

## Strømningsmåling

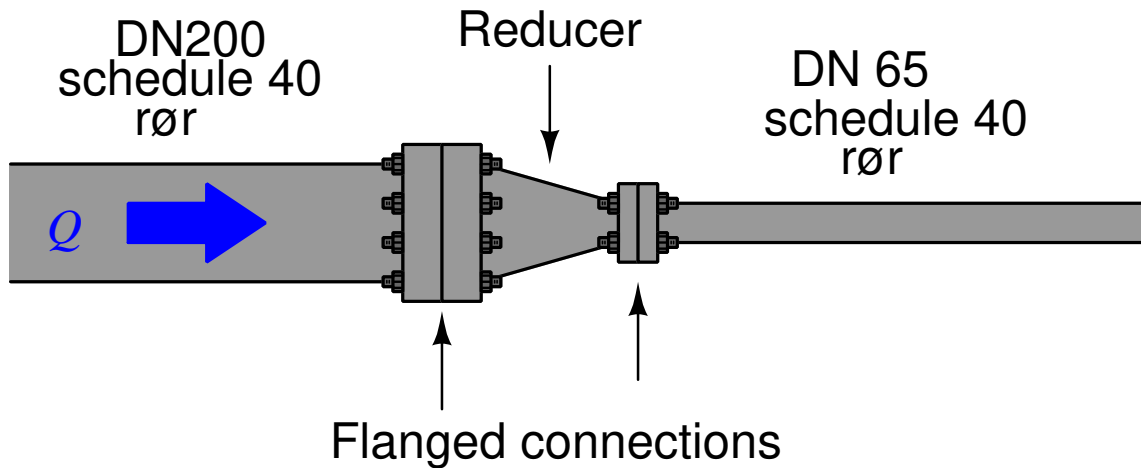
Kompetansemål:

- montere, konfigurere, kalibrere og idriftsettelse digitale og analoge målesystemer
- måle fysiske størrelser i automatiserte anlegg

## Oppgaver

### Oppgave 1

Vi har et rør som det strømmer olje med en strømningsrate på  $120 \text{ m}^3/\text{h}$  og en temperatur på  $50^\circ\text{C}$ . Begge seksjonene er etter schedule 40. Den første delen av røret har dimensjon DN200 (ID=202.74mm) og den andre delen har dimensjon DN65 (ID=62.68mm)



Regn ut hastigheten for fluidet i røret i hver av seksjonene. Regn også ut den volumetriske strømningsraten i *gallons per minute* (GPM).

I hvilken seksjon av røret har oljestrømmen høyest reynolds nummer?

### Suggestions for Socratic discussion

- This question is a good application of the *Law of Continuity*, but this law is really nothing more than an expression of a more fundamental law in physics. What is this more fundamental law, and what does it tell us about flow through a pipe?
- Once we know the fluid velocity in one section of the pipe, show how we may calculate the velocity in the other section of the pipe using nothing but a ratio of pipe diameters ( $\frac{7.981}{2.469}$ ), rather than re-calculate the continuity formula again ( $v = \frac{Q}{A}$ ).
- Where along this pipe will individual fluid molecules possess the greatest kinetic energy?

Schedule 40 Pipe 8 Inch (DN200 mm)

Standard : ANSI/ASME B36.10(Steel Pipe)

– Size : NPS 8 Inch

– Size : DN200 mm

– Inside Dimeter(Pipe ID) : 202.74 mm

– Outside Dimeter(Pipe OD) : 219.1 mm

– Pipe Wall Thickness : 8.18 mm

– Pipe Weight : 42.55 Kilogram per meter (kg/m)

– Pipe Weight Including Water : 74.81 Kilogram per meter (kg/m)

NPS = Nominal pipe size(inch) / DN = Diameter nominal(mm)

Schedule 40 Pipe 2 1/2 Inch (DN65 mm)

Standard : ANSI/ASME B36.10(Steel Pipe)

– Size : NPS 2 1/2 Inch

– Size : DN65 mm

– Inside Dimeter(Pipe ID) : 62.68 mm

– Outside Dimeter(Pipe OD) : 73 mm

– Pipe Wall Thickness : 5.16 mm

– Pipe Weight : 8.63 Kilogram per meter (kg/m)

– Pipe Weight Including Water : 11.71 Kilogram per meter (kg/m)

NPS = Nominal pipe size(inch) / DN = Diameter nominal(mm)

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### Oppgave 2

A flowmeter installed in a DN150 schedule 40 pipe (internal diameter = 154.051 mm) to measure the flow of olive oil requires a Reynolds number of at least 12,500 to function properly. Calculate the minimum flow rate of oil through this pipe that the flowmeter can measure, assuming the oil's density is  $917.9 \text{ kg/m}^3$  and its absolute viscosity is 111 centipoise.

Additionally, calculate the minimum average flowing velocity of the olive oil for the flowmeter to properly function.

### **Suggestions for Socratic discussion**

- How may a piping system be modified to increase the Reynolds number of the flow, for the sake of measuring that flow rate with a flowmeter requiring a high Reynolds number? Keep in mind that the actual flow rate is fixed here – we must vary something else to boost Reynolds number for any given flow rate.
- Does the temperature of the liquid have any effect on its Reynolds number? Why or why not?
- If this pipe were flowing water rather than olive oil, what would the minimum flow rate be to satisfy the Reynolds number requirement of this flowmeter?

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### Oppgave 3

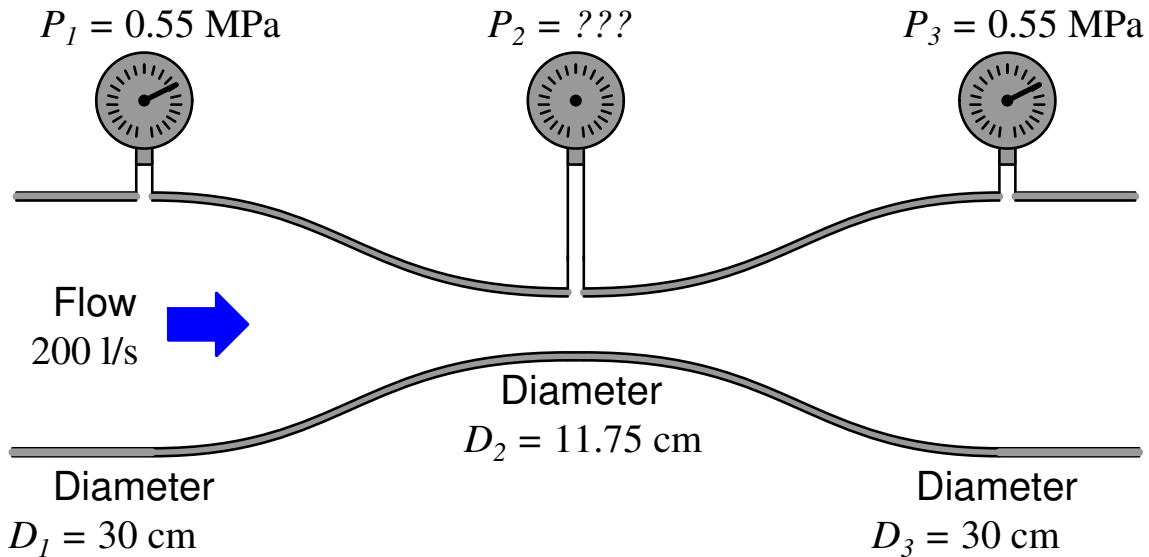
Read and outline the “Bernoulli’s Equation” subsection of the “Fluid Mechanics” section of the “Physics” chapter in your *Lessons In Industrial Instrumentation* textbook. Note the page numbers where important illustrations, photographs, equations, tables, and other relevant details are found. Prepare to thoughtfully discuss with your instructor and classmates the concepts and examples explored in this reading.

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Oppgave 4

Bruk Bernoulli's formel for å regne ut trykket  $P_2$ . Massetettheten til fluidet er  $\rho = 800 \text{ kg/m}^3$



Bernoulli's formel:

$$z_1 \rho g + \frac{v_1^2 \rho}{2} + P_1 = z_2 \rho g + \frac{v_2^2 \rho}{2} + P_2$$

Where,

$z$  = Height of fluid, in meter (m)

$\rho$  = Mass density of fluid, in kg per kubikkmeter ( $\text{kg/m}^3$ )

$g$  = Acceleration of gravity ( $9.81 \text{ m/s}^2$ )

$v$  = Hastigheten til fluidet i meter per sekund (m/s)

$P$  = Trykket av fluidet i Pascal ( $\text{Pa} = \text{N/m}^2$ )

Til slutt regn ut differansetrykket i dette venturi måleelementet. ( $\Delta P$ )

**Suggestions for Socratic discussion**

- The textbook outlines a general strategy for generating a problem-solving plan when tackling problems with complex mathematical formulae. Specifically, this strategy involved writing out the formulae and linking variables between formulae with arrow symbols. Explain how this strategy works, and show how it may be applied to the solution of this problem.
- A very helpful strategy for tackling Bernoulli's equation problems is to create a table in which to place each of the "head" terms of that equation. Explain why this is helpful to manage this specific type of problem.
- Once we know the velocity of the fluid ( $v$ ) at any point in the tube, is there a way to easily solve for the velocity in any other point in the tube based on a ratio of tube diameters? For instance, here we know there is a 5:12 ratio of diameters from

the throat to the mouth of the tube. How can we employ this 5:12 ratio to easily determine the velocity at one point (either mouth or throat) knowing the velocity at another?

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#### Oppgave 5

As best as possible, define *Reynolds number* for a fluid flow using your own words.

Regn ut reynolds nummer for 32 liter vann per sekund (at 20° C) som strømmer i et rør med en diameter på 22 cm.

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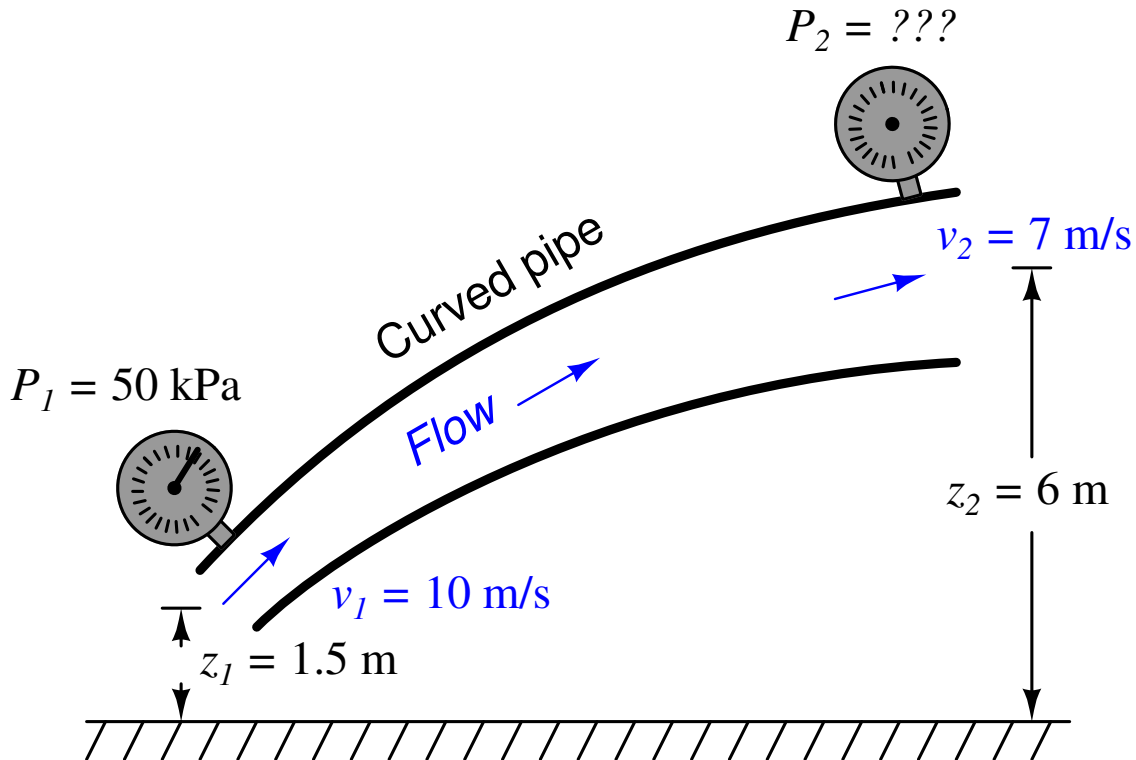
#### Oppgave 6

Jeg kan fylle et kar på 4 liter kjøkken springen på 30 sekunder. Røret til kjøkkenspringen har en ID=12.5mm. Regn ut Reynolds tall for denne strømmingen. Vil det være turbulent eller laminær stømning?

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Oppgave 7

Regn ut trykket på utløpet av dette røret ( $P_2$ ), om en antar at det strømmer vann ( $\rho = 998.19$ ) og at strømmingen skjer uten friksjon. (en får ikke trykktap som følge av friksjon mot rørveggen).



Bernoulli's equation:

$$z_1 \rho g + \frac{v_1^2 \rho}{2} + P_1 = z_2 \rho g + \frac{v_2^2 \rho}{2} + P_2$$

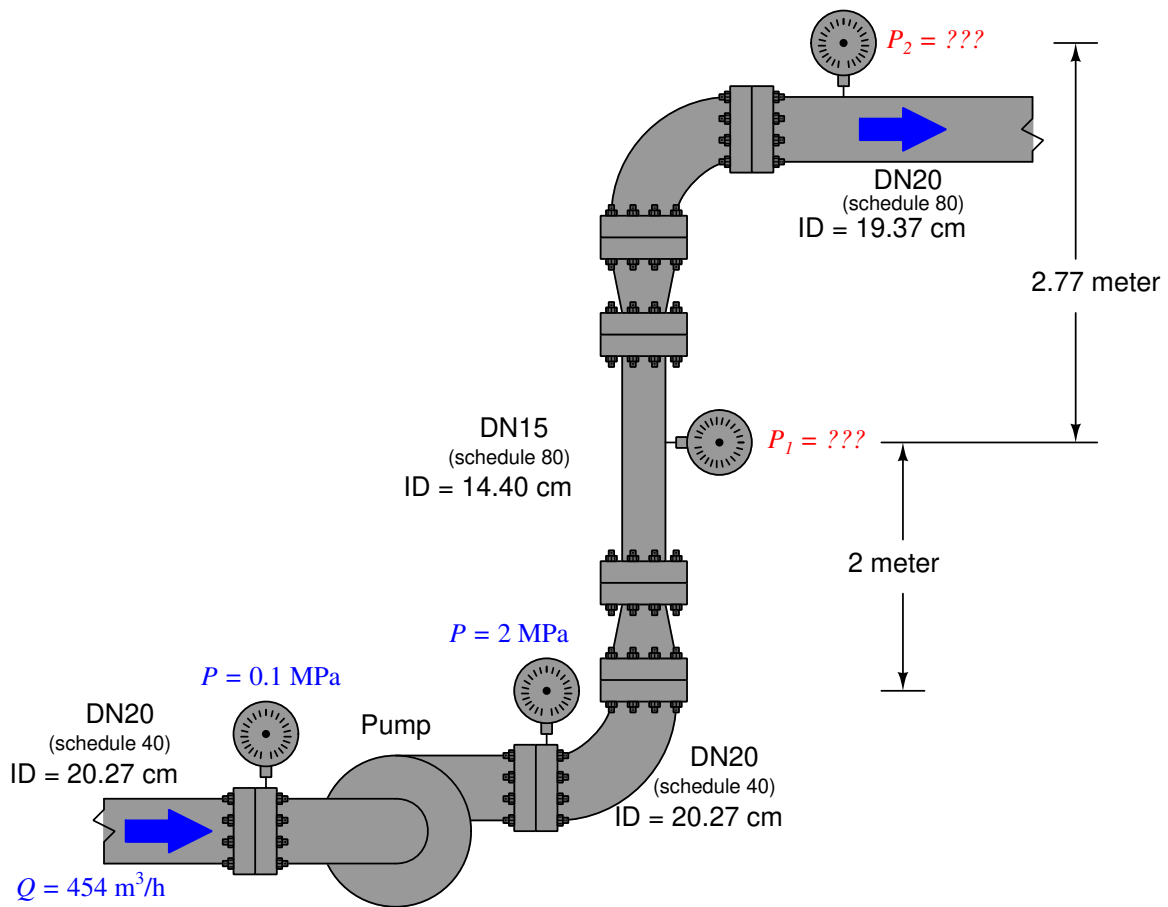
**Suggestions for Socratic discussion**

- One way students commonly fail to arrive at the correct answers with Bernoulli's Law calculations is by using incompatible units of measurement. Show how all the units of measurement provided to you in this question are compatible in their given forms, with no need for conversion.

[file i00450](#)

Oppgave 8

Regn ut trykkene  $P_1$  and  $P_2$ , anta at massetettheten til fluidet er  $886.45 \text{ kg/m}^3$ .

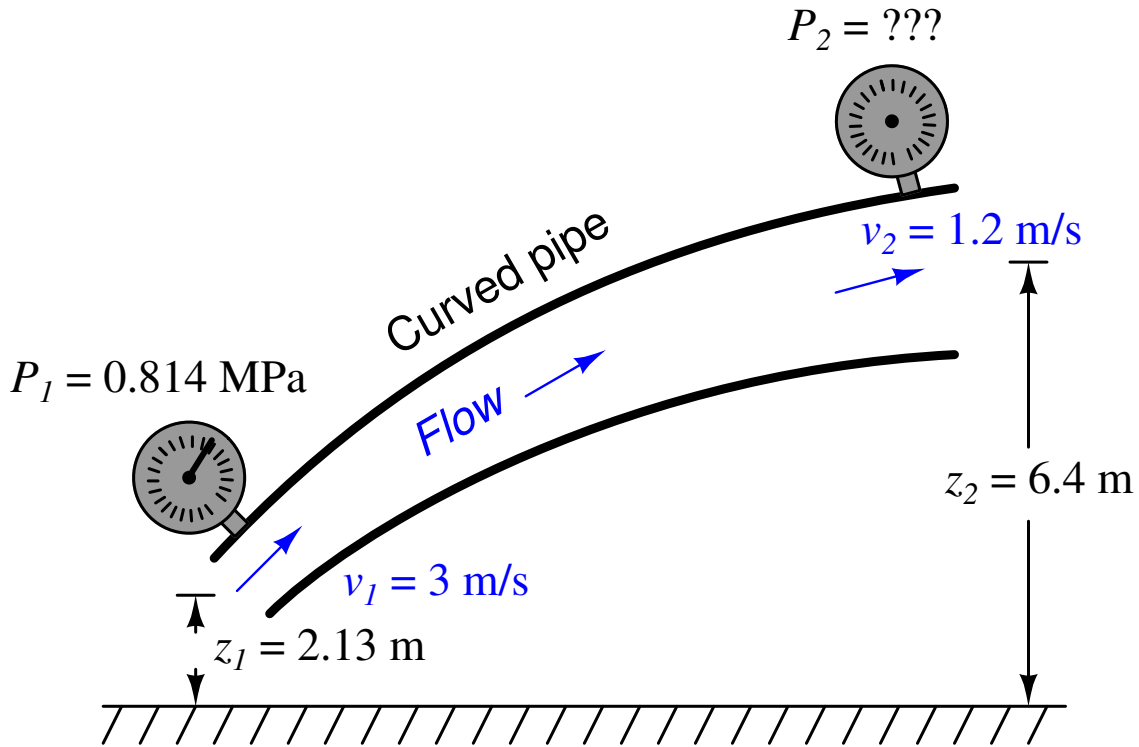


Also, comment on whether or not Bernoulli's equation could be used to compare the suction and discharge pressures of the pump, being that those two pressures (145 and 302 PSI) are measured on the same size pipe, with the same flow rate, and very similar elevations (heights).

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Opgave 9

Calculate the pressure at the discharge end of this pipe ( $P_2$ ), assuming water as the fluid (with a mass density  $\rho = 1005.5 \text{ kg/m}^3$ ),  $9.81 \text{ m/s}^2$  as the acceleration of gravity ( $g$ ), and frictionless flow (no pressure loss due to friction):



Bernoulli's equation:

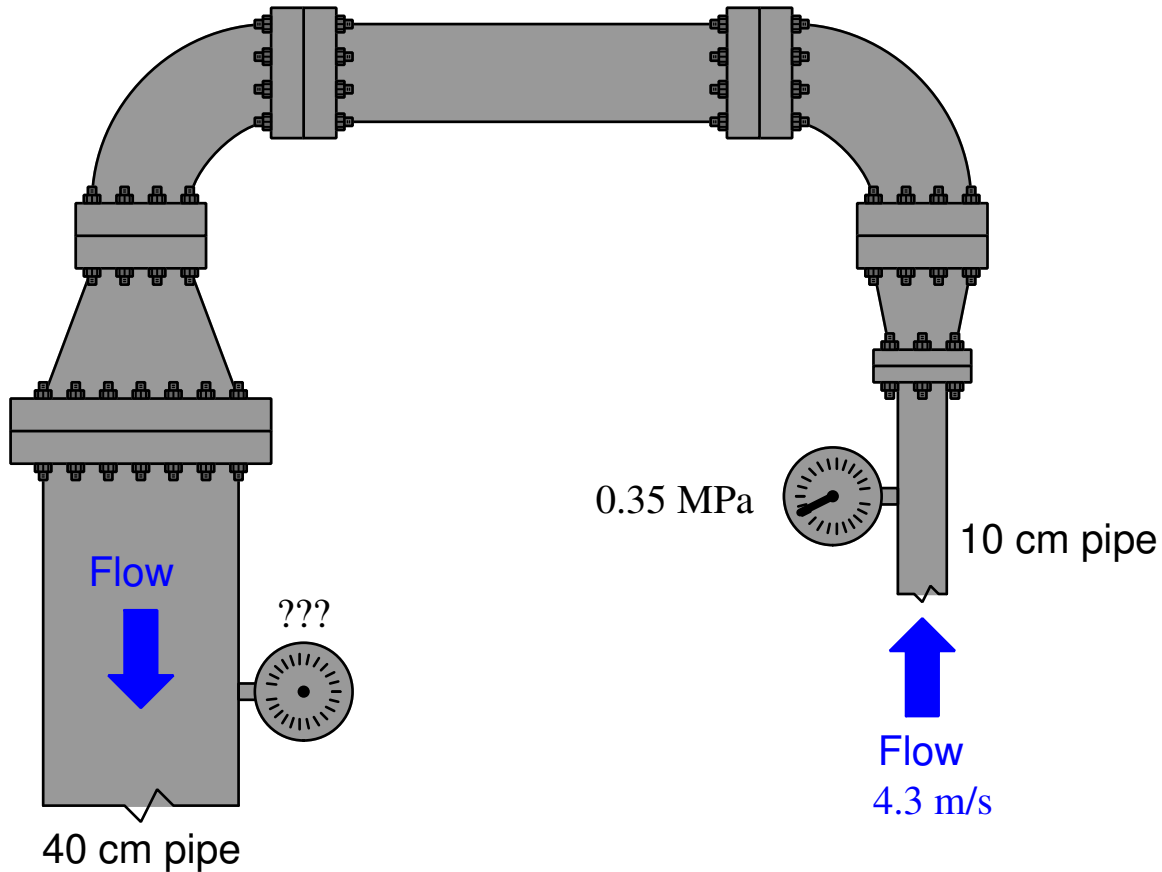
$$z_1 \rho g + \frac{v_1^2 \rho}{2} + P_1 = z_2 \rho g + \frac{v_2^2 \rho}{2} + P_2$$

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### Opgave 10

The following illustration shows a portion of water piping from an overhead view, looking down toward the ground (a “birds-eye” view). The pipe itself is completely level (parallel) with the ground, so that all points along the pipe centerline are at the same height:



The inlet pressure gauge shows 0.35 MPa, and the velocity of the water entering through the 10 cm pipe is known to be 4.3 meters per second. Both pressure gauges are fixed at the centerline of the pipe, and are thus at the exact same height. Calculate the pressure registered at the outlet gauge (on the 40 cm pipe section) in units of MPa, assuming inviscid (frictionless) flow throughout, and a mass density for water of  $\rho = 1005.5 \text{ kg/m}^3$ .

**Bernoulli's equation:**

$$z_1 \rho g + \frac{v_1^2 \rho}{2} + P_1 = z_2 \rho g + \frac{v_2^2 \rho}{2} + P_2$$

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## Oppgave 11

The rate of volumetric flow through *any* head-generating flow element is proportional to the square root of the differential pressure measured across it, so long as the flow regime is “fully-developed” turbulent:

$$Q \propto \sqrt{P}$$

Re-write this proportionality in the form of an equation, then solve for the new constant of proportionality ( $k$ ) given these full-flow ratings for an orifice plate:

- Full flow  $Q = 270 \text{ m}^3/\text{h}$
- $\Delta P$  at full flow = 25 kPa

Now that you have a value for  $k$ , solve for the differential pressure across the orifice plate at these flow rates:

- $Q = 110 \text{ m}^3/\text{h}$  ;  $\Delta P = \underline{\hspace{2cm}}$  kPa
- $Q = 55 \text{ m}^3/\text{h}$  ;  $\Delta P = \underline{\hspace{2cm}}$  kPa
- $Q = 140 \text{ m}^3/\text{h}$  ;  $\Delta P = \underline{\hspace{2cm}}$  kPa
- $Q = 215 \text{ m}^3/\text{h}$  ;  $\Delta P = \underline{\hspace{2cm}}$  kPa

### **Suggestions for Socratic discussion**

- Explain why we need not pay attention to maintaining compatible units of measurement for flow and pressure when solving this type of problem the way we did when using Bernoulