	.0489	.0492	.0494	.0497	.0500	.0502	.0505	.0508	.0510	.0513
100	.0484	.0486	.0489	.0491	.0494	.0496	.0499	.0502	.0504	.0507	.0510
125	.0481	.0484	.0486	.0489	.0491	.0494	.0496	.0499	.0502	.0505	.0507
150	.0480	.0482	.0484	.0487	.0489	.0492	.0495	.0497	.0500	.0503	.0505
175	.0478	.0481	.0483	.0486	.0488	.0491	.0493	.0496	.0498	.0501	.0504
200	.0477	.0480	.0482	.0484	.0487	.0489	.0492	.0495	.0497	.0500	.0503
250	.0476	.0478	.0480	.0483	.0485	.0488	.0490	.0493	.0496	.0498	.0501
300	.0475	.0477	.0480	.0482	.0484	.0487	.0490	.0492	.0495	.0497	.0500
350	.0474	.0477	.0479	.0482	.0484	.0486	.0489	.0492	.0494	.0497	.0500
400	.0474	.0477	.0479	.0481	.0484	.0486	.0489	.0491	.0494	.0497	.0499
450	.0474	.0477	.0479	.0481	.0484	.0486	.0489	.0491	.0494	.0497	.0499
500	.0475	.0477	.0479	.0482	.0484	.0487	.0489	.0492	.0494	.0497	.0500
550	.0475	.0477	.0480	.0482	.0485	.0487	.0490	.0492	.0495	.0497	.0500
600	.0476	.0478	.0480	.0483	.0485	.0488	.0490	.0493	.0495	.0498	.0501

$\frac{1.0618}{\sqrt{p_f{}^s}}$, For *Bellows-Type* Meters

Pressure, psig	Steam Quality, Per Cent										
	100	99	98	97	96	95	94	93	92	91	90
1	.0534	.0537	.0539	.0542	.0545	.0548	.0551	.0554	.0557	.0560	.0563
5	.0530	.0533	.0535	.0538	.0541	.0544	.0547	.0550	.0553	.0556	.0559
10	.0526	.0529	.0531	.0534	.0537	.0540	.0543	.0546	.0549	.0552	.0555
15	.0523	.0526	.0528	.0531	.0534	.0537	.0539	.0542	.0545	.0548	.0551
20	.0520	.0523	.0526	.0528	.0531	.0534	.0537	.0540	.0543	.0546	.0549
25	.0518	.0521	.0524	.0526	.0529	.0532	.0535	.0537	.0540	.0543	.0546
50	.0511	.0513	.0516	.0518	.0521	.0524	.0527	.0529	.0532	.0535	.0538
75	.0506	.0508	.0511	.0514	.0516	.0519	.0522	.0525	.0527	.0530	.0533
100	.0503	.0505	.0508	.0510	.0513	.0516	.0518	.0521	.0524	.0527	.0530
125	.0500	.0503	.0505	.0508	.0510	.0513	.0516	.0519	.0521	.0524	.0527
150	.0498	.0501	.0503	.0506	.0509	.0511	.0514	.0517	.0519	.0522	.0525
175	.0497	.0499	.0502	.0504	.0507	.0510	.0512	.0515	.0518	.0521	.0524
200	.0496	.0498	.0501	.0503	.0506	.0509	.0511	.0514	.0517	.0520	.0522
250	.0494	.0497	.0499	.0502	.0504	.0507	.0510	.0512	.0515	.0518	.0521
300	.0493	.0496	.0498	.0501	.0503	.0506	.0509	.0511	.0514	.0517	.0520
350	.0493	.0495	.0498	.0500	.0503	.0505	.0508	.0511	.0513	.0516	.0519
400	.0493	.0495	.0498	.0500	.0503	.0505	.0508	.0511	.0513	.0516	.0519
450	.0493	.0495	.0498	.0500	.0503	.0505	.0508	.0511	.0513	.0516	.0519
500	.0493	.0496	.0498	.0501	.0503	.0506	.0508	.0511	.0514	.0516	.0519
550	.0494	.0496	.0499	.0501	.0504	.0506	.0509	.0511	.0514	.0517	.0520
600	.0494	.0497	.0499	.0502	.0504	.0507	.0509	.0512	.0515	.0517	.0520

SUPERHEATED STEAM

$\frac{1.0219}{\sqrt{p_f{}^s}}$, For *Mercury-Type* Meters

Pressure, psig	Total Steam Temperature, °F										
	300	350	400	450	500	550	600	700	800	1000	1200
25	.0486	.0470	.0455	.0441	.0429	.0418	.0408	.0390	.0374	.0347	.0325
50	.0491	.0473	.0457	.0443	.0431	.0419	.0409	.0390	.0374	.0347	.0325
75		.0476	.0459	.0445	.0432	.0420	.0410	.0391	.0374	.0347	.0325
100		.0479	.0461	.0446	.0433	.0421	.0410	.0391	.0375	.0347	.0326
125		.0483	.0464	.0448	.0434	.0422	.0411	.0392	.0375	.0348	.0326
150			.0466	.0450	.0436	.0423	.0412	.0392	.0376	.0348	.0326
175			.0469	.0452	.0437	.0424	.0413	.0393	.0376	.0348	.0326
200			.0472	.0454	.0439	.0425	.0414	.0393	.0376	.0348	.0326
250				.0458	.0442	.0428	.0415	.0395	.0377	.0349	.0326
300				.0463	.0445	.0430	.0417	.0396	.0378	.0349	.0326
350				.0468	.0448	.0433	.0419	.0397	.0379	.0349	.0327
400				.0473	.0452	.0435	.0421	.0398	.0379	.0350	.0327
450					.0456	.0438	.0423	.0399	.0380	.0350	.0327
500					.0460	.0441	.0425	.0401	.0381	.0351	.0327
600					.0470	.0447	.0430	.0403	.0383	.0352	.0328
700						.0454	.0435	.0406	.0385	.0352	.0328
800						.0462	.0440	.0409	.0386	.0353	.0329
900						.0471	.0446	.0412	.0388	.0354	.0329
1000						.0482	.0452	.0415	.0390	.0355	.0330
1100							.0459	.0418	.0392	.0356	.0330
1200							.0467	.0422	.0394	.0357	.0330
1300							.0476	.0425	.0396	.0358	.0331
1400							.0486	.0429	.0398	.0358	.0331
1500							.0499	.0433	.0400	.0359	.0332

