Industrial Flow Measurement

Seminar Presented by
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Seminar Presenter

Seminar Outline

- ***Introduction***
- *Fluid Flow Fundamentals*
- *Performance Measures*
- *Linearization and Compensation*
- *Totalization*
- *Flowmeter Calibration*
- *Measurement of Flowmeter Performance*
- *Miscellaneous Considerations*
- *Flowmeter Technologies*
- *Flowmeter Selection*

Introduction

- *Working Definition of a Process*
- *Why Measure Flow?*

Working Definition of a Process

- *A process is anything that changes*

Why Measure Flow?

- *Flow measurements provide information about the process*
- *The information that is needed depends on the process*

Why Measure Flow?

- *Custody transfer*
  - *Measurements are often required to determine the total quantity of fluid that passed through the flowmeter for billing purposes*

Why Measure Flow?

- *Monitor the process*
  - *Flow measurements can be used to ensure that the process is operating satisfactorily*

Why Measure Flow?

- *Improve the process*
  - *Flow measurements can be used for heat and material balance calculations that can be used to improve the process*

Why Measure Flow?

- *Monitor a safety parameter*
  - *Flow measurements can be used to ensure that critical portions of the process operate safely*

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- *Miscellaneous Considerations*
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- *Flowmeter Selection*

Fluid Flow Fundamentals

- ***Temperature***
- *Pressure*
- *Density and Fluid Expansion*
- *Types of Flow*
- *Inside Pipe Diameter*
- *Viscosity*
- *Reynolds Number and Velocity Profile*
- *Hydraulic Phenomena*

Temperature

- *Measure of relative hotness/coldness*
  - *Water freezes at 0°C (32°F)*
  - *Water boils at 100°C (212°F)*

Temperature

- *Removing heat from fluid lowers temperature*
  - *If all heat is removed, absolute zero temperature is reached at approximately -273°C (-460°F)*

Temperature

- *Absolute temperature scales are relative to absolute zero temperature*
  - *Absolute zero temperature = 0 K (0°R)*
    - *Kelvin = °C + 273*
    - *° Rankin = °F + 460*

Temperature

- *Absolute temperature is important for flow measurement*

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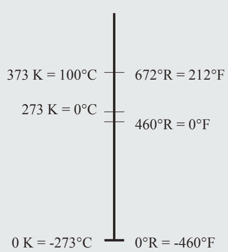
Temperature



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Temperature

Problem

- *The temperature of a process increases from 20°C to 60°C. For the purposes of flow measurement, by what percentage has the temperature increased?*

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Temperature

- *It is tempting to answer that the temperature tripled (60/20), but the ratio of the absolute temperatures is important for flow measurement*
  - *(60+273)/(20+273) = 1.137*
  - *13.7% increase*

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Fluid Flow Fundamentals

- *Temperature*
- ***Pressure***
- *Density and Fluid Expansion*
- *Types of Flow*
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Pressure

- *Pressure is defined as the ratio of a force divided by the area over which it is exerted (P=F/A)*

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Pressure

Problem

- *What is the pressure exerted on a table by a 2 inch cube weighing 5 pounds?*
  - *(5 lb) / (4 inch^2) = 1.25 lb/in^2*
  - *If the cube were balanced on a 0.1 inch diameter rod, the pressure on the table would be 636 lb/in^2*

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Pressure

- *Atmospheric pressure is caused by the force exerted by the atmosphere on the surface of the earth*
  - *2.31 feet WC / psi*
  - *10.2 meters WC / bar*

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Pressure

- *Removing gas from a container lowers the pressure in the container*
  - *If all gas is removed, absolute zero pressure (full vacuum) is reached at approximately -1.01325 bar (-14.696 psig)*

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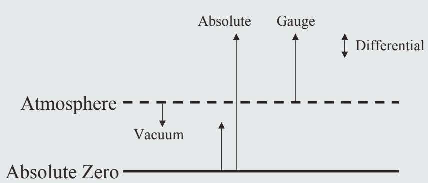
Pressure

- *Absolute pressure scales are relative to absolute zero pressure*
  - *Absolute zero pressure*
    - *Full vacuum = 0 bar abs (0 psia)*
    - *bar abs = bar + 1.01325*
    - *psia = psig + 14.696*

Pressure



Pressure

- *<u>Absolute</u> pressure is important for flow measurement*

Pressure

Problem

- *The pressure of a process increases from 1 bar to 3 bar. For the purposes of flow measurement, by what percentage has the pressure increased?*

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Pressure

- *It is tempting to answer that the pressure tripled (3/1), but the ratio of the absolute pressures is important for flow measurement*
  - *(3+1.01325)/(1+1.01325) = 1.993*
  - *99.3% increase*

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Fluid Flow Fundamentals

- *Temperature*
- *Pressure*
- ***Density and Fluid Expansion***
- *Types of Flow*
- *Inside Pipe Diameter*
- *Viscosity*
- *Reynolds Number and Velocity Profile*
- *Hydraulic Phenomena*

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Density and Fluid Expansion

- *Density is defined as the ratio of the mass of a fluid divided its volume ($\rho=m/V$)*

Density and Fluid Expansion

- *Specific Gravity of a liquid is the ratio of its operating density to that of water at standard conditions*
  - $SG = \rho_{liquid} / \rho_{water\ at\ standard\ conditions}$

Density and Fluid Expansion

Problem

- *What is the density of air in a 3.2 ft3 filled cylinder that has a weight of 28.2 and 32.4 pounds before and after filling respectively?*

Density and Fluid Expansion

- *The weight of the air in the empty cylinder is taken into account*
  - *Mass =(32.4-28.2)+(3.2•0.075) = 4.44 lb*
  - *Volume = 3.2 ft^3*
  - *Density = 4.44/3.2 = 1.39 lb/ft^3*

Density and Fluid Expansion

- *The density of most liquids is nearly unaffected by pressure*
- *Expansion of liquids*
  - $V = V_0 (1 + \beta \cdot \Delta T)$
    - *V = new volume*
    - V_0 *= old volume*
    - *β = cubical coefficient of expansion*
    - *ΔT = temperature change*

Density and Fluid Expansion

Problem

- *What is the change in density of a liquid caused by a 10°C temperature rise where β is 0.0009 per °C ?*

Density and Fluid Expansion

- *Calculate the new volume*
  - $V = V_0 (1 + 0.0009 \bullet 10) = 1.009\ V_0$
  - *The volume of the liquid increased to 1.009 times the old volume, so the new density is (1/1.009) or 0.991 times the old density*

Density and Fluid Expansion

- *Expansion of solids*
  - $V = V_0 (1 + \beta \bullet \Delta T)$
    - *where* $\beta = 3 \bullet \alpha$
    - α *= linear coefficient of expansion*
- *Temperature coefficient*
  - *Stainless steel temperature coefficient is approximately 0.5% per 100°C*

Density and Fluid Expansion

Problem

- *What is the increase in size of metal caused by a 50°C temperature rise where the metal has a temperature coefficient of 0.5% per 100°C ?*

Density and Fluid Expansion

- *Calculate the change in size*
  - *(0.5 • 50) = 0.25%*
  - *Metals (such as stainless steel) can exhibit significant expansion*

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Density and Fluid Expansion

- *Boyle's Law states the the volume of an ideal gas at constant temperature varies inversely with absolute pressure*
  - *V = K / P*

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Density and Fluid Expansion

- *New volume can be calculated*
  - $V = K / P$
  - $V_0 = K / P_0$
- *Dividing one equation by the other yields*
  - $V/V_0 = P_0 / P$

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Density and Fluid Expansion

Problem

- *How is the volume of an ideal gas at constant temperature and a pressure of 28 psig affected by a 5 psig pressure increase?*

Density and Fluid Expansion

- *Calculate the new volume*
  - $V/V_0 = (28+14.7) / (28+5+14.7) = 0.895$
  - $V = 0.895\ V_0$
  - *Volume decreased by 10.5%*

Density and Fluid Expansion

- *Charles' Law states the the volume of an ideal gas at constant pressure varies directly with <u>absolute</u> temperature*
  - $V = K \bullet T$

Density and Fluid Expansion

- *New volume can be calculated*
  - $V = K \cdot T$
  - $V_0 = K \cdot T_0$
- *Dividing one equation by the other yields*
  - $V/V_0 = T / T_0$

Density and Fluid Expansion

Problem

- *How is the volume of an ideal gas at constant pressure and a temperature of 15ºC affected by a 10ºC decrease in temperature?*

Density and Fluid Expansion

- *Calculate the new volume*
  - $V/V_0 = (273+15-10) / (273+15) = 0.965$
  - $V = 0.965\ V_0$
  - *Volume decreased by 3.5%*

Density and Fluid Expansion

- *Ideal Gas Law combines Boyle's and Charles' Laws*
  - $PV = n R T$

Density and Fluid Expansion

- *New volume can be calculated*
  - $P \bullet V = n \bullet R \bullet T$
  - $P_0 \bullet V_0 = n \bullet R \bullet T_0$
- *Dividing one equation by the other yields*
  - $V/V_0 = (P_0/P) \bullet (T / T_0)$

Density and Fluid Expansion

Problem

- *How is the volume of an ideal gas at affected by a 10.5% decrease in volume due to temperature and a 3.5% decrease in volume due to pressure?*

Density and Fluid Expansion

- *Calculate the new volume*
  - $V/V_0 = 0.895 \cdot 0.965 = 0.864$
  - $V = 0.864\ V_0$
  - *Volume decreased by 13.6%*

Density and Fluid Expansion

- *Non-Ideal Gas Law takes into account non-ideal behavior*
  - $PV = n\ R\ T\ Z$

Density and Fluid Expansion

- *New volume can be calculated*
  - $P \cdot V = n \cdot R \cdot T \cdot Z$
  - $P_0 \cdot V_0 = n \cdot R \cdot T_0 \cdot Z_0$
- *Dividing one equation by the other yields*
  - $V/V_0 = (P_0/P) \cdot (T / T_0) \cdot (Z / Z_0)$

Density and Fluid Expansion

- *For liquids, specific gravity is the ratio of the density of the liquid to the density of water at standard conditions*

Density and Fluid Expansion

- *For gases, specific gravity is the ratio of the density of the gas to the density of air at standard conditions*
  - *Specific gravity is commonly used to describe the ratio of the density of the gas at standard conditions to the density of air at standard conditions*

Density and Fluid Expansion

- *Standard conditions*
  - *Pressure*
    - *14.696 psia, 1 atmosphere*
    - *14.7 psia*
    - *14.4 psia*
    - *1 bar absolute*
    - *4 oz.*

Density and Fluid Expansion

- *Standard conditions*
  - *Temperature*
    - *15°C (59°F)*
    - *68°F*
    - *70°F*
    - *0°C*

Fluid Flow Fundamentals

- *Temperature*
- *Pressure*
- *Density and Fluid Expansion*
- ***Types of Flow***
- *Inside Pipe Diameter*
- *Viscosity*
- *Reynolds Number and Velocity Profile*
- *Hydraulic Phenomena*

Types of Flow

- $Q = A \cdot v$
  - *Q is the volumetric flow rate*
  - *A is the cross-sectional area of the pipe*
  - *v is the average velocity of the fluid in the pipe*

Types of Flow

- *Typical Volumetric Flow Units($Q = A \bullet v$)*
  - *$ft^2 \bullet ft/sec = ft^3/sec$*
  - *$m^2 \bullet m/sec = m^3/sec$*
  - *gallons per minute (gpm)*
  - *liters per minute (lpm)*
  - *cubic centimeters per minute (ccm)*

Types of Flow

- *$W = \rho \bullet Q$*
  - *W is the mass flow rate*
  - *ρ is the fluid density*
  - *Q is the volumetric flow rate*

Types of Flow

- *Typical Mass Flow Units ($W = \rho \bullet Q$)*
  - *$lb/ft^3 \bullet ft^3/sec = lb/sec$*
  - *$kg/m^3 \bullet m^3/sec = kg/sec$*
  - *standard cubic feet per minute (scfm)*
  - *standard liters per minute (slpm)*
  - *standard cubic centimeters per minute(sccm)*

Types of Flow

- *$Q = A \bullet v$*
- *$W = \rho \bullet Q$*
  - *Q* — *volumetric flow rate*
  - *W* — *mass flow rate*
  - *v* — *fluid velocity*
  - *$\frac{1}{2} \rho v^2$* — *inferential flow rate*

Fluid Flow Fundamentals

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Inside Pipe Diameter

- *The inside pipe diameter (ID) is important for flow measurement*
  - *Pipes of the same size have the same outside diameter (OD)*
    - *Welding considerations*
  - *Pipe wall thickness, and hence its ID, is determined by its schedule*

Inside Pipe Diameter

- *Pipe wall thickness increases with increasing pipe schedule*
  - *Schedule 40 pipes are considered "standard" wall thickness*
  - *Schedule 5 pipes have thin walls*
  - *Schedule 160 pipes have thick walls*

Inside Pipe Diameter

- *Nominal pipe size*
  - *For pipe sizes 12-inch and smaller, the nominal pipe size is the approximate ID of a Schedule 40 pipe*
  - *For pipe sizes 14-inch and larger, the nominal pipe size is the OD of the pipe*

Fluid Flow Fundamentals

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Viscosity

- *Viscosity is the ability of the fluid to flow over itself*
- *Units*
  - *cP, cSt*
  - *Saybolt Universal (at 100ºF, 210 ºF)*
  - *Saybolt Furol (at 122ºF, 210 ºF)*

Viscosity

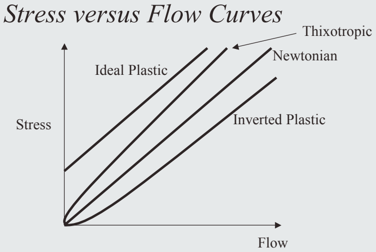
- *Viscosity can be highly temperature dependent*
  - *Water*
  - *Honey at 40°F, 80°F, and 120°F*
  - *Peanut butter*

Viscosity

- *At a given temperature:*
  - *Newtonian fluids have constant viscosity*
  - *the viscosity of a Non-Newtonian fluid varies when different amounts of sheer stress is applied*

Viscosity

- *Stress versus Flow Curves*



Fluid Flow Fundamentals

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Velocity Profile and Reynolds Number

- *Reynolds number is the ratio of inertial forces to viscous forces in the flowing stream*
  - $R_D = 3160 \cdot Q_{gpm} \cdot SG / (\mu_{cP} \cdot D_{in})$

Velocity Profile and Reynolds Number

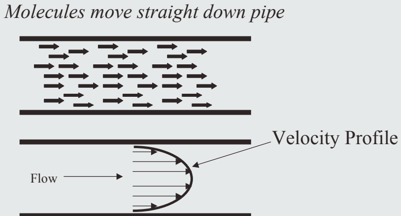
- *Reynolds number can be used as an indication of how the fluid is flowing in the pipe*
- *Flow regimes based on R_D*
  - *Laminar* *< 2000*
  - *Transitional* *2000 - 4000*
  - *Turbulent* *> 4000*

Velocity Profile and Reynolds Number

- *Not all molecules in the pipe flow at the same velocity*
- *Molecules near the pipe wall move slower; molecules in the center of the pipe move faster*

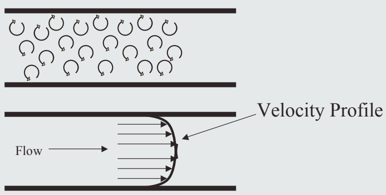
Velocity Profile and Reynolds Number

- *Laminar Flow Regime*
  - *Molecules move straight down pipe*



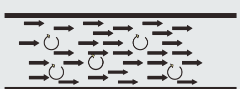
Velocity Profile and Reynolds Number

- *Turbulent Flow Regime*
  - *Molecules migrate throughout pipe*



Velocity Profile and Reynolds Number

- *Transitional Flow Regime*
  - *Molecules exhibit both laminar and turbulent behavior*

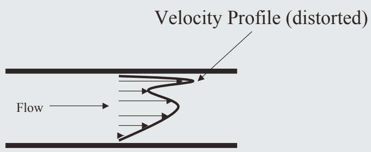


Velocity Profile and Reynolds Number

- *Many flowmeters require a good velocity profile to operate accurately*
- *Obstructions in the piping system can distort the velocity profile*
  - *Elbows, tees, fittings, valves*

Velocity Profile and Reynolds Number

- *A distorted velocity profile can introduce significant errors into the measurement of most flowmeters*



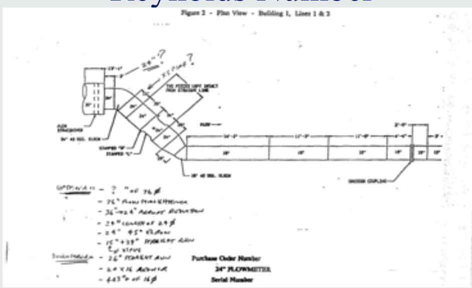
Velocity Profile and Reynolds Number

- *Good velocity profiles can be developed*
  - *Straight run upstream and downstream*
    - *No fittings or valves*
    - *Upstream is usually longer and more important*
  - *Flow conditioner*

Velocity Profile and Reynolds Number

- *Good velocity profiles can be developed*
  - *Locate control valve downstream of flowmeter*
    - *Upstream control valve should be a warning that all aspects of the flow measurement system should be checked carefully*

Velocity Profile and Reynolds Number



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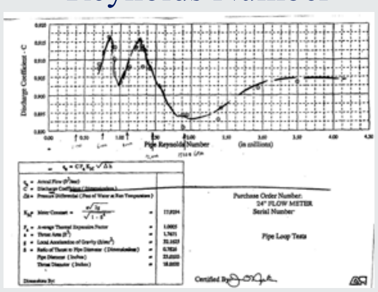
Velocity Profile and Reynolds Number



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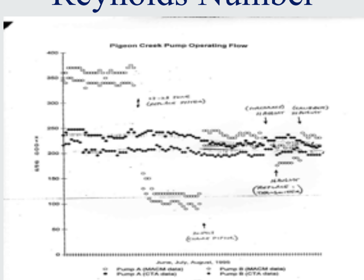
Velocity Profile and Reynolds Number



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Fluid Flow Fundamentals

- *Temperature*
- *Pressure*
- *Density and Fluid Expansion*
- *Types of Flow*
- *Inside Pipe Diameter*
- *Viscosity*
- *Reynolds Number and Velocity Profile*
- ***Hydraulic Phenomena***

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Hydraulic Phenomena

- *Vapor pressure is defined as the pressure at which a liquid and its vapor can exist in equilibrium*
  - *The vapor pressure of water at 100°C is atmospheric pressure (1.01325 bar abs) because water and steam can coexist*

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Hydraulic Phenomena

- *A saturated vapor is in equilibrium with its liquid at its vapor pressure*
  - *Saturated steam at atmospheric pressure is at a temperature of 100°C*

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Hydraulic Phenomena

- *A superheated vapor is a saturated vapor that is at a higher temperature than its saturation temperature*
  - *Steam at atmospheric pressure that is at 150°C is a superheated vapor with 50°C of superheat*

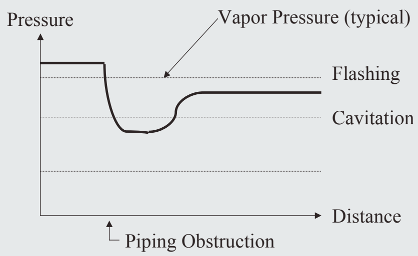
Hydraulic Phenomena

- *Flashing is the formation of gas (bubbles) in a liquid after the pressure of the liquid falls below its vapor pressure*
  - *Reducing the pressure of water at 100°C below atmospheric pressure (say 0.7 bar abs) will cause the water to boil*

Hydraulic Phenomena

- *Cavitation is the formation and subsequent collapse of gas (bubbles) in a liquid after the pressure of the liquid falls below and then rises above its vapor pressure*
  - *Can cause severe damage in pumps and valves*

Hydraulic Phenomena

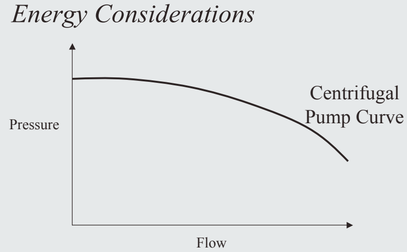


Hydraulic Phenomena

- *Energy Considerations*
  - *Claims are sometimes made that flowmeters with a lower pressure drop will save energy*

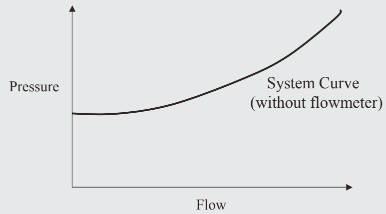
Hydraulic Phenomena

- *Energy Considerations*



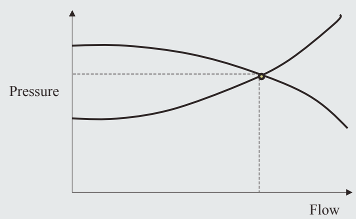
Hydraulic Phenomena

- *Energy Considerations*



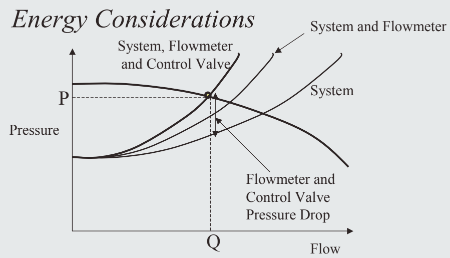
Hydraulic Phenomena

- *Energy Considerations*



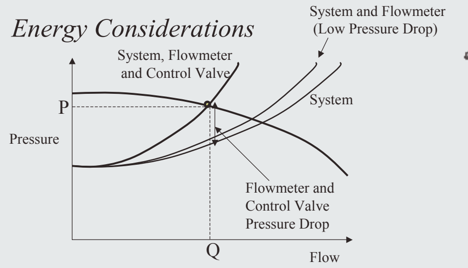
Hydraulic Phenomena

- *Energy Considerations*



Hydraulic Phenomena

- *Energy Considerations*



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Hydraulic Phenomena

- *Energy Considerations*
  - *The pump operates at the same flow and pressure, so no energy savings are achieved by installing a flowmeter with a lower pressure drop*

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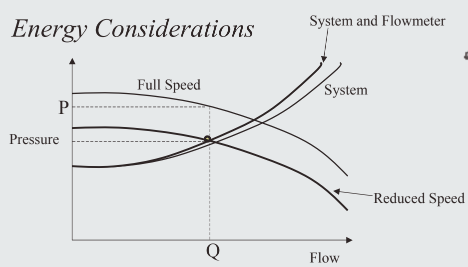
Hydraulic Phenomena

- *Energy Considerations*



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Hydraulic Phenomena

- *Energy Considerations*
  - *Operating the pump at a reduced speed generates the same flow but requires a lower pump discharge pressure*
    - *Hydraulic energy generated by the pump better matches the load*
    - *Energy savings are proportional to the cube of the speed*

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- *Miscellaneous Considerations*
- *Flowmeter Technologies*
- *Flowmeter Selection*

Performance Measures

- *Performance Criteria*
- *Performance Statements*
- *Repeatability*
- *Linearity*
- *Accuracy*
- *Composite Accuracy*
- *Turndown*
- *Rangeability*

Performance Criteria

- *Installation complexity and cost*
- *Maintenance*
- *Accuracy*
- *Linearity*
- *Repeatability*

Performance Criteria

- *Dependence on fluid properties*
- *Hydraulic considerations of flowmeter*
- *Hydraulic considerations of fluid*
- *Operating Costs*
- *Reliability*
- *Safety*

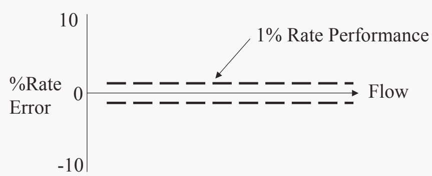
Performance Statements

- *Percent of rate*
- *Percent of full scale*
- *Percent of meter capacity (upper range limit)*
- *Percent of calibrated span*

Performance Statements

- *1% of rate performance at different flow rates with a 0-100 unit flow range*
  - *100% flow → 0.01•100 1.00 unit*
  - *50% flow → 0.01•50 0.50 unit*
  - *25% flow → 0.01•25 0.25 unit*
  - *10% flow → 0.01•10 0.10 unit*

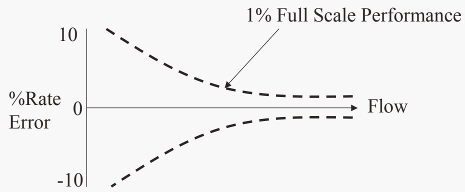
Performance Statements



Performance Statements

- *1% of full scale performance at different flow rates with a 0-100 unit flow range*
  - *100% flow → 0.01•100 1 unit = 1% rate*
  - *50% flow → 0.01•100 1 unit = 2% rate*
  - *25% flow → 0.01•100 1 unit = 4% rate*
  - *10% flow → 0.01•100 1 unit = 10% rate*

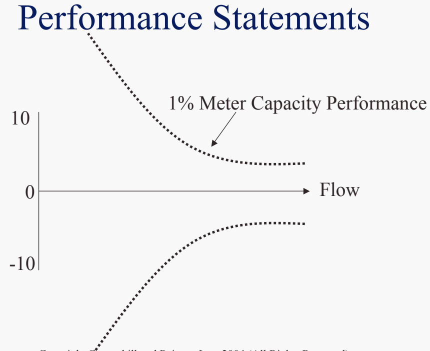
Performance Statements



Performance Statements

- *1% of meter capacity (or upper range limit) performance at different flow rates with a 0-100 unit flow range (URL=400)*
  - *100% flow → 0.01•400 4 units = 4% rate*
  - *50% flow → 0.01•400 4 units = 8% rate*
  - *25% flow → 0.01•400 4 units = 16% rate*
  - *10% flow → 0.01•400 4 units = 40% rate*

Performance Statements



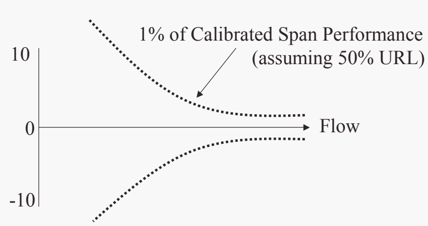
Performance Statements

- *Performance expressed as a percent of calibrated span is similar to full scale and meter capacity statements where the absolute error is a percentage of the calibrated span*

Performance Statements

- *1% of calibrated span performance at different flow rates with a 0-100 unit flow range (URL=400, calibrated span=200)*
  - *100% flow → 0.01•200 2 units = 2% rate*
  - *50% flow → 0.01•200 2 units = 4% rate*
  - *25% flow → 0.01•200 2 units = 8% rate*
  - *10% flow → 0.01•200 2 units = 20% rate*

Performance Statements



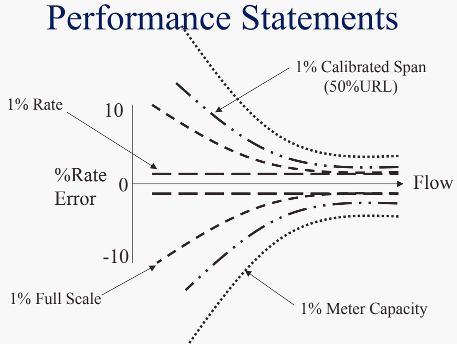
Performance Statements

- *A calibrated span statement becomes a full scale statement when the instrument is calibrated to full scale*
- *A calibrated span statement becomes a meter capacity statement when the instrument is calibrated at URL*

Performance Statements

- *Performance specified as a percent of rate, percent of full scale, percent of meter capacity, and percent of calibrated span are different*

Performance Statements



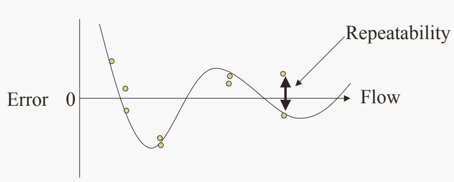
Performance Statements

- *Performance statements can be manipulated because their meaning may not be clearly understood*
- *Technical assistance may be needed to analyze the statements*

Repeatability

- *Repeatability is the ability of the flowmeter to reproduce a measurement each time a set of conditions is repeated*

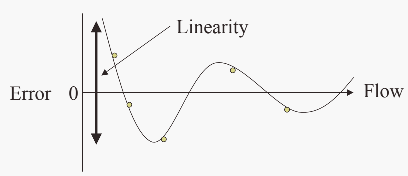
Repeatability



Linearity

- *Linearity is the ability of the relationship between flow and flowmeter output (often called the characteristic curve or signature of the flowmeter) to approximate a linear relationship*

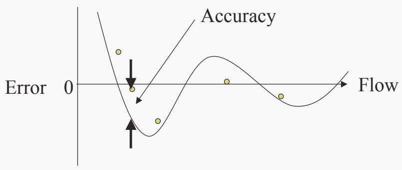
Linearity



Accuracy

- *Accuracy is the ability of the flowmeter to produce a measurement that corresponds to its characteristic curve*

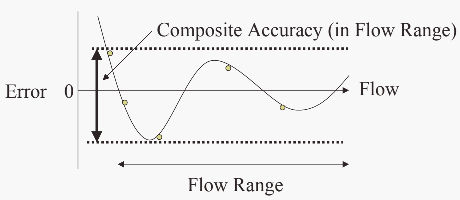
Accuracy



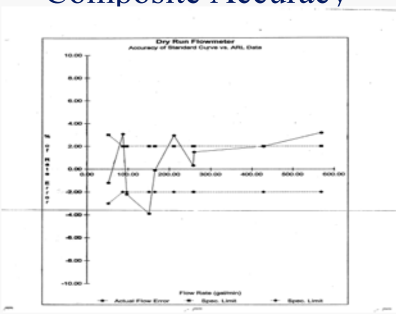
Composite Accuracy

- *Flowmeter suppliers often specify the composite accuracy that represents the combined effects of repeatability, linearity and accuracy*

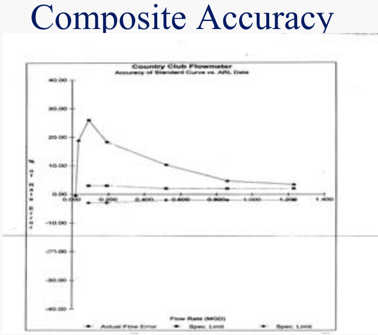
Composite Accuracy



Composite Accuracy



Composite Accuracy



Turndown

- *Performance statements apply over a range of operation*
- *Turndown is the ratio of the maximum flow that the flowmeter will measure within the stated accuracy to the minimum flow that can be measured within the stated accuracy*

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Rangeability

- *Rangeability is a measure of how much the range (full scale) can be adjusted*

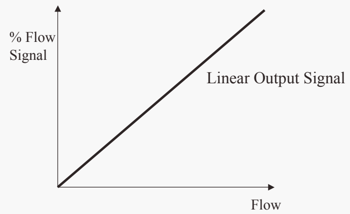
Seminar Outline

- *Introduction*
- *Fluid Flow Fundamentals*
- *Performance Measures*
- ***Linearization and Compensation***
- *Totalization*
- *Flowmeter Calibration*
- *Measurement of Flowmeter Performance*
- *Miscellaneous Considerations*
- *Flowmeter Technologies*
- *Flowmeter Selection*

Linearization and Compensation

- *Linear and nonlinear flowmeters*
- *Gas density compensation*
  - *Pressure*
  - *Temperature*
  - *Tap location*
- *Liquid temperature compensation*
- *Flow computers*

Linear Flowmeters



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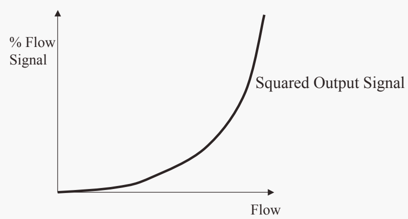
Nonlinear Flowmeters



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Linear and Nonlinear Flowmeters

Output	*Linear Flowmeter*	*Nonlinear Flowmeter*
1 %	*1 %*	*10 %*
10 %	*10 %*	*31.6 %*
25 %	*25 %*	*50 %*
50 %	*50 %*	*70.7 %*
100 %	*100 %*	*100 %*

** Note the large gain at low flows for nonlinear flowmeters*

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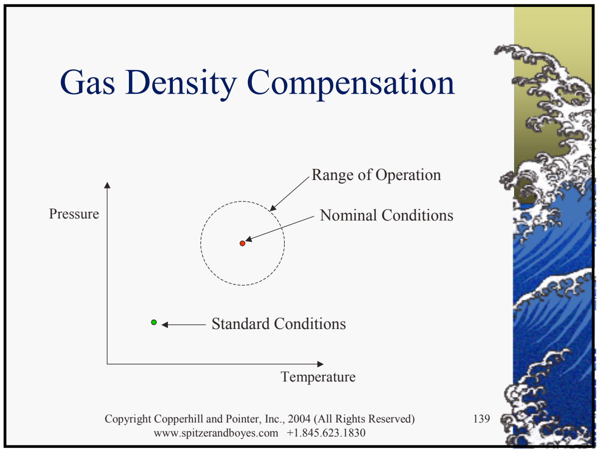

Gas Density Compensation
Range of Operation
Pressure
Nominal Conditions
Standard Conditions
Temperature
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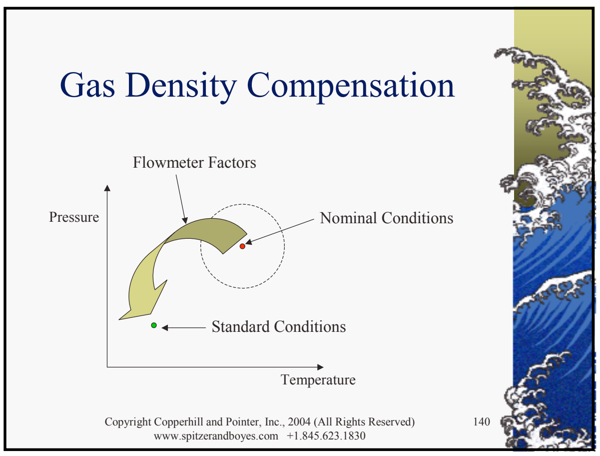

Gas Density Compensation
Flowmeter Factors
Pressure
Nominal Conditions
Standard Conditions
Temperature
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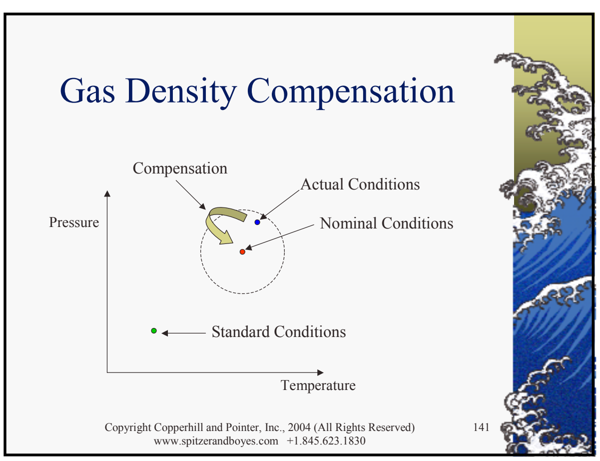

Gas Density Compensation
Compensation
Actual Conditions
Pressure
Nominal Conditions
Standard Conditions
Temperature
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Gas Density Compensation

- *Gas Laws*
- *Laboratory data*
- *Handbook information*
- *Mathematical relationship*
  - *Typically a function of pressure, temperature, and composition)*

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Gas Density Compensation

- *Gas Laws*

$$V_{nom} = \frac{(P \cdot T_{nom} \cdot Z_{nom}) \cdot V}{(P_{nom} \cdot T \cdot Z)}$$

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Gas Density Compensation

- *Gas Laws*

$$V_{nom} = constant \cdot \frac{P}{(T \cdot Z)} \cdot V$$

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Gas Density Compensation

- *Effects can be large (see table in text)*
  - *Temperature*
    - *1% per 3°C at 300K*
  - *Pressure*
    - *10% per bar at 9 bar (gauge)*
    - *1% per psi at 85 psig*

Gas Density Compensation

- *Density affects the output of squared output flowmeters approximately half as much as linear output flowmeters*
  - *Pressure effects are lower for squared output flowmeters*
  - *Temperature effects are lower for squared output flowmeters*

Liquid Density Compensation

- *Typically temperature correction*

Pressure Tap Location

- *Pressure tap*
  - *Usually upstream*
  - *May be in the flowmeter body*
  - *Some flowmeters allow downstream*

Pressure Tap Location

- *Temperature tap*
  - *Usually downstream to reduce turbulence*
    - *Upstream temperature tap should be a warning that all aspects of the flow measurement system should be checked carefully*
  - *May be within the flowmeter body*

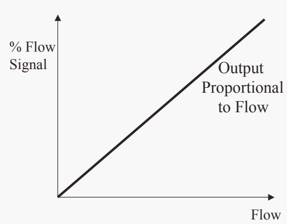
Flow Computers

- *Density compensation*
  - *Pressure, temperature, and compressibility*
- *Reynolds number compensation*
- *Flowmeter expansion*
- *Other…*

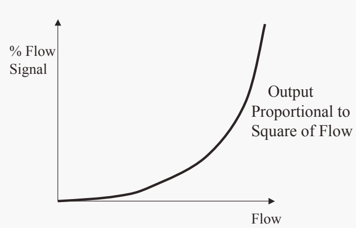
Seminar Outline

- *Introduction*
- *Fluid Flow Fundamentals*
- *Performance Measures*
- *Linearization and Compensation*
- ***Totalization***
- *Flowmeter Calibration*
- *Measurement of Flowmeter Performance*
- *Miscellaneous Considerations*
- *Flowmeter Technologies*
- *Flowmeter Selection*

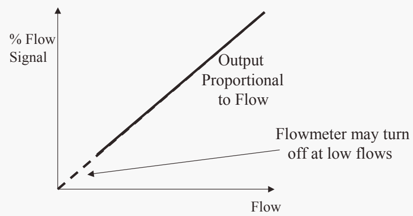
Analog Flowmeter (Linear)



Analog Flowmeter (Nonlinear)



Digital Flowmeter (Linear)



Totalization

- *Analog flowmeter*
  - *Integrator (0.5% rate performance)*
  - *Indicator (optional)*

Totalization

- *Digital flowmeter*
  - *Count pulses (±1 pulse)*
  - *f/I converter (0.5% rate) and indicator (optional)*

Totalization

- *Digital flowmeter with analog output*
  - *Inherent flowmeter performance*
  - *Analog output circuit*
    - *Add approximately 0.06% of full scale*
  - *f/I converter (0.5% rate) and indicator*

Totalization

- *Digital flowmeters seem to be superior to analog flowmeter*
  - *Inherent performance may not be equal*
  - *Digital flowmeters generally turn off at flow flow rates*
  - *Analog output circuit*
    - *Add approximately 0.06% of full scale*

Seminar Outline

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Calibration

- *Calibration is performing adjustments to the instrument so that it measures within accuracy constraints*
  - *Comparison of measurement with "true" value*

Flowmeter Calibration

- *Calibration of many variables is static*
  - *Level – tape, ruler*
  - *Pressure – force and area*
  - *Temperature – freezing/boiling water*

Flowmeter Calibration

- *Calibration of flowmeters is dynamic*
  - *Primary standard uses time and weight*

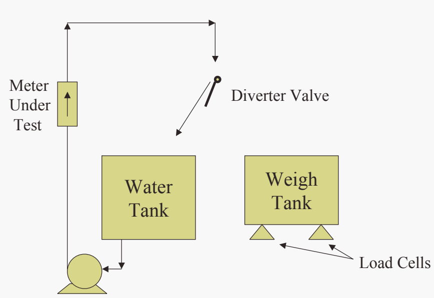
Flowmeter Calibration

- *Ideally, flowmeter calibration should be performed under operating conditions*
  - *Usually not practical and often impossible*
  - *Use another calibration technique as a surrogate*

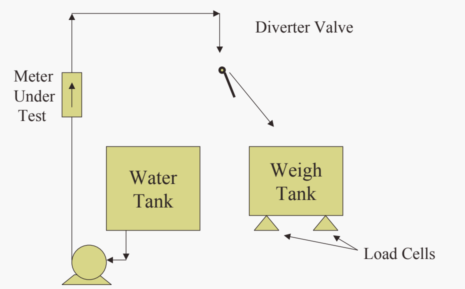
Flowmeter Calibration

- *Wet calibration*
  - *Primary flow laboratory*
  - *Flow calibration facility*
- *Dry calibration*
  - *Physical dimensions*
  - *Electronic techniques*
- *Verification of operation*

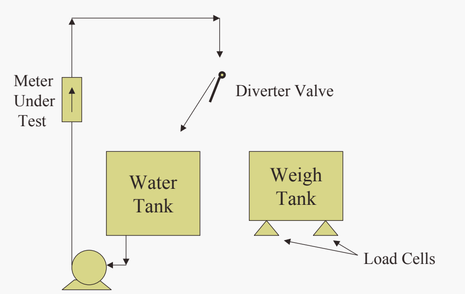
Primary Flowmeter Laboratory



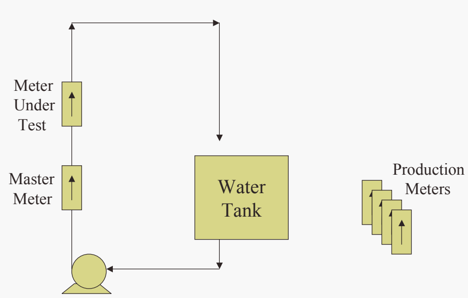
Primary Flowmeter Laboratory



Primary Flowmeter Laboratory



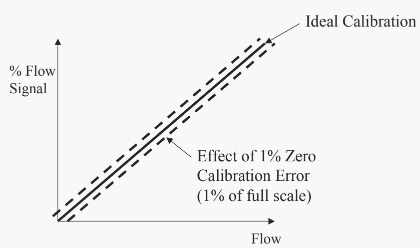
Flow Calibration Facility



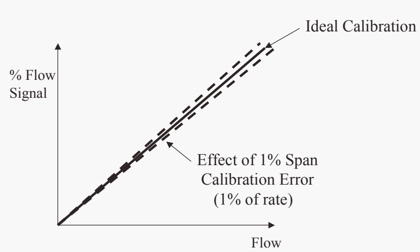
Dry Calibration

- *Dry calibration*
  - *Verify physical dimensions*
  - *Electronic techniques*
    - *Zero*
    - *Span*
    - *Scaling factor*
    - *Analog output*

Effect of Zero Calibration



Effect of Span Calibration



Calibration

- *Instruments with zero and span adjustments tend to have percent of full scale accuracy*
- *Instruments with a span adjustment and no zero adjustment tend to have percent of rate accuracy*
- *There are exceptions*

Seminar Outline

- *Introduction*
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- ***Measurement of Flowmeter Performance***
- *Miscellaneous Considerations*
- *Flowmeter Technologies*
- *Flowmeter Selection*

Measurement of Flowmeter Performance

- *Flow measurement system components*
  - *Flow range*
  - *Flowmeter*
  - *Transmitter*

Measurement of Flowmeter Performance

- *Flow measurement system components*
  - *Linearization*
  - *Digital conversion*
  - *Indicator*
  - *Totalization*

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Measurement of Flowmeter Performance

- *Overall flow measurement system performance*
  - *Combine components statistically (do not add mathematically)*
  - *Accuracy*
  - *Uncertainty (ISO GUM)*

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Seminar Outline

- *Introduction*
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- ***Miscellaneous Considerations***
- *Flowmeter Technologies*
- *Flowmeter Selection*

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Miscellaneous Considerations

- *Materials of construction*
  - *Corrosion*
  - *Abrasion/erosion*
  - *Pressure and temperature*
  - *Flange ratings*
  - *Contamination*

Miscellaneous Considerations

- *Velocity profile*
  - *Straight run*
    - *Reductions up/downstream of straight run*
    - *Flanges are part of straight run*
      - *Remove internal welding beads*
    - *Align gaskets so they do not intrude into pipe*
    - *Align flowmeter so it is centered in the pipe*

Miscellaneous Considerations

- *Velocity profile*
  - *Flow conditioner*
  - *Control valve downstream*
  - *Temperature tap downstream*
  - *Pressure tap upstream*

Miscellaneous Considerations

- *Piping considerations*
  - *Orientation*
    - *Full pipe*
    - *Single phase flow*
    - *Homogeneous flow*

Miscellaneous Considerations

- *Piping considerations*
  - *Support flowmeter*
    - *Do not have flowmeter supporting piping*
  - *Alignment*
    - *Axial*
    - *Face-to-face*
    - *Do not "spring" pipe*

Miscellaneous Considerations

- *Piping considerations*
  - *Bypass piping*
  - *Hydro-test considerations*
  - *Dirt*
  - *Coating*

Miscellaneous Considerations

- *Wiring*
  - *2-wire*
    - *Signal wires provide loop power*
  - *3-wire*
    - *Extra wire for power*
  - *4-wire*
    - *Separate signal and power wires (in separate conduits unless low voltage power is used)*

Miscellaneous Considerations

- *Safety*
  - *Grounding*
    - *Required for some flowmeters*
    - *Safety consideration for some services (oxygen)*
  - *Leakage*
  - *Area electrical classification*
  - *Lubricants and contamination*

Seminar Outline

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- ***Flowmeter Technologies***
- *Flowmeter Selection*

Flowmeter Technologies

- ***Introduction***
- *Differential Pressure*
- *Magnetic*
- *Mass*
- *Open Channel*
- *Oscillatory*
- *Positive Displacement*
- *Target*
- *Thermal*
- *Turbine*
- *Ultrasonic*
- *Variable Area*
- *Correlation*
- *Insertion*
- *Bypass*

Flowmeter Classes

- *Wetted moving parts*
  - *Positive displacement*
  - *Turbine*
  - *Variable area*

Flowmeter Classes

- *Wetted with no moving parts*
  - *Differential pressure*
  - *Oscillatory*
  - *Target*
  - *Thermal*

Flowmeter Classes

- *Obstructionless*
  - *Coriolis mass*
  - *Magnetic*
  - *ultrasonic*

Flowmeter Classes

- *Non-wetted (external)*
  - *Ultrasonic*
  - *Correlation*

Flowmeter Measurements

- *Volume*
  - *Positive displacement*

Flowmeter Measurements

- *Velocity*
  - *Magnetic*
  - *Oscillatory*
  - *Turbine*
  - *Ultrasonic*
  - *correlation*

Flowmeter Measurements

- *Inferential*
  - *Differential pressure*
  - *Target*
  - *Variable area*

Flowmeter Measurements

- *Mass*
  - *Coriolis mass*
  - *Thermal*

Flowmeter Technology Sections

- *Technologies are in alphabetical order*
- *Technology sections have similar organization*

Flowmeter Technologies

- *Introduction*
- ***Differential Pressure***
- *Magnetic*
- *Mass*
- *Open Channel*
- *Oscillatory*
- *Positive Displacement*
- *Target*

Thermal
Turbine
Ultrasonic
Variable Area
Correlation
Insertion
Bypass

Principle of Operation

- *A piping restriction is used to develop a pressure drop that is measured and used to infer fluid flow*
  - *Primary Flow Element*
  - *Transmitter (differential pressure)*

Principle of Operation

- *Bernoulli's equation states that energy is approximately conserved across a constriction in a pipe*
  - *Static energy (pressure head)*
  - *Kinetic energy (velocity head)*
  - *Potential energy (elevation head)*

Principle of Operation

- *Bernoulli's equation*
  - $P/(\rho \bullet g) + \frac{1}{2}v^2/g + y = \text{constant}$

P = absolute pressure
ρ = density
g = acceleration of gravity
v = fluid velocity
y = elevation

Principle of Operation

- *Equation of Continuity*
  - $Q = A \bullet v$

Q = flow (volumetric)
A = cross-sectional area
v = fluid velocity (average)

Principle of Operation

- *Apply the equation of continuity and Bernoulli's equation for flow in a horizontal pipe*
  - *Acceleration of gravity is constant*
  - *No elevation change*

Principle of Operation

- *Apply Bernoulli's equation upstream and downstream of a restriction*
- $P_1 + ½\,\rho \bullet v_1^2 = P_2 + ½\,\rho \bullet v_2^2$

Principle of Operation

- *Solve for the pressure difference and use the equation of continuity*
- $(P_1 - P_2) = ½\,\rho \bullet v_2^2 - ½\,\rho \bullet v_1^2$

  $= ½\,\rho\,[v_2^2 - v_1^2]$

  $= ½\,\rho\,[(A_1/A_2)^2 – 1] \bullet v_1^2$

  $= ½\,\rho\,[(A_1/A_2)^2 – 1] \bullet Q^2/A_1^2$

  $= constant \bullet \rho \bullet Q^2$

Principle of Operation

- *ΔP = constant • ρ • Q^2*
  - *Fluid density affects the measurement*
  - *Pressure drop is proportional to the square of the flow rate*
    - *Squared output flowmeter*
    - *Double the flow… four times the differential*

Principle of Operation

- *Q = constant • $(\Delta P/\rho)^{1/2}$*
  - *Fluid density affects the measurement*
  - *Flow rate is proportional to the square root of the differential pressure produced*
    - *Often called "square root flowmeter"*

Principle of Operation

- *Q is proportional to $1/\rho^{1/2}$*
- *Fluid density affects the measurement by approximately -1/2% per % density change*

Principle of Operation

- *Liquid density changes are usually small*
- *Gas and vapor density changes can be large and may need compensation for accurate flow measurement*
  - *Flow computers*
  - *Multivariable differential pressure transmitters*

Principle of Operation

Problem

- *What is the effect on a differential pressure flowmeter when the operating pressure of a gas is increased from 6 to 7 bar?*
  - *To simplify calculations, assume that atmospheric pressure is 1 bar abs*

Principle of Operation

- *The ratio of the densities is (7+1)/(6+1) = 1.14*
  - *The density of the gas increased 14 percent*
- *The flow measurement is proportional to the inverse of the square root of the density which is* $(1/1.14)^{1/2} = 0.94$
  - *The flow measurement will be approximately 6 percent low*

Principle of Operation

Problem

- *Calculate the differential pressures produced at various percentages of full scale flow*
  - *Assume 0-100% flow corresponds to 0-100 differential pressure units*

Principle of Operation

Differential pressure as a function of flow

Flow	*ΔP*	
100 %	*100*	*dp units*
50 %	*25*	*“ “*
20 %	*4*	*“ “*
10 %	*1*	*“ “*

Principle of Operation

- *Low flow measurement can be difficult*
  - *For example, only ¼ of the differential pressure is generated at 50 percent of the full scale flow rate. At 10 percent flow, the signal is only 1 percent of the differential pressure at full scale.*

Principle of Operation

Problem

- *What is the differential pressure turndown for a 10:1 flow range?*
  - *$0.1^2 = 0.01$, so at 10% flow the differential pressure is 1/100 of the differential pressure at 100% flow*
  - *The differential pressure turndown is 100:1*

Principle of Operation

- *Noise can create problems at low flow rates*
  - *0-10% flow corresponds to 0-1 dp units*
  - *90-100% flow corresponds to 81-100% dp units*

Principle of Operation

- *Noise at low flow rates can be reduced by low flow characterization*
  - *Force to zero*
  - *Linear relationship at low flow rates*

Principle of Operation

- *Square root relationship generally applies when operating above the Reynolds number constraint for the primary flow element*
  - *Operating below the constraint causes the flow equation to become linear with differential pressure (and viscosity)*
  - *Applying the incorrect equation will result in flow measurement error*

Principle of Operation

Problem

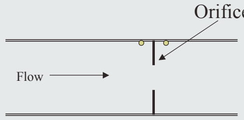
- *If the Reynolds number at 100% flow is 10,000, what is the turndown for accurate measurement if the primary flow element must operate in the turbulent flow regime?*
  - *10,000/4000, or 2.5:1*

Principle of Operation

Problem

- *Will the flowmeter operate at 10% flow?*
  - *It will create a differential pressure… however, Reynolds number will be below the constraint, so the flow measurement will not conform to the square root equation (and will not be accurate)*

Orifice Plate
Primary Flow Element



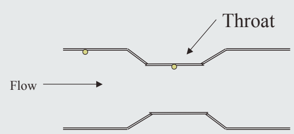
Orifice Plate
Primary Flow Elements

- *Concentric*
- *Conical*
- *Eccentric*
- *Integral*
- *Quadrant*
- *Segmental*

Orifice Plate Taps

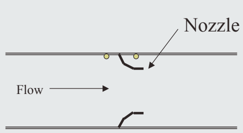
	Upstream	***Downstream***
Corner	*0D*	*0D*
Flange	*1 inch*	*1 inch*
Full flow	*2.5D*	*8D*
Radius	*1D*	*0.5D*
Vena Contracta	*1D*	*vena contracta*

Venturi
Primary Flow Element



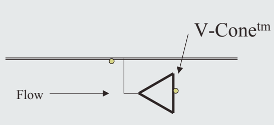
 223

Flow Nozzle
Primary Flow Element



 224

V-Cone^{tm}
Primary Flow Element



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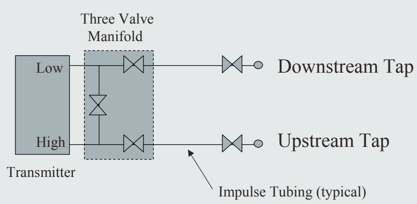
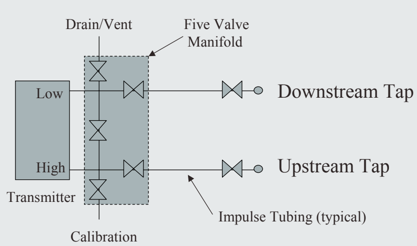
Differential Pressure Multi-Valve Manifold Designs

- *Multi-valve manifolds are used to isolate the transmitter from service for maintenance and calibration*
  - *One-piece integral assembly*
  - *Mounted on transmitter*

Differential Pressure Multi-Valve Manifold Designs



Differential Pressure Multi-Valve Manifold Designs



Differential Pressure Multi-Valve Manifold Designs

- *Removal from service*
  - *Open bypass valve (hydraulic jumper)*
  - *Close block valves*
  - *Be sure to close bypass valve to calibrate*
  - *Use calibration and vent/drain valves (five valve manifold)*

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Differential Pressure Multi-Valve Manifold Designs

- *Return to service*
  - *Open bypass valve (hydraulic jumper)*
  - *Open block valves*
  - *Close bypass valve*

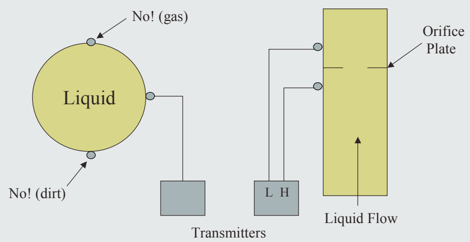
 230

Differential Pressure Multi-Valve Manifold Designs

- *Removal and return to service procedure may be different when flow of fluid in tubing/transmitter is dangerous*
  - *High pressure superheated steam*

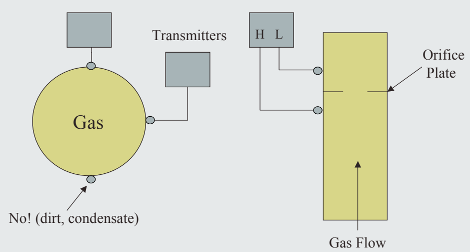
 231

Impulse Tubing



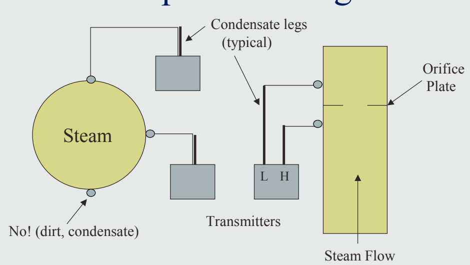
 232

Impulse Tubing



 233

Impulse Tubing



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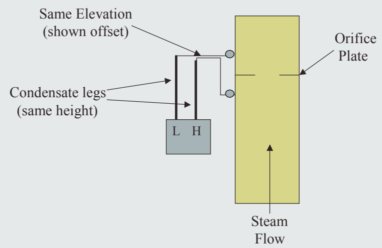
Impulse Tubing



Impulse Tubing

- *Liquids* *avoid collection of gas*
- *Gas* *avoid collection of liquid*
- *Vapor* *form condensate legs*
- *Hot* *locate transmitter far from taps*
- *Cold* *insulate and/or heat trace*

Flowmeter Technologies

- *Introduction*
- *Differential Pressure*
- ***Magnetic***
- *Mass*
- *Open Channel*
- *Oscillatory*
- *Positive Displacement*
- *Target*

Thermal
Turbine
Ultrasonic
Variable Area
Correlation
Insertion
Bypass

Principle of Operation

- *Faraday's Law of Electromagnetic Induction defines the magnitude of the voltage induced in a conductive medium moving at a right angle through a magnetic field*
  - *Most notably applied to electrical power generation*

Principle of Operation

- *Faraday's Law*

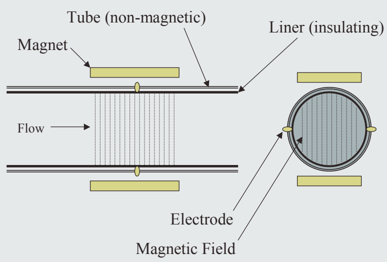
$$E = constant \cdot B \cdot L \cdot v$$

  - *B is the magnetic flux density*
  - *L is the path length*
  - *v is the velocity of the medium*

Principle of Operation

- ***Experiment***
  - *Galvanometer with wire between terminals*
  - *Horseshoe magnet*
  - *Moving the wire through the magnetic field moves the galvanometer indicator*
    - *Moving wire in opposite direction moves indicator in opposite direction*
    - *Moving wire faster moves indicator higher*

Principle of Operation



Principle of Operation

- *Magnetic flowmeters direct electromagnetic energy into the flowing stream*
- *Voltage induced at the electrodes by the conductive flowing stream is used to determine the velocity of fluid passing through the flowmeter*

Principle of Operation

- *Induced voltage*

$$E = constant \cdot B \cdot D \cdot v$$

- *Substituting $Q = A \cdot v$ and assuming that A, B, and D are constant yields:*

$$E = constant \cdot Q$$

Principle of Operation

- *The induced voltage at the electrodes is directly proportional to the flow rate*

$$E \alpha Q$$

Principle of Operation AC Excitation

- *Magnet is excited by an AC waveform*
- *Voltage waveform at electrode is also an AC waveform*

Principle of Operation AC Excitation

- *AC excitation was subject to:*
  - *Stray voltages in the process liquid*
  - *Electrochemical voltage potential between the electrode and process fluid*

Principle of Operation
AC Excitation

- *AC excitation was subject to:*
  - *Inductive coupling of the magnets within the flowmeter*
  - *Capacitive coupling between signal and power circuits*
  - *Capacitive coupling between interconnection wiring*

Principle of Operation
AC Excitation

- *Zero adjustments were used to compensate for these influences and the effect of electrode coating*
  - *Percent of full scale accuracy*

Principle of Operation
AC Excitation

- *Feeding power to the primary element, then back to the transmitter reduces the possibility of inducing voltage from the power wiring*
  - *Electromagnet is the large power draw*
  - *Signal voltage could be induced from wiring carrying current to the magnet*

Principle of Operation DC Excitation

- *Pulsed DC excitation reduces drift by turning the magnet on and off*

Magnet On = Signal + Noise

Magnet Off = Noise

Principle of Operation DC Excitation

- *Noise is canceled by subtracting these two measurements*

Signal + Noise – Noise = Signal

Principle of Operation DC Excitation

- *DC magnetic flowmeters automatically self-zero*
  - *Percent of rate accuracy*
  - *The 4mA analog output zero adjustment is not set automatically and still maintains a percent of full scale accuracy*

Principle of Operation DC Excitation

- *Response time can be compromised*

Magnetic Flowmeter Designs

- *Ceramic*
- *Electrodeless*
- *Low Flow*
- *Medium Flow*
- *High Flow*

Magnetic Flowmeter Designs

- *High Noise*
- *Low Conductivity*
- *Partially-full*
- *Response - Fast*
- *Sanitary*
- *Two-wire*

Magnetic Flowmeter Designs

- *External/Internal Coils*
- *Flanged*
- *Wafer*
- *Miniature*

Flowmeter Technologies

- *Introduction*
- *Differential Pressure*
- *Magnetic*
- ***Mass***
- *Open Channel*
- *Oscillatory*
- *Positive Displacement*
- *Target*

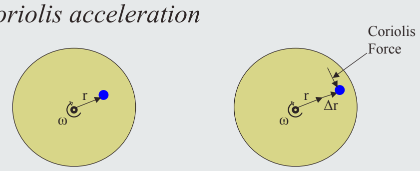
Thermal
Turbine
Ultrasonic
Variable Area
Correlation
Insertion
Bypass

Principle of Operation

- *Coriolis mass flowmeters use the properties of mass to measure mass*
  - *Thermal mass flowmeters assume constant thermal properties*

Principle of Operation

- *Coriolis acceleration*



Man Standing Still   Man Moving Outward

Principle of Operation

- *Man Standing Still*
  - *Velocity in tangential plane is constant*

$$
\begin{aligned}
F_{tang} &= m \bullet a_{tang} \\
&= m \bullet \Delta v_{tang} / \Delta t \\
&= m \bullet (r \bullet \omega - r \bullet \omega) / \Delta t \\
&= m \bullet 0 / \Delta t \\
&= 0 \text{ (no force in tangential plane)}
\end{aligned}
$$

Principle of Operation

- *Man Moving Outward*
  - *Velocity in tangential plane changes*

$$
\begin{aligned}
F_{tang} &= m \bullet a_{tang} \\
&= m \bullet \Delta v_{tang} / \Delta t \\
&= m \bullet ((r + \Delta r) \bullet \omega - r \bullet \omega) / \Delta t \\
&= m \bullet \Delta r \bullet \omega / \Delta t \\
&\neq 0 \text{ (force in tangential plane)}
\end{aligned}
$$

Principle of Operation

- *Components that produce Coriolis force*
  - *Rotation*
  - *Motion towards/away from center of rotation*
  - *Resultant Coriolis acceleration*

Principle of Operation

- *U-tube Coriolis mass flowmeter*
  - *Rotation*
    - *Oscillation about a plane parallel to the centerline of the piping connections*

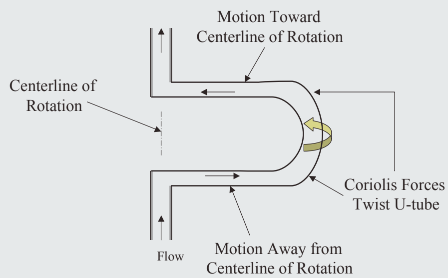
Principle of Operation

- *U-tube Coriolis mass flowmeter*
  - *Motion towards/away from center of rotation*
    - *Mass flow through U-tube towards/away from the centerline of piping connections*

Principle of Operation

- *U-tube Coriolis mass flowmeter*
  - *Coriolis force*
    - *Twist of U-tube*

Principle of Operation



Principle of Operation

Experiment

- *Hold a garden hose with both hands so it sags near the floor (like a U-tube)*
  - *Turning water on/off has little affect on the position of the hose*

Principle of Operation

Experiment

- *Swing the hose toward and away from your body*
  - *Turning on the water will cause the sides of the U-tube to move towards/away from you*
  - *Stopping the swinging will stop the movement and relax the U-tube*

Principle of Operation

- *Coriolis acceleration is proportional to the mass flow*
- *Coriolis acceleration generates a force*
- *Coriolis force twists the U-tube*

Principle of Operation

- *Mass flow is proportional to the Coriolis force that twists the U-tube*
  - *Measure the twist of the U-tube*

Principle of Operation

- *Amount of twist depends on mechanical properties of the U-tube*
  - *Material*
  - *Wall thickness*
  - *Temperature*

Principle of Operation

- *Temperature Measurement*
  - *Pipe wall temperature is measured to compensate for material properties*
  - *Many Coriolis mass flowmeters offer (an optional) temperature measurement output*
    - *Not process temperature*
    - *Outside pipe wall temperature*

Principle of Operation

- *Density Measurement*
  - *The frequency of oscillation is related to fluid density*
  - *Many Coriolis mass flowmeters offer (an optional) density measurement output*

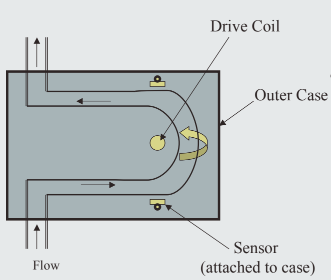
Principle of Operation

- *Viscosity Measurement*
  - *In the laminar flow regime, the mass flow measurement, temperature measurement, and external differential pressure measurement across the flowmeter is used to calculate viscosity*

Principle of Operation

- *Viscosity Measurement*
  - *To counteract the effects of pipe vibration, one Coriolis mass flowmeter uses a weight that twists the tube*
  - *Measurement of the forces due this twist are used to determine the fluid viscosity*

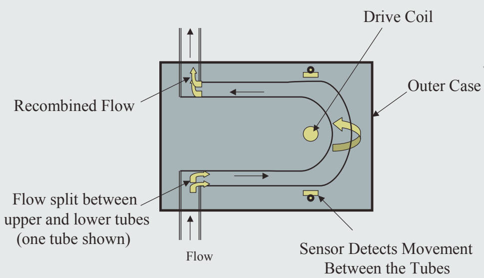
Tube Geometry – Single U-tube



Tube Geometry – Single U-tube

- *First practical design*
- *Sensors connected to case*
  - *Measure movement relative to case*
  - *Susceptible to pipe vibration*
  - *Rigid support structures*
    - *Metal plate*
    - *Concrete foundation*

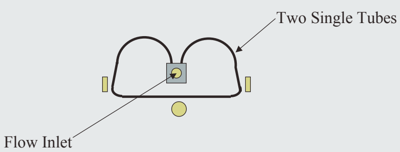
Tube Geometry – Dual U-tube



Tube Geometry – Dual U-tube

- *Flow split between two tubes*
- *Sensors connected to case*
  - *Measure relative movement of tubes*
  - *Reduced susceptibility to pipe vibration*
  - *Mount flowmeter in piping*

Tube Geometry – B-Tube



B-tube Design

Foxboro

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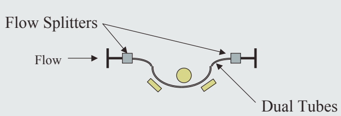
Tube Geometry – Curved Tube



Curved Tube Design

Endress+Hauser, Micromotion, Oval

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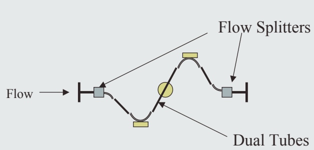
Tube Geometry – Curved Tube



Curved Tube Design

ABB

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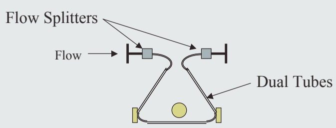
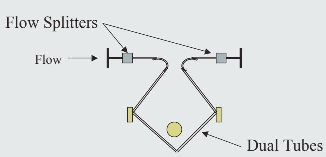
Tube Geometry – Delta



Delta Tube Design

Micromotion

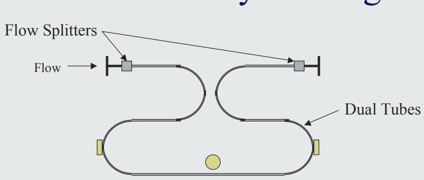
Tube Geometry – Diamond



Diamond Tube Design

Kueppers

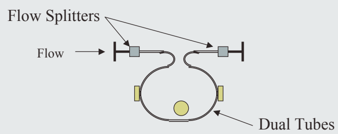
Tube Geometry – Omega



Omega Tube Design

Actaris (Schlumberger)

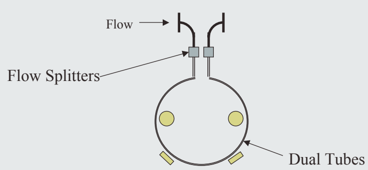
Tube Geometry – Omega



Omega Tube Design

Heinrichs

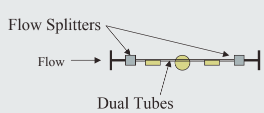
Tube Geometry – Round



Round Tube Design

Rheonik

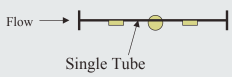
Tube Geometry – Straight



Straight Dual Tube Design

Endress+Hauser

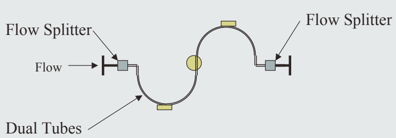
Tube Geometry – Straight



Straight Single Tube Design

Brooks, Endress+Hauser, Krohne, Micromotion, Oval

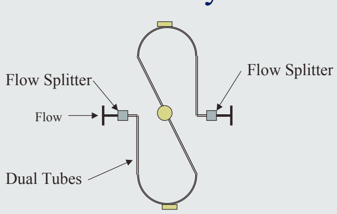
Tube Geometry – S-Tube



S-Tube Design

FMC Energy Systems

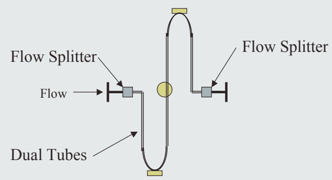
Tube Geometry – S-Tube



S-Tube Design

FMC Energy Systems

Tube Geometry – S-Tube



S-Tube Design

Krohne

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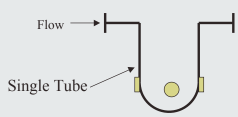
Tube Geometry– U-Tube

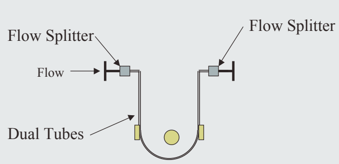


Single U-Tube Design

Brooks, Micromotion

293

Tube Geometry– U-Tube

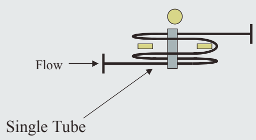


Dual U-Tube Design

Micromotion, Oval, Yokogawa

294

Tube Geometry – U-Tube



U-Tube Design
Danfoss

 295

Fluid Characteristics

- *Single-phase homogeneous*
  - *Liquid*
  - *Gas*
  - *Vapor*

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Fluid Characteristics

- *Two-phase*
  - *Liquid/solid*
  - *Liquid/gas*
- *Avoid flashing*

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Fluid Characteristics

- *Within accurate flow range*
- *Corrosion and erosion*
- *Immiscible fluids*

Piping and Hydraulics

- *For liquid applications, keep the flowmeter full of liquid*
  - *Hydraulic design*
    - *Vertical riser preferred*
    - *Avoid inverted U-tube*

Piping and Hydraulics

- *For liquid applications, orient to self-fill and self-drain*
  - *Self-filling is important to ensure a full pipe*
    - *If not, special precautions must be taken when zeroing the flowmeter*
    - *If not, gas/vapor can accumulate, especially at low flow conditions*

Piping and Hydraulics

- *For liquid applications, keep the flowmeter full of liquid*
  - *Hydraulic design*
    - *Be careful when flowing downwards*
    - *Be careful when flowing by gravity*

Piping and Hydraulics

- *For gas/vapor applications, keep the flowmeter full of gas/vapor*
  - *Hydraulic design*
    - *Self-draining*
    - *Vertical preferred*
    - *Avoid U-tube*

Piping and Hydraulics

- *For gas/vapor applications, calculate pressure drop carefully*
  - *Mass flow range of a given size flowmeter is fixed*
  - *Relatively small mass occupies a relatively large volume*
  - *High velocity and high pressure drop result*
  - *Flowmeter will operate low in its range*

Performance

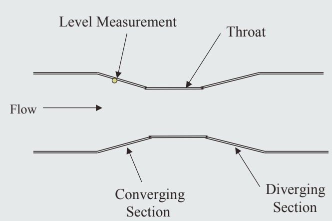
- *Premium*
  - *Typical: 0.1% rate plus zero stability*
- *Low cost*
  - *Typical: larger of 0.5% rate or zero stability*
- *Analog output*
  - *Typical: up to 0.1% of full scale*
  - *Sometimes not available*

Flowmeter Technologies

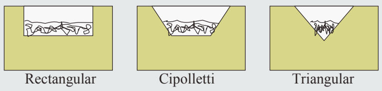
- *Introduction*
- *Differential Pressure*
- *Magnetic*
- *Mass*
- ***Open Channel***
- *Oscillatory*
- *Positive Displacement*
- *Target*

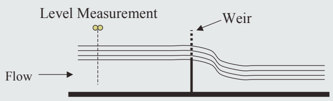
Thermal
Turbine
Ultrasonic
Variable Area
Correlation
Insertion
Bypass

Open Channel - Flume Primary Flow Element



Open Channel - Weir Primary Flow Element





Flowmeter Technologies

- *Introduction*
- *Differential Pressure*
- *Magnetic*
- *Mass*
- *Open Channel*
- ***Oscillatory***
- *Positive Displacement*
- *Target*
- *Thermal*
- *Turbine*
- *Ultrasonic*
- *Variable Area*
- *Correlation*
- *Insertion*
- *Bypass*

Principle of Operation

- *Fluidic flowmeters are flowmeters that generate oscillations as a result of flow*
  - *The number of oscillations can be related to the flow rate*

Principle of Operation

- *Examples of fluidic phenomena*
  - *Wind whistling through branches of trees*
  - *Swirls downstream of a rock in a flowing stream*
  - *Flag waving in breeze*

Principle of Operation

- *Fluidic flowmeters*
  - *Fluidic flowmeter (Coanda effect)*
  - *Vortex precession flowmeter (swirl)*
  - *Vortex shedding flowmeter*

Coanda Effect Fluidic Flowmeter

- *Coanda Effect*
  - *Flow tends to attach itself to flat surface*
- *Fluidic oscillator*
  - *Passages allow portion of flow to feed back and impinge on incoming stream*
  - *Alternating attachment*

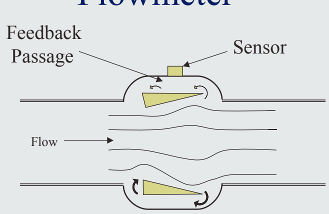
Coanda Effect Fluidic Flowmeter

- *Frequency of alternating attachments is proportional to flow*
  - *Doubling the flow doubles the number of attachments*

Coanda Effect Fluidic Flowmeter

- *Reynolds number constraints*
  - *Over 500*

Coanda Effect Fluidic Flowmeter



Coanda Effect Fluidic Flowmeter

- *Sensors*
  - *Deflection*
  - *Thermal*

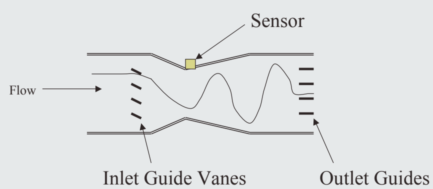
Vortex Precession Flowmeter

- *Often called a "swirlmeter"*
- *Inlet vanes cause the flow to spin and form a cyclone*
- *The tip of the cyclone moves around the inside pipe wall (precession)*
- *Outlet vanes remove swirl from the flow*

Vortex Precession Flowmeter

- *Speed that vortex rotates around the pipe is proportional to flow*
  - *Doubling the flow doubles the precession*

Vortex Precession Flowmeter



Vortex Precession Flowmeter

- *Sensors*
  - *Piezoelectric*

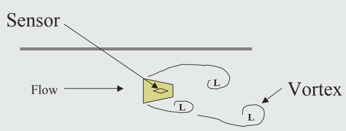
Vortex Shedding Flowmeter

- *An obstruction (bluff body or strut) is located in the flow stream*
  - *Low flow - fluid flows around obstruction*
  - *High flow - alternating vortices are formed*
    - *Number of vortices formed is proportional to fluid velocity*

Vortex Shedding Flowmeter

- *The sensing system detects the vortices created*
- *The frequency of the vortices passing the sensing system is proportional to fluid velocity*

Vortex Shedding Flowmeter



Vortex Shedding Flowmeter

- *Bluff body is typically approximately 20% of the pipe ID*
  - *Pressure drop across similar vortex shedders in the same service is similar*
    - *For liquids: 5 psid at 15 ft/sec*
      400 mbar at 5 m/s

Vortex Shedding Flowmeter

Problem

- *What is the approximate pressure drop across a vortex shedder at 7.5 ft/sec?*

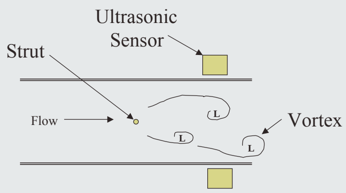
Vortex Shedding Flowmeter

- *(5 • 7.5/15) = 2.5 psig might be tempting, but in the turbulent flow regime, the pressure drop across a restriction varies as the square of the flow*
  - *Double the flow, four times the differential*
  - *The pressure drop will be 5 • $(7.5/15)^2$ = 1.25 psig approximately*

Vortex Shedding Flowmeter

- *Strut design is like a "piano wire"*
  - *Gas flow measurement*
  - *Low pressure drop*

Vortex Shedding Flowmeter



Vortex Shedding Flowmeter Sensing Systems

- *Shedder and sensing system tradeoffs are made in the design process to:*
  - *operate linearly*
  - *operate at low velocity*
  - *operate at low Reynolds numbers*

Vortex Shedding Flowmeter Sensing Systems

- *Shedder and sensing system tradeoffs are made in the design process to:*
  - *reduce the effect of short straight run*
  - *reduce the effects of misalignment*
  - *reduce the effects of vibration*

Vortex Shedding Flowmeter Sensing Systems

- *Shedder and sensing system tradeoffs are made in the design process to:*
  - *reduce the possibility of leaks*
    - *All-welded body designs*

Vortex Shedding Flowmeter Sensing Systems

- *Hydraulic energy to operate the sensing system is usually provided by the fluid*
  - *Flowmeter turns off at low velocity*

Vortex Shedding Flowmeter Sensing Systems

- *Velocity constraint is a function of density*
  - *Lower density increases low velocity limit*
  - *Higher density decreases low velocity limit*

Vortex Shedding Flowmeter Sensing Systems

- *Typical Velocity Constraints*
  - *Water* 0.35 m/s 1 ft/sec
  - *Free air* 6.5 m/s 21 ft/sec
  - *Air (8 bar)* 3.5 m/s 11.5 ft/sec

Vortex Shedding Flowmeter Sensing Systems

- *Reynolds Number Constraint*
- *Sufficient Reynolds number is needed to generate oscillations*
  - *Flowmeter turns off at low Reynolds numbers*

Vortex Shedding Flowmeter Sensing Systems

- *Reynolds number constraints*
  - *Linear operation* over 10-30,000
  - *Turn off* 3-10,000
  - *Nonlinear* between turn off / linear
  - *Small sizes*
    - *Lower Reynolds number limits*

Vortex Shedding Flowmeter Sensing Systems

- *Both Reynolds number and velocity constraints must be satisfied for vortex shedding flowmeters to operate*

Vortex Shedding Flowmeter Sensing Systems

Problem

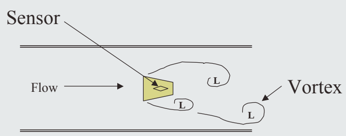
- *Will a vortex shedding flowmeter measure the flow of a liquid operating at a Reynolds number of 1,000,000 at a velocity of 0.1 m/s?*
  - *No --- the velocity is below the minimum velocity constraint*

Vortex Shedding Flowmeter Sensing Systems

Problem

- *Will a vortex shedding flowmeter measure the flow of a liquid operating at a Reynolds number of 100 at a velocity of 10 m/s?*
  - *No --- the velocity is below the minimum Reynolds number constraint*

Vortex Shedding Sensor Deflection



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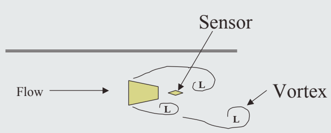
Vortex Shedding Sensor Deflection



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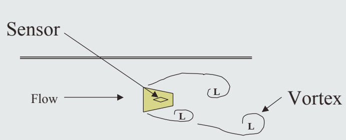
Vortex Shedding Sensor Differential Pressure



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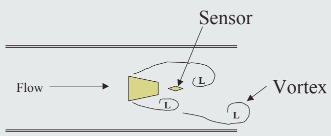
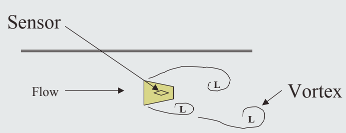
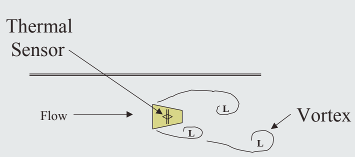
Vortex Shedding Sensor Differential Pressure



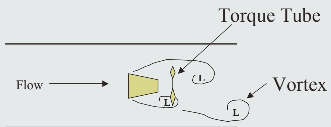
Vortex Shedding Sensor Shedder Twist



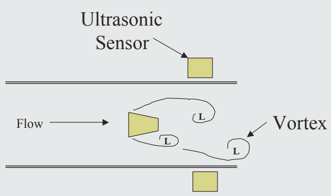
Vortex Shedding Sensor Thermal



Vortex Shedding Sensor Torque Tube



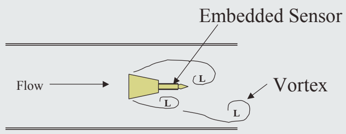
Vortex Shedding Sensor Ultrasonic



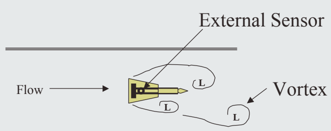
Vortex Shedding Flowmeter Sensing Systems

- *Vibration effects*
- *Acceleration compensation*
  - *Fishtail design with embedded sensor*
  - *Fishtail design with counterbalancing*
  - *Torque tube design*
  - *Shedder twist design*

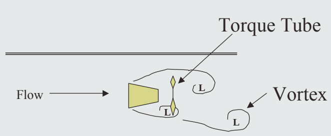
Vortex Shedding Sensor Fishtail Design



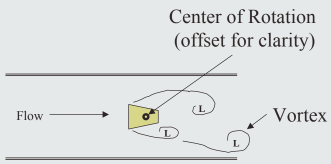
Vortex Shedding Sensor Fishtail Design



Vortex Shedding Sensor Torque Tube



Vortex Shedding Sensor Shedder Twist



Vortex Shedding Flowmeter Sensing Systems

- *Early designs were not balanced*
- *Subsequent designs were balanced*
- *No mass designs (such as thermal and ultrasonic) do not have to be acceleration compensated*

Vortex Shedding Sensor Multivariable

- *Embedded temperature sensors*
- *Embedded flow computer*
  - *Pressure and temperature compensation*
  - *Reynolds number compensation*

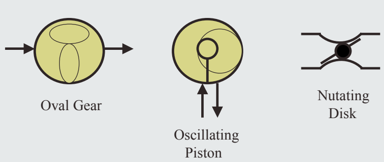
Flowmeter Technologies

- *Introduction*
- *Differential Pressure*
- *Magnetic*
- *Mass*
- *Open Channel*
- *Oscillatory*
- ***Positive Displacement***
- *Target*
- *Thermal*
- *Turbine*
- *Ultrasonic*
- *Variable Area*
- *Correlation*
- *Insertion*
- *Bypass*

Positive Displacement Flowmeter

- *Positive displacement flowmeters measure flow by repeatedly entrapping fluid within the flowmeter*
  - *Moving parts with tight tolerances*
  - *Bearings*
  - *Many shapes*

Positive Displacement Flowmeters



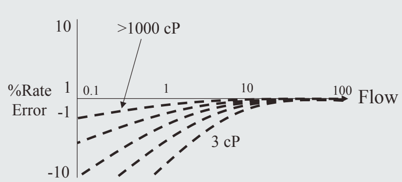
Positive Displacement Flowmeter

- *Sensing systems*
  - *Mechanical*
  - *Magnetic*
  - *Radio frequency*
  - *Optical*

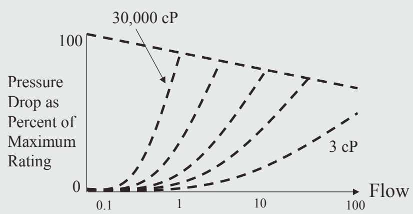
Positive Displacement Flowmeter

- *Maintenance*
  - *Plugging*
  - *Bearing wear*
  - *Abrasion*
  - *Leaks*

Positive Displacement Flowmeter



Positive Displacement Flowmeter



Flowmeter Technologies

- *Introduction*
- *Differential Pressure*
- *Magnetic*
- *Mass*
- *Open Channel*
- *Oscillatory*
- *Positive Displacement*
- ***Target***
- *Thermal*
- *Turbine*
- *Ultrasonic*
- *Variable Area*
- *Correlation*
- *Insertion*
- *Bypass*

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Target Flowmeter

- *Target flowmeters determine flow by measuring the force exerted on a body (target) suspended in the flow stream*

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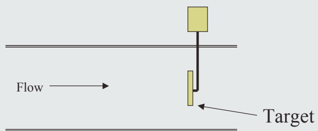
Target Flowmeter



Target Flowmeter

- *Dynamic balance with flowing stream*
- *Same equations as differential pressure flowmeters*
  - *Affected by density (+1% specific gravity change affects flowmeter by -0.5%)*

Target Flowmeter

- *Maintenance*
  - *Target wear*
  - *Coating*
  - *Leaks*
  - *Drift*

Flowmeter Technologies

- *Introduction*
- *Differential Pressure*
- *Magnetic*
- *Mass*
- *Open Channel*
- *Oscillatory*
- *Positive Displacement*
- *Target*
- ***Thermal***
- *Turbine*
- *Ultrasonic*
- *Variable Area*
- *Correlation*
- *Insertion*
- *Bypass*

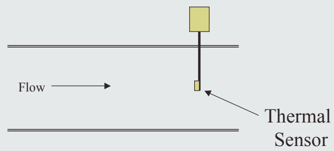
Thermal Flowmeter

- *Thermal flowmeters use the thermal properties of the fluid to measure flow*
  - *Hot Wire Anemometer*
  - *Thermal Profile*

Thermal Flowmeter
Hot Wire Anemometer

- *Hot wire anemometers determine flow by measuring the amount of energy needed to heat a probe whose heat loss changes with flow rate*

Thermal Flowmeter
Hot Wire Anemometer



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Thermal Flowmeter
Thermal Profile

- *Thermal profile flowmeters determine flow by measuring the temperature difference that results in a heated tube when the fluid transfers heat from the upstream portion to the downstream portion of the flowmeter*

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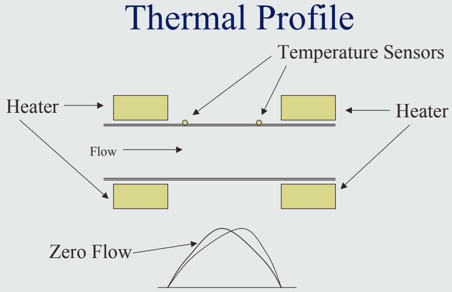
Thermal Flowmeter
Thermal Profile



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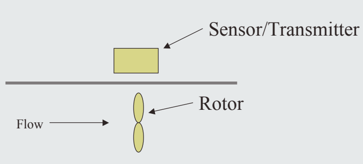
Flowmeter Technologies

- *Introduction*
- *Differential Pressure*
- *Magnetic*
- *Mass*
- *Open Channel*
- *Oscillatory*
- *Positive Displacement*
- *Target*
- *Thermal*
- ***Turbine***
- *Ultrasonic*
- *Variable Area*
- *Correlation*
- *Insertion*
- *Bypass*

Turbine Flowmeter

- *Fluid flow causes a rotor to spin whereby the rotor speed is proportional to fluid velocity*
  - *Primary Flow Element*
  - *Transmitter*

Turbine Flowmeter



Turbine Flowmeter

- *The sensor detects the rotor blades*
- *The frequency of the rotor blades passing the sensor is proportional to fluid velocity*

Turbine Flowmeter

- *Operating constraints*
  - *Turbulent flow regime*
  - *10-600mm (0.5 to 24 inch)*
  - *Application-specific designs have limited temperature capability (natural gas)*
  - *Minimum/maximum velocity*
  - *Lubricity (often difficult to quantify)*

Turbine Flowmeter

- *Maintenance*
  - *Bearing wear*
  - *Rotor damage*
  - *Sensor failure*

Turbine Flowmeter

- *Designs*
  - *Axial*
  - *Paddle wheel*
  - *Propeller*
  - *Tangential*

Flowmeter Technologies

- *Introduction*
- *Differential Pressure*
- *Magnetic*
- *Mass*
- *Open Channel*
- *Oscillatory*
- *Positive Displacement*
- *Target*

Thermal
Turbine
Ultrasonic
Variable Area
Correlation
Insertion
Bypass

Principle of Operation

- *Ultrasonic flowmeters direct ultrasonic energy into the flowing stream*
- *Information from the remnants of this energy is used to determine the velocity of fluid passing through the flowmeter*

Principle of Operation

- *Sensing the remnants is predicated upon a complete ultrasonic circuit*
  - *Transmitting device*
  - *Entry pipe wall (and liner)*
  - *Fluid (and reflections off pipe wall)*
  - *Exit pipe wall (and liner)*
  - *Receiving device*

Principle of Operation

- *To function properly, all parts of the ultrasonic circuit must allow sufficient energy to pass*

Principle of Operation

- *Weak signals may cause the flowmeter to be erratic or cease to function*
  - *Paint*
  - *Dry ultrasonic coupling compound*
  - *Pipe wall coating or corrosion*
  - *Poorly bonded liner*
  - *Tuberculation (barnacles)*

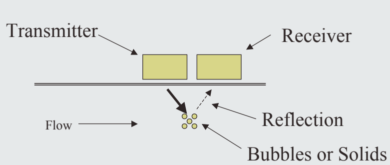
Principle of Operation

- *Ultrasonic noise may cause the flowmeter to be erratic or cease to function*
  - *Nearby radio transmitter*
  - *Control valve with "quiet" trim*

Principle of Operation Doppler Ultrasonic

- *Doppler ultrasonic flowmeters reflect ultrasonic energy from particles, bubbles and/or eddies flowing in the fluid*

Principle of Operation Doppler Ultrasonic



Principle of Operation Doppler Ultrasonic

- *Under no flow conditions, the frequencies of the ultrasonic beam and its reflection are the same*
- *With flow in the pipe, the difference between the frequency of the beam and its reflection increases proportional to fluid velocity*

Principle of Operation Doppler Ultrasonic

- *Doppler Equation*

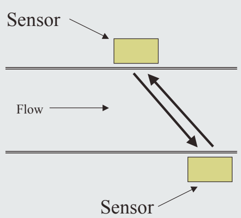
$$v_f = K \bullet \Delta f$$

  - *K = constant*
  - v_f *= velocity of fluid where ultrasonic energy is reflected*
  - Δf *= difference between the transmitted and reflected frequencies*

Principle of Operation Transit Time Ultrasonic

- *Transit time (time-of-flight) ultrasonic flowmeters alternately transmit ultrasonic energy into the fluid in the direction and against the direction of flow*

Principle of Operation
Transit Time Ultrasonic



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Principle of Operation
Transit Time Ultrasonic

- *The time difference between ultrasonic energy moving upstream and downstream in the fluid is used to determine fluid velocity*

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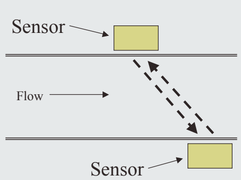
Principle of Operation
Transit Time Ultrasonic

- *Under no flow conditions, the time for the ultrasonic energy to travel upstream and downstream are the same*



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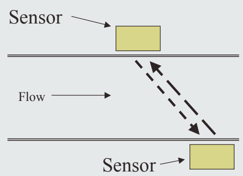
Principle of Operation
Transit Time Ultrasonic

- *With flow in the pipe, the time for the ultrasonic energy to travel upstream will be greater than the downstream time*



Principle of Operation
Transit Time Ultrasonic

- *Transit Time Equation*

$$v_p = \frac{K \bullet (T_u - T_d)}{T_u \bullet T_d}$$

  - v_p = *average fluid velocity in the path*
  - K = *constant*
  - T_u = *upstream transit time in fluid*
  - T_d = *downstream transit time in fluid*

Principle of Operation
Transit Time Ultrasonic

- T_u *and* T_d *are dependent upon the speed of sound in the fluid*
- *Some designs use measurements and equations that are not dependent upon the speed of sound in the fluid*

Principle of Operation
Pulse Repetition Ultrasonic

- *Pulse repetition (sing-around) ultrasonic flowmeters alternately transmit ultrasonic energy into the fluid in the direction and against the direction of flow*
- *The receipt of one ultrasonic pulse triggers the sending of a new ultrasonic pulse*

Principle of Operation
Pulse Repetition Ultrasonic

- *The frequency that the pulses are repeated is used to determine fluid velocity*

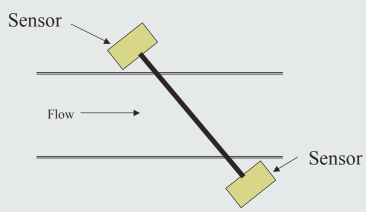
Principle of Operation
Pulse Repetition Ultrasonic

- *Pulse Repetition Equation*

$$v_p = K \bullet (f_u - f_d)$$

  - v_p = *average fluid velocity in the path*
  - K = *constant*
  - f_u = *frequency of upstream transit time period*
  - f_d = *frequency of downstream transit time period*

Single Path Geometry



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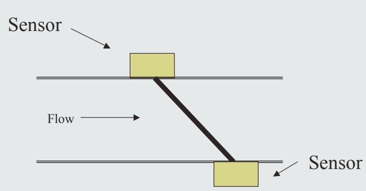
Single Path Geometry



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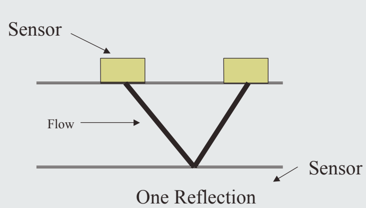
Single Path Geometry



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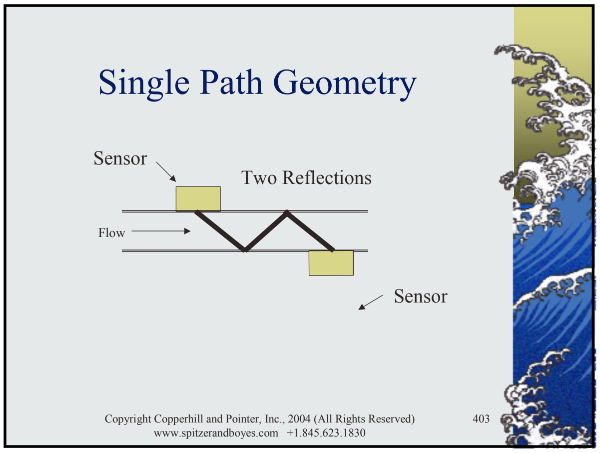
Single Path Geometry
Sensor
Two Reflections
Flow
Sensor
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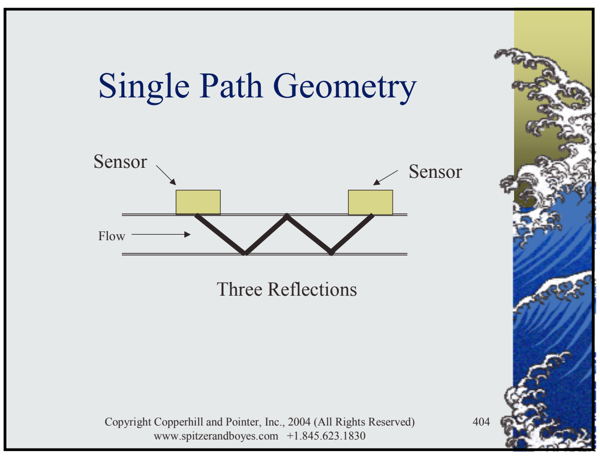
Single Path Geometry
Sensor
Sensor
Flow
Three Reflections
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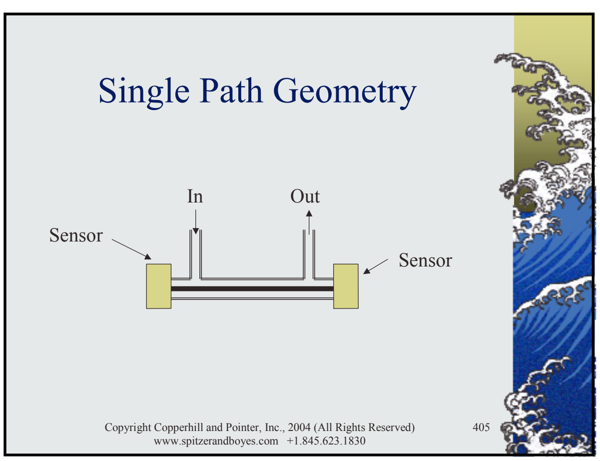
Single Path Geometry
In
Out
Sensor
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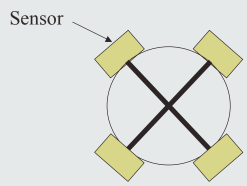
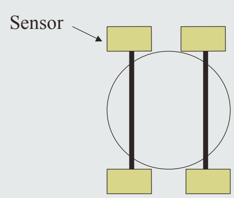
Multiple Path Geometry



Chordal Path Geometry



Ultrasonic Flowmeters

- *Applications (general)*
  - *Large pipes*
  - *Flashing fluids*
  - *Corrosive fluids*
  - *Hazardous fluids*

Ultrasonic Flowmeters

- *Applications (specific)*
  - *Custody transfer*
    - *Natural gas*
    - *Petroleum products*
  - *Stack gas*
  - *Flare gas*

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Flowmeter Technologies

- *Introduction*
- *Differential Pressure*
- *Magnetic*
- *Mass*
- *Open Channel*
- *Oscillatory*
- *Positive Displacement*
- *Target*
- *Thermal*
- *Turbine*
- *Ultrasonic*
- ***Variable Area***
- *Correlation*
- *Insertion*
- *Bypass*

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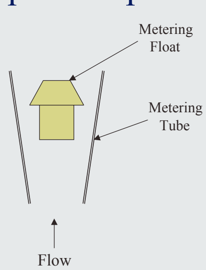
Principle of Operation



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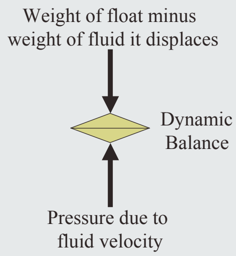
Principle of Operation



Flowmeter Technologies

- *Introduction*
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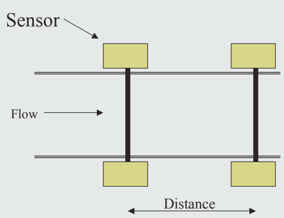
- *Variable Area*
- ***Correlation***
- *Insertion*
- *Bypass*

Correlation Flowmeters Principle of Operation

- *Correlation flowmeters determine fluid velocity by measuring parameters associated with the flowing stream at different places in the piping*

Correlation Flowmeters
Ultrasonic



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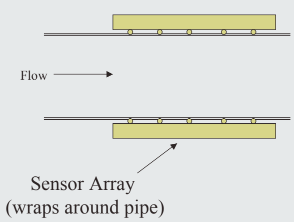
Correlation Flowmeters
Pressure Sensor Array



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Flowmeter Technologies

- *Introduction*
- *Differential Pressure*
- *Magnetic*
- *Mass*
- *Open Channel*
- *Oscillatory*
- *Positive Displacement*
- *Target*

Thermal
Turbine
Ultrasonic
Variable Area
Correlation
Insertion
Bypass

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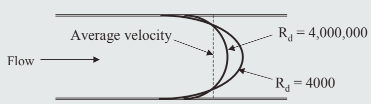
Insertion Flowmeter

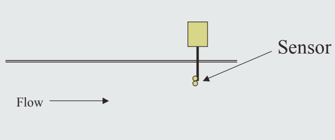
- *Insertion flowmeter infer the flow in the entire pipe by measuring flow at one or more strategic locations in the pipe*

Insertion Flowmeter

Theoretical Velocity Profile



Insertion Flowmeter



Insertion Flowmeter

- *Technologies*
  - *Differential Pressure*
  - *Magnetic*
  - *Target*
  - *Thermal*
  - *Turbine*
  - *Vortex*

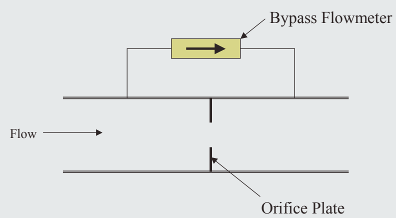
Flowmeter Technologies

- *Introduction*
- *Differential Pressure*
- *Magnetic*
- *Mass*
- *Open Channel*
- *Oscillatory*
- *Positive Displacement*
- *Target*
- *Thermal*
- *Turbine*
- *Ultrasonic*
- *Variable Area*
- *Correlation*
- *Insertion*
- ***Bypass***

Principle of Operation

- *Divide the flowing fluid into a large and small flowing stream*
  - *It is important to ensure a known ratio between these flows*
- *Measure the flow of the small stream to infer the total flow of the fluid*

Bypass Flowmeter Orifice Plate



Seminar Outline

- *Introduction*
- *Fluid Flow Fundamentals*
- *Performance Measures*
- *Linearization and Compensation*
- *Totalization*
- *Flowmeter Calibration*
- *Measurement of Flowmeter Performance*
- *Miscellaneous Considerations*
- *Flowmeter Technologies*
- ***Flowmeter Selection***

Factors in Flowmeter Selection

- *Flowmeter classes*
  - *Wetted moving parts*
  - *No wetted moving parts*
  - *Obstructionless*
  - *Non-wetted (external)*

Factors in Flowmeter Selection

- *Flowmeter measurements*
  - *Volume*
  - *Velocity*
  - *Mass*
  - *Inferential*

Factors in Flowmeter Selection

- *Performance*
  - *Accuracy*
- *End use*
  - *Indication*
  - *Control*
  - *Totalization*
  - *Alarm*

Factors in Flowmeter Selection

- *Power requirements*
- *Safety*
- *Rangeability*
- *Materials of construction*
- *Maintainability*

Factors in Flowmeter Selection

- *Ease of application*
- *Ease of installation*
- *Installed cost*
- *Operating cost*
- *Maintenance cost*

Data for Flowmeter Selection

- *Performance*
- *Fluid properties*
  - *Fluid name*
  - *Fluid state(s)*
  - *Compatibility of materials*
  - *Pressure and temperature*

Data for Flowmeter Selection

- *Fluid properties*
  - *Specific gravity and density*
  - *Fluid viscosity*
  - *Operating range*
  - *Other (conductivity, thermal capacity, vapor pressure…)*

Data for Flowmeter Selection

- *Installation*
  - *Pipe size*
  - *Differential pressure*
  - *Pipe vibration*
  - *Pulsating flow*
  - *Straight run*
  - *Ambient conditions*

Data for Flowmeter Selection

- *Operation*
  - *Maintenance*
  - *Availability of parts and service*
  - *Installed cost*
  - *Operating cost*

Data for Flowmeter Selection

- *Future considerations*
  - *Plant expansion*
- *Risk*

Flowmeter Selection

- *Typical selection process*
  - *Trial and error until one "works"*
  - *Potential lost opportunity*

Flowmeter Selection

- *Proposed selection process*
  - *Disqualify inappropriate technologies using technical and non-technical criteria*
  - *Select the best flowmeter from the remaining technologies*

Flowmeter Selection

- *Technical criteria*
  - *Items or issues that absolutely disqualify a technology*
- *Non-technical criteria*
  - *Preferences*

Review and Questions

- *Introduction*
- *Fluid Flow Fundamentals*
- *Performance Measures*
- *Linearization and Compensation*
- *Totalization*
- *Flowmeter Calibration*
- *Measurement of Flowmeter Performance*
- *Miscellaneous Considerations*
- *Flowmeter Technologies*
- *Flowmeter Selection*

Industrial Flow Measurement

Seminar Presented by
David W. Spitzer
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