$\frac{1.0618}{\sqrt{p_f{}^s}}$, For *Bellows-Type* Meters

Pressure, psig	Total Steam Temperature, °F										
	300	350	400	450	500	550	600	700	800	1000	1200
25	.0505	.0488	.0472	.0459	.0446	.0435	.0424	.0405	.0388	.0360	.0338
50	.0510	.0491	.0475	.0460	.0447	.0436	.0425	.0405	.0389	.0361	.0338
75		.0494	.0477	.0462	.0449	.0437	.0426	.0406	.0389	.0361	.0338
100		.0498	.0479	.0464	.0450	.0438	.0426	.0407	.0389	.0361	.0338
125		.0501	.0482	.0466	.0451	.0439	.0427	.0407	.0390	.0361	.0338
150			.0485	.0468	.0453	.0440	.0428	.0408	.0390	.0361	.0338
175			.0488	.0470	.0454	.0441	.0429	.0408	.0391	.0362	.0339
200			.0491	.0472	.0456	.0442	.0430	.0409	.0391	.0362	.0339
250				.0476	.0459	.0444	.0432	.0410	.0392	.0362	.0339
300				.0481	.0462	.0447	.0434	.0411	.0393	.0363	.0339
350				.0486	.0466	.0449	.0436	.0412	.0393	.0363	.0339
400				.0492	.0470	.0452	.0438	.0414	.0394	.0364	.0340
450					.0474	.0455	.0440	.0415	.0395	.0364	.0340
500					.0478	.0458	.0442	.0416	.0396	.0364	.0340
600					.0488	.0465	.0446	.0419	.0398	.0365	.0341
700						.0472	.0451	.0422	.0400	.0366	.0341
800						.0480	.0457	.0425	.0401	.0367	.0341
900						.0489	.0463	.0428	.0403	.0368	.0342
1000						.0500	.0469	.0431	.0405	.0369	.0342
1100							.0477	.0435	.0407	.0370	.0343
1200							.0485	.0438	.0409	.0371	.0343
1300							.0494	.0442	.0412	.0372	.0344
1400							.0505	.0446	.0414	.0372	.0344
1500							.0518	.0450	.0416	.0373	.0345

Table 1. STEAM FACTORS, C_s [7]

MERCURY TYPE METERS

$$0.2731\sqrt{\frac{13.5568-G_l}{G_l}}\sqrt{\frac{G_f}{G_l}}$$

Degrees A.P.I. at 60°F	Liquid specific gravity at 60°F	Temperature										
		0	20	40	60	80	100	125	150	200	250	300
152.5	.50	1.4605	1.4394	1.4178	1.3956	1.3728	1.3495	1.3194	1.2883	1.2225	1.1515	1.0740
145.9	.51	1.4426	1.4226	1.4022	1.3813	1.3599	1.3379	1.3096	1.2804	1.2188	1.1525	1.0806
140.6	.52	1.4252	1.4064	1.3871	1.3574	1.3473	1.3266	1.3000	1.2726	1.2150	1.1531	1.0862
135.5	.53	1.4084	1.3906	1.3725	1.3540	1.3350	1.3155	1.2906	1.2649	1.2109	1.1531	1.0909
130.5	.54	1.3921	1.3754	1.3583	1.3408	1.3230	1.3047	1.2813	1.2572	1.2066	1.1527	1.0949
125.8	.55	1.3763	1.3606	1.3445	1.3281	1.3113	1.2942	1.2722	1.2496	1.2023	1.1519	1.0982
121.2	.56	1.3610	1.3462	1.3311	1.3157	1.2999	1.2838	1.2632	1.2420	1.1978	1.1508	1.1008
116.7	.57	1.3462	1.3323	1.3181	1.3036	1.2888	1.2737	1.2544	1.2345	1.1932	1.1494	1.1029
112.5	.58	1.3319	1.3188	1.3054	1.2918	1.2779	1.2637	1.2455	1.2269	1.1881	1.1471	1.1036
108.3	.59	1.3182	1.3058	1.2932	1.2803	1.2672	1.2538	1.2367	1.2191	1.1827	1.1442	1.1036
104.3	.60	1.3050	1.1932	1.2813	1.2691	1.2567	1.2441	1.2279	1.2114	1.1770	1.1409	1.1028
100.5	.61	1.2924	1.2812	1.2698	1.2582	1.2463	1.2343	1.2189	1.2032	1.1706	1.1364	1.1003
96.7	.62	1.2801	1.2694	1.2586	1.2475	1.2362	1.2248	1.2101	1.1952	1.1642	1.1318	1.0977
93.1	.63	1.2683	1.2581	1.2477	1.2371	1.2263	1.2153	1.2014	1.1871	1.1576	1.1267	1.0943
89.6	.64	1.2568	1.2470	1.2370	1.2269	1.2166	1.2061	1.1928	1.1792	1.1510	1.1216	1.0909
86.2	.65	1.2457	1.2363	1.2267	1.2170	1.2071	1.1970	1.1842	1.1711	1.1442	1.1161	1.0868
82.9	.66	1.2349	1.2258	1.2166	1.2072	1.1977	1.1881	1.1758	1.1633	1.1375	1.1106	1.0826
79.7	.67	1.2244	1.2156	1.2067	1.1977	1.1886	1.1793	1.1675	1.1554	1.1307	1.1049	1.0781
76.6	.68	1.2142	1.2057	1.1971	1.1884	1.1796	1.1707	1.1593	1.1477	1.1240	1.0993	1.0737
73.6	.69	1.2042	1.1960	1.1877	1.1793	1.1708	1.1622	1.1513	1.1402	1.1173	1.0937	1.0691
70.6	.70	1.1944	1.1865	1.1785	1.1704	1.1622	1.1539	1.1434	1.1327	1.1107	1.0880	1.0645
67.8	.71	1.1848	1.1772	1.1695	1.1617	1.1538	1.1458	1.1357	1.1254	1.1043	1.0826	1.0601
65.0	.72	1.1754	1.1681	1.1607	1.1531	1.1455	1.1378	1.1281	1.1182	1.0980	1.0771	1.0556
62.3	.73	1.1663	1.1592	1.1520	1.1448	1.1374	1.1300	1.1207	1.1111	1.0917	1.0717	1.0511
59.7	.74	1.1573	1.1505	1.1436	1.1366	1.1295	1.1224	1.1134	1.1042	1.0856	1.0664	1.0467
57.2	.75	1.1486	1.1419	1.1353	1.1285	1.1217	1.1149	1.1062	1.0974	1.0795	1.0611	1.0422
54.7	.76	1.1398	1.1335	1.1271	1.1206	1.1141	1.1075	1.0992	1.0908	1.0738	1.0562	1.0383
52.3	.77	1.1313	1.1252	1.1191	1.1129	1.1067	1.1004	1.0925	1.0844	1.0682	1.0515	1.0345
49.9	.78	1.1230	1.1172	1.1113	1.1053	1.0993	1.0933	1.0857	1.0780	1.0624	1.0465	1.0303
47.6	.79	1.1149	1.1093	1.1036	1.0979	1.0921	1.0863	1.0790	1.0717	1.0568	1.0416	1.0261
45.4	.80	1.1070	1.1015	1.0961	1.0906	1.0850	1.0794	1.0724	1.0654	1.0511	1.0365	1.0217
43.2	.81	1.0992	1.0940	1.0887	1.0834	1.0780	1.0727	1.0659	1.0591	1.0454	1.0315	1.0173
41.1	.82	1.0917	1.0866	1.0815	1.0763	1.0712	1.0660	1.0595	1.0529	1.0397	1.0263	1.0127
39.0	.83	1.0843	1.0793	1.0744	1.0694	1.0644	1.0594	1.0531	1.0468	1.0340	1.0211	1.0081
36.9	.84	1.0771	1.0723	1.0674	1.0626	1.0578	1.0529	1.0468	1.0406	1.0283	1.0159	1.0033
35.0	.85	1.0700	1.0653	1.0606	1.0559	1.0512	1.0465	1.0406	1.0346	1.0227	1.0107	0.9986
33.0	.86	1.0631	1.0585	1.0539	1.0493	1.0448	1.0402	1.0344	1.0286	1.0170	1.0054	0.9937
31.1	.87	1.0563	1.0518	1.0474	1.0429	1.0384	1.0339	1.0283	1.0227	1.0115	1.0002	0.9889
29.3	.88	1.0497	1.0453	1.0409	1.0365	1.0322	1.0278	1.0223	1.0169	1.0059	0.9950	0.9840
27.5	.89	1.0431	1.0389	1.0346	1.0303	1.0260	1.0217	1.0164	1.0111	1.0004	0.9898	0.9791
25.7	.90	1.0367	1.0325	1.0283	1.0241	1.0200	1.0158	1.0106	1.0054	0.9950	0.9846	0.9743
24.0	.91	1.0305	1.0263	1.0222	1.0181	1.0140	1.0099	1.0048	0.9997	0.9895	0.9794	0.9694
22.3	.92	1.0243	1.0203	1.0162	1.0122	1.0081	1.0041	0.9991	0.9941	0.9842	0.9743	0.9645
20.7	.93	1.0183	1.0143	1.0103	1.0063	1.0023	0.9984	0.9935	0.9886	0.9789	0.9692	0.9597
19.0	.94	1.0123	1.0084	1.0044	1.0005	0.9966	0.9928	0.9879	0.9831	0.9736	0.9642	0.9549
17.5	.95	1.0065	1.0026	0.9987	0.9949	0.9910	0.9872	0.9825	0.9778	0.9685	0.9593	0.9502
15.9	.96	1.0007	0.9969	0.9931	0.9893	0.9855	0.9818	0.9771	0.9725	0.9634	0.9544	0.9456
14.4	.97	0.9950	0.9912	0.9875	0.9838	0.9801	0.9764	0.9718	0.9673	0.9584	0.9486	0.9410
12.9	.98	0.9894	0.9857	0.9820	0.9783	0.9747	0.9711	0.9666	0.9622	0.9535	0.9449	0.9365
11.4	.99	0.9839	0.9802	0.9766	0.9730	0.9694	0.9659	0.9615	0.9571	0.9486	0.9402	0.9320
10.0	1.00	0.9785	0.9749	0.9713	0.9677	0.9642	0.9607	0.9564	0.9522	0.9438	0.9356	0.9276
8.6	1.01	0.9730	0.9695	0.9660	0.9626	0.9591	0.9557	0.9514	0.9472	0.9389	0.9307	0.9229
7.2	1.02	0.9677	0.9643	0.9608	0.9574	0.9541	0.9507	0.9465	0.9423	0.9340	0.9258	0.9177
5.8	1.03	0.9624	0.9591	0.9557	0.9524	0.9491	0.9458	0.9416	0.9375	0.9293	0.9210	0.9129
4.6	1.04	0.9572	0.9540	0.9507	0.9474	0.9442	0.9409	0.9368	0.9327	0.9246	0.9163	0.9081

BELLOWS TYPE METERS

$$\frac{1.0057}{\sqrt{G_l}}\sqrt{\frac{G_f}{G_l}}$$

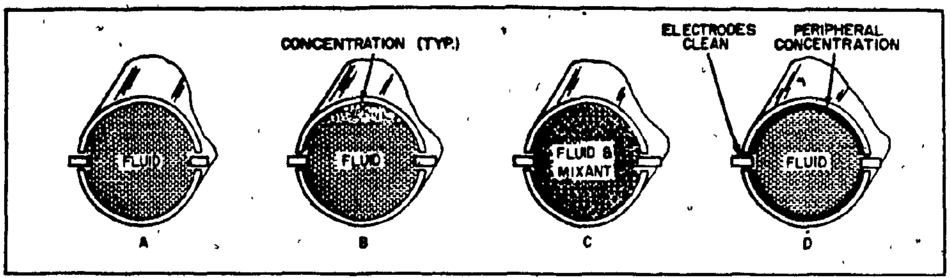
Degrees A.P.I. at 60°F	Liquid specific gravity at 60°F	Temperature										
		0	20	40	60	80	100	125	150	200	250	300
152.5	.50	1.4885	1.4669	1.4449	1.4223	1.3991	1.3753	1.3446	1.3129	1.2459	1.1735	1.0946
145.9	.51	1.4707	1.4504	1.4296	1.4083	1.3864	1.3640	1.3352	1.3054	1.2426	1.1750	1.1017
140.6	.52	1.4535	1.4344	1.4147	1.3947	1.3741	1.3530	1.3259	1.2980	1.2391	1.1760	1.1078
135.5	.53	1.4369	1.4189	1.4004	1.3814	1.3621	1.3423	1.3168	1.2906	1.2355	1.1765	1.1131
130.5	.54	1.4209	1.4038	1.3864	1.3686	1.3504	1.3317	1.3078	1.2832	1.2316	1.1766	1.1175
125.8	.55	1.4053	1.3892	1.3728	1.3561	1.3390	1.3215	1.2990	1.2759	1.2276	1.1762	1.1213
121.2	.56	1.3902	1.3751	1.3597	1.3439	1.3278	1.3114	1.2903	1.2687	1.2235	1.1755	1.1244
116.7	.57	1.3756	1.3614	1.3469	1.3321	1.3170	1.3016	1.2818	1.2615	1.2193	1.1745	1.1270
112.5	.58	1.3616	1.3482	1.3345	1.3205	1.3063	1.2918	1.2732	1.2542	1.2145	1.1726	1.1282
108.3	.59	1.3481	1.3354	1.3225	1.3093	1.2959	1.2822	1.2647	1.2468	1.2095	1.1702	1.1286
104.3	.60	1.3350	1.3230	1.3108	1.2984	1.2857	1.2727	1.2562	1.2393	1.2042	1.1672	1.1282
100.5	.61	1.3227	1.3112	1.2995	1.2877	1.2756	1.2632	1.2475	1.2314	1.1981	1.1630	1.1261
96.7	.62	1.3107	1.2997	1.2886	1.2772	1.2657	1.2540	1.2390	1.2237	1.1920	1.1587	1.1238
93.1	.63	1.2991	1.2886	1.2779	1.2671	1.2560	1.2448	1.2305	1.2159	1.1857	1.1540	1.1208
89.6	.64	1.2878	1.2777	1.2675	1.2571	1.2466	1.2358	1.2222	1.2082	1.1794	1.1493	1.1178
86.2	.65	1.2769	1.2672	1.2574	1.2474	1.2373	1.2270	1.2138	1.2005	1.1728	1.1440	1.1140
82.9	.66	1.2663	1.2570	1.2475	1.2379	1.2282	1.2182	1.2057	1.1928	1.1664	1.1388	1.1101
79.7	.67	1.2560	1.2470	1.2379	1.2287	1.2193	1.2097	1.1976	1.1853	1.1599	1.1335	1.1060
76.6	.68	1.2460	1.2373	1.2285	1.2196	1.2105	1.2014	1.1897	1.1778	1.1535	1.1281	1.1018
73.6	.69	1.2362	1.2278	1.2193	1.2107	1.2020	1.1932	1.1819	1.1705	1.1471	1.1228	1.0976
70.6	.70	1.2267	1.2186	1.2104	1.2020	1.1936	1.1851	1.1743	1.1633	1.1408	1.1174	1.0933
67.8	.71	1.2173	1.2095	1.2016	1.1935	1.1854	1.1772	1.1668	1.1562	1.1346	1.1122	1.0891
65.0	.72	1.2082	1.2006	1.1930	1.1852	1.1774	1.1695	1.1595	1.1493	1.1285	1.1071	1.0850
62.3	.73	1.1992	1.1919	1.1845	1.1771	1.1695	1.1619	1.1523	1.1425	1.1225	1.1020	1.0808
59.7	.74	1.1905	1.1834	1.1763	1.1691	1.1618	1.1545	1.1452	1.1358	1.1166	1.0969	1.0766
57.2	.75	1.1819	1.1751	1.1682	1.1613	1.1543	1.1472	1.1383	1.1292	1.1108	1.0919	1.0725
54.7	.76	1.1734	1.1669	1.1603	1.1536	1.1469	1.1401	1.1316	1.1229	1.1053	1.0873	1.0689
52.3	.77	1.1650	1.1588	1.1525	1.1461	1.1397	1.1332	1.1250	1.1168	1.1000	1.0829	1.0653
49.9	.78	1.1570	1.1509	1.1449	1.1387	1.1326	1.1263	1.1185	1.1106	1.0945	1.0782	1.0614
47.6	.79	1.1490	1.1432	1.1374	1.1315	1.1256	1.1196	1.1121	1.1045	1.0891	1.0735	1.0575
45.4	.80	1.1413	1.1357	1.1301	1.1244	1.1187	1.1130	1.1057	1.0984	1.0837	1.0687	1.0535
43.2	.81	1.1338	1.1284	1.1229	1.1174	1.1119	1.1064	1.0994	1.0924	1.0783	1.0639	1.0493
41.1	.82	1.1264	1.1212	1.1159	1.1106	1.1053	1.0999	1.0932	1.0864	1.0728	1.0590	1.0450
39.0	.83	1.1193	1.1142	1.1090	1.1039	1.0987	1.0936	1.0871	1.0805	1.0674	1.0541	1.0406
36.9	.84	1.1122	1.1073	1.1023	1.0973	1.0923	1.0873	1.0810	1.0746	1.0619	1.0490	1.0361
35.0	.85	1.1054	1.1005	1.0957	1.0908	1.0860	1.0811	1.0750	1.0688	1.0565	1.0441	1.0316
33.0	.86	1.0987	1.0939	1.0892	1.0845	1.0797	1.0750	1.0690	1.0630	1.0511	1.0390	1.0270
31.1	.87	1.0921	1.0875	1.0828	1.0782	1.0736	1.0690	1.0632	1.0574	1.0457	1.0341	1.0224
29.3	.88	1.0856	1.0811	1.0766	1.0721	1.0676	1.0630	1.0574	1.0517	1.0404	1.0291	1.0178
27.5	.89	1.0793	1.0749	1.0705	1.0660	1.0616	1.0572	1.0517	1.0461	1.0351	1.0241	1.0131
25.7	.90	1.0731	1.0688	1.0644	1.0601	1.0558	1.0514	1.0460	1.0407	1.0299	1.0192	1.0085
24.0	.91	1.0671	1.0628	1.0585	1.0543	1.0500	1.0458	1.0405	1.0352	1.0247	1.0142	1.0038
22.3	.92	1.0611	1.0569	1.0527	1.0485	1.0443	1.0402	1.0350	1.0298	1.0195	1.0093	0.9992
20.7	.93	1.0553	1.0511	1.0470	1.0429	1.0388	1.0347	1.0296	1.0245	1.0144	1.0044	0.9946
19.0	.94	1.0495	1.0454	1.0414	1.0373	1.0333	1.0292	1.0242	1.0193	1.0094	0.9997	0.9900
17.5	.95	1.0438	1.0398	1.0358	1.0318	1.0279	1.0239	1.0190	1.0141	1.0045	0.9949	0.9855
15.9	.96	1.0383	1.0343	1.0304	1.0264	1.0225	1.0187	1.0138	1.0091	0.9996	0.9903	0.9811
14.4	.97	1.0328	1.0289	1.0250	1.0211	1.0173	1.0135	1.0088	1.0041	0.9948	0.9857	0.9768
12.9	.98	1.0274	1.0235	1.0197	1.0159	1.0121	1.0084	1.0037	0.9991	0.9901	0.9812	0.9725
11.4	.99	1.0221	1.0183	1.0145	1.0108	1.0071	1.0034	0.9988	0.9943	0.9854	0.9767	0.9682
10.0	1.00	1.0168	1.0131	1.0094	1.0057	1.0020	0.9984	0.9939	0.9895	0.9808	0.9723	0.9640
8.6	1.01	1.0116	1.0079	1.0043	1.0007	0.9971	0.9936	0.9891	0.9847	0.9761	0.9676	0.9592
7.2	1.02	1.0064	1.0029	0.9993	0.9958	0.9923	0.9888	0.9844	0.9801	0.9714	0.9629	0.9545
5.8	1.03	1.0013	0.9979	0.9944	0.9909	0.9875	0.9840	0.9797	0.9754	0.9669	0.9583	0.9498
4.6	1.04	0.9963	0.9929	0.9896	0.9862	0.9828	0.9794	0.9751	0.9709	0.9623	0.9538	0.9452

Table 2. LIQUID FLOWING - TEMPERATURE FACTORS, C_{ld} [7]

$$\sqrt{\frac{1.0000}{G}}$$

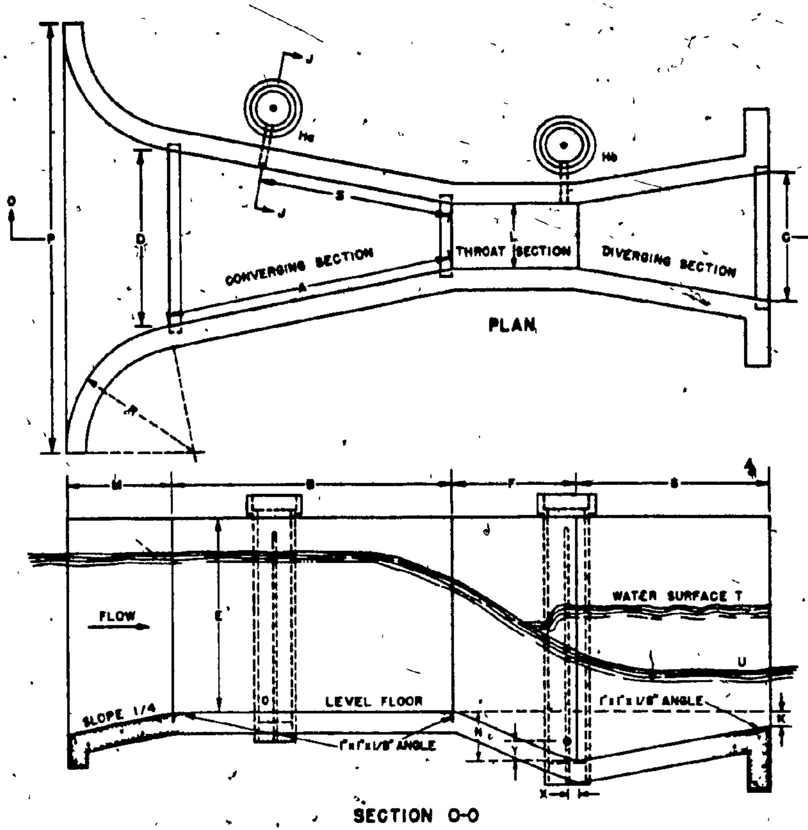
Specific gravity G	Factor F_g	Specific gravity G	Factor F_g	Specific gravity G	Factor F_g	Specific gravity G	Factor F_g
0.500	1.4142	0.675	1.2172	0.850	1.0847	1.05	0.9759
0.505	1.4072	0.680	1.2127	0.855	1.0815	1.06	0.9713
0.510	1.4003	0.685	1.2082	0.860	1.0783	1.07	0.9667
0.515	1.3935	0.690	1.2039	0.865	1.0752	1.08	0.9623
0.520	1.3868	0.695	1.1995	0.870	1.0721	1.09	0.9578
0.525	1.3801	0.700	1.1952	0.875	1.0690	1.10	0.9535
0.530	1.3736	0.705	1.1910	0.880	1.0660	1.11	0.9492
0.535	1.3672	0.710	1.1868	0.885	1.0630	1.12	0.9449
0.540	1.3608	0.715	1.1826	0.890	1.0600	1.13	0.9407
0.545	1.3546	0.720	1.1785	0.895	1.0570	1.14	0.9366
0.550	1.3484	0.725	1.1744	0.900	1.0541	1.15	0.9325
0.555	1.3423	0.730	1.1704	0.905	1.0512	1.16	0.9285
0.560	1.3363	0.735	1.1664	0.910	1.0483	1.17	0.9245
0.565	1.3304	0.740	1.1625	0.915	1.0454	1.18	0.9206
0.570	1.3245	0.745	1.1586	0.920	1.0426	1.19	0.9167
0.575	1.3188	0.750	1.1547	0.925	1.0398	1.20	0.9129
0.580	1.3131	0.755	1.1509	0.930	1.0370	1.21	0.9091
0.585	1.3074	0.760	1.1471	0.935	1.0342	1.22	0.9054
0.590	1.3019	0.765	1.1433	0.940	1.0314	1.23	0.9017
0.595	1.2964	0.770	1.1396	0.945	1.0287	1.24	0.8980
0.600	1.2910	0.775	1.1359	0.950	1.0260	1.25	0.8944
0.605	1.2856	0.780	1.1323	0.955	1.0233	1.26	0.8909
0.610	1.2804	0.785	1.1287	0.960	1.0206	1.27	0.8874
0.615	1.2752	0.790	1.1251	0.965	1.0180	1.28	0.8839
0.620	1.2700	0.795	1.1215	0.970	1.0153	1.29	0.8805
0.625	1.2649	0.800	1.1180	0.975	1.0127	1.30	0.8771
0.630	1.2599	0.805	1.1146	0.980	1.0102	1.31	0.8737
0.635	1.2549	0.810	1.1111	0.985	1.0076	1.32	0.8704
0.640	1.2500	0.815	1.1077	0.990	1.0050	1.33	0.8671
0.645	1.2451	0.820	1.1043	0.995	1.0025	1.34	0.8639
0.650	1.2403	0.825	1.1010	1.00	1.0000	1.35	0.8607
0.655	1.2356	0.830	1.0976	1.01	0.9950	1.36	0.8575
0.660	1.2309	0.835	1.0944	1.02	0.9901	1.37	0.8544
0.665	1.2263	0.840	1.0911	1.03	0.9853	1.38	0.8513
0.670	1.2217	0.845	1.0879	1.04	0.9806	1.39	0.8482

Table 3. GAS DENSITY FACTORS, C_g [7]



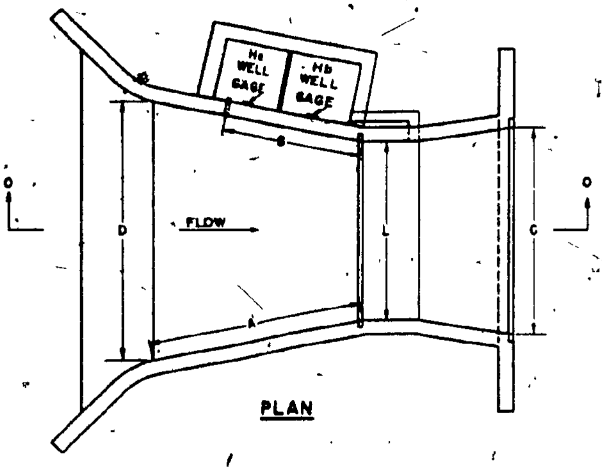
PRIME FLUID CONDITION	MIXANT OR CONCENTRATION	METER PIPE CONDITION	REF FIG	INDICATED VOLUMETRIC FLOW RATE	
	NATURE			MIXTURE	FLUID ONLY
Homogeneous	Conductive	Full	A	—	Accurate
	Non-conductive e g air	Full	B	High	—
With Uniformly Dispersed Mixant	Conductive Particles (solid, emulsion or slurry)	Full	C	Accurate	—
	Magnetic Particles (solid or slurry)	Full	C	High	—
With Solid Concentration — Peripherally Distributed (clean electrodes)	Non-conductive	Full	D	—	Not Predictable
With Solid Concentration — Peripherally Distributed (clean electrodes)	The coating the same conductivity as the fluid	Full	D	—	Accurate
~~With~~ Solid Concentration Peripherally Distributed (clean electrodes)	The coating very highly conductive compared to the fluid	Full	D	—	Low
Non-Conductive Electrode Film	—	Full	E	—	Low
With Liquid or Solid Concentration (top or bottom)	Non-Conductive (solid)	Full	B	Accurate	—
	Highly Conductive (liquid or solid)	Full	B	Partially Compensated Errors, not predictable	
	Magnetic Particles	Full	B	High	—

Table 4. MAGNETIC FLOWMETER - FLUID AND METERING CONDITIONS [29]

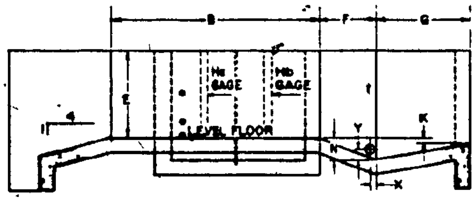


L	A	S	B	C	D	E	F	G	K	N	R	M	P	X	Y	Free-flow Capacity	
																Min.	Max.
Ft. In.	Ft. In.	Ft. In.	Ft. In.	Ft. In.	Ft. In.	Ft. In.	Ft. In.	Ft. In.	In.	In.	Ft. In.	Ft. In.	Ft. In.	In.	In.	Sec.-Ft.	Sec.-Ft.
0–3	1–6⅜	1–¼	1–6	0–7	0–10$\frac{3}{16}$	2–0	0–6	1–0	1	2¼	1–4	1–0	2–6¼	1	1½	.03	1.9
0–6	2–0$\frac{7}{16}$	1–4$\frac{5}{16}$	2–0	1–3½	1–3⅝	2–0	1–0	2–0	3	4½	1–4	1–0	2–11½	2	3	.05	3.9
0–9	2–10⅝	1–11⅛	2–10	1–3	1–10⅝	2–6	1–0	1–6	3	4½	1–4	1–0	3–6½	2	3	.09	8.9
1–0	4–6	3–0	4–4⅞	2–0	2–9¼	3–0	2–0	3–0	3	9	1–8	1–3	4–10¾	2	3	.11	16.1
1–6	4–9	3–2	4–7⅞	2–6	3–4⅜	3–0	2–0	3–0	3	9	1–8	1–3	5–6	2	3	.15	24.6
2–0	5–0	3–4	4–10⅞	3–0	3–11½	3–0	2–0	3–0	3	9	1–8	1–3	6–1	2	3	.42	33.1
3–0	5–6	3–8	5–4¾	4–0	5–1⅞	3–0	2–0	3–0	3	9	1–8	1–3	7–3½	2	3	.61	50.4
4–0	6–0	4–0	5–10⅝	5–0	6–4¼	3–0	2–0	3–0	3	9	2–0	1–6	8–10¾	2	3	1.3	67.9
5–0	6–6	4–4	6–4½	6–0	7–6⅝	3–0	2–0	3–0	3	9	2–0	1–6	10–1¼	2	3	1.6	85.6
6–0	7–0	4–8	6–10⅜	7–0	8–9	3–0	2–0	3–0	3	9	2–0	1–6	11–3½	2	3	2.6	103.5
7–0	7–6	5–0	7–4¼	8–0	9–11⅜	3–0	2–0	3–0	3	9	2–0	1–6	12–6	2	3	3.0	121.4
8–0	8–0	5–4	7–10⅛	9–0	11–1¾	3–0	2–0	3–0	3	9	2–0	1–6	13–8¼	2	3	3.5	139.5

Table 5. DIMENSIONS AND CAPACITIES OF SMALL PARSHALL FLUMES [40]



PLAN



SECTION O-O

L	A	S	B	C	D	E	F	G	K	N	X	Y	Free-flow Capacity	
													Max.	Min.
Ft In.	Ft In.	Ft. In	Ft. In	Ft. In	Ft In	Ft In	Ft.	Ft.	In.	Ft. In.	In.	In.	Sec.-Ft.	Sec.-Ft.
10–0	14–3⅜	6–0	14–0	14–8	15–7¼	4–0	3	6	6	1–1½	12	9	200	6
12–0	16–3¾	6–8	16–0	18–4	18–4¾	5–0	3	8	6	1–1½	12	9	350	8
15–0	25–6	7–8	25–0	24–0	25–0	6–0	4	10	9	1–6	12	9	600	8
20–0	25–6	9–4	25–0	29–4	30–0	7–0	6	12	12	2–3	12	9	1,000	10
25–0	25–6	11–0	25–0	34–8	35–0	7–0	6	13	12	2–3	12	9	1,200	15
30–0	26–6	12–8	26–0	45–4	40–4¼	7–0	6	14	12	2–3	12	9	1,500	15
40–0	27–6	16–0	27–0	56–8	50–9½	7–0	6	16	12	2–3	12	9	2,000	20
50–0	27–6	19–4	27–0		60–9½	7–0	6	20	12	2–3	12	9	3,000	25

Table 6. DIMENSIONS AND CAPACITIES OF LARGE PARSHALL FLUMES [40]

TABLE 7

FACTORS TO BE CONSIDERED IN FLOWMETER SELECTION

Chapter	Primary flow element (flowmeter)	Fluid	Range of max. flow gpm cfm	Max. Pressure (psi)	Max. Temp. (°C)	Output type	Pressure loss as % of differential produced	Accuracy (%) of flow	Rangeability	Sizes (inches)	Straight Upstream Piping required	Maximum Viscosity (cstk)	Relative Cost
II	Concentric orifice	Liquid Gas, & Steam	0-3500 50-100 000	Above 1400	Above 300	Square Root	50-90	±1	4:1	1 & up	10-30D	3 000	low
	Venturi tube	Liquid, & Gas	0-15000 100-500 000	Above 1000	Above 200	Square Root	10-20	±1	4:1	4 & up	5-10D	3 000	very high
	Flow nozzle	Liquid, Gas, & Steam	0-15000 100-500 000	Above 1000	Above 200	Square Root	30-70	±1.5	4:1	4 & up	10-30D	3 000	medium
	Dall tube	Liquid & Gas	0-20 000 100-100 000	1000	Above 200	Square Root	5-10	±1	4:1	2 & up	5-10D	1 000	high
	Pilot tube	Liquid	1-100	150	100	Square Root	negligible	±2	3:1	-	20-30D	-	low
	Elbow	Liquid	-	Line	Process	Square Root	none	±2	3:1	line	20D	unlimited	medium
III	Rotameter	Liquid, Gas	0-4000 0-1000	1000	300	Linear	Very low	±3	10:1	1/4-12	none	100	medium
IV	Positive displ.	Liquid	0-1000	Varies	150	Linear	low	±0.5	10:1	1-16	10D	2 000	medium
V	Turbine	Liquid Gas	0-50000 0-300 000	1500	300	Linear	1 velocity head	±0.25	10:1	2-12	5-10D	30	high
	Magnetic	Liquids slurries	0-50 000	Varies	120	Linear	none	±0.5	10:1	1/8-72	none	unlimited	medium
	Ultrasonic	Slurries	0-1000	1 500	300	Linear	none	±1	10:1	-	none	1 000	high
	Vortex shedding	Liquid, steam & gas	10-10000 10-8000	1000	120	Linear	30-60	±1	10:1	2-8	10-20D	100	medium
VI	V-notch weir	Liquids	2-100 000	-	-	5/2	negligible	±4	30:1	-	none	unlimited	medium
	Parshall flume	Liquids, slurries	10-700 000	-	-	3/2	negligible	±3	10:1	8" & up	none	unlimited	high

Note: All data in this table was supplied by manufacturers listed in Table 9.

TABLE 8

FLOWMETERS APPLICATION AREAS

Chapter	Primary Flow element	Pulp Stock	Slurry	Liquids containing suspended solids	Dirty fluids	Liquids with entrained vapours	Vapours containing liquids	Viscous fluids	Flows with varying viscosities	Low flow rates	Ease of capacity change	Ease of installation	Ease of Maintenance
II	Concentric Orifice	Not good	Not good	Not good	Not good	good	good	not good	not good	not good	excellent	very good	good
	Venturi tube	not good	not good	not good	very good	excellent	excellent	not good	not good	not good	very good	very good	very good
	Flow nozzle	not good	good	good	good	good	good	good	good	not good	very good	very good	very good
	Dall tube	not good	good	good	good	good	very good	good	good	not good	very good	good	good
	Pitot tube	not good	not good	not good	not good	good	not good	good	not good	not good	good	very good	good
	Elbow meter	not good	good	good	very good	good	good	not good	good	not good	good	excellent	very good
III	Rotameter	good	good	good	good	good	good	good	very good	very good	good	excellent	very good
IV	Positive displacement	good	good	good	good	not good	not good	excellent	good	very good	very good	very good	good
V	Turbine meter	not good	not good	not good	good	good	not good	good	good	excellent	very good	excellent	good
	Magnetic flowmeter	excellent	excellent	excellent	excellent	excellent	-	excellent	excellent	excellent	very good	excellent	excellent
	Ultrasonic flowmeter	very good	very good	excellent	excellent	excellent	-	-	-		excellent	excellent	excellent
	Vortex shedding	not good	not good	not good	not good	very good	excellent	-	good	-	excellent	excellent	excellent
VI	Weirs & flumes	good	good	good	good	good	-	good	good	not good	good	good	very good

Note: Information in this table are Personal gained through experience and through correspondence with Application Engineers.

TABLE 9
MANUFACTURERS OF FLOW MEASURING DEVICES

MANUFACTURER	ORIFICE PLATE	VENTURI TUBE	FLOW NOZZLE	DALL TUBE	PITOT TUBE	ELBOW	ROTAMETER	POSITIVE DISPL.	TURBINE	MAGNETIC	ULTRASONIC	VORTEX SHEDDING	WEIRS AND FLUMES
Accurate Metering Systems									X				
Ametek - Schutte & Koerting							X						
BIF - General Signal	X	X	X	X									
Badger Meter	X	X	X	X				X					X
Brandt Industries					X								
Bristol - Acco	X	X											
Brooks - Emerson Electric							X	X	X	X		X	
C-E Invalco - Combustion Engr.									X				X
Canadian Meter Div. - Singer	X	X	X	X				X	X				X
Daniel Industries	X	X	X	X					X				
Dieterich Standard Corp.					A'BAR								
Drexelbrook Engineering Co.													X
Dwayer Instruments Inc.					X								
Endress & Howser Inc.											X		X
Fielding Crossman		X	X	X									
Fischer & Porter		X	X	X			X		X	X	X	X	X
Flow-Dyne Engineering Inc.		X	X	X									X
Flow Systems Corp.		X	X	X				X	X	X	X		
Foxboro Co.	X	X	X	X	X	X			X	X		X	X
Hersey Products Inc.								X	X		X		
Honeywell Process Control	X	X	X					X					
ITT Barton								X	X				X
Leeds & Northrup		X	X										
Meriam Instrument	X				X								
Neptune/Eastech Inc.												X	
Neptune Measurement Co.								X	X				
Peco Robinson	X	X	X	X									
Rochester International								X	X				
Taylor - Sybron Corp.	X	X	X							X			X
Tech Tube Corp.	X	X	X	X									
Veeder - Root Inc.								X					
Wallace & Tiernan - Pennwalt							X						
Waugh Controls Corp.								X	X			X	
Wesmar											X		
Western Meter						X							
Westinghouse	X										X		X
Yokogawa Electric Works												X	

NOTE: All data was supplied by manufacturers and representatives active in the Canadian market (July 1981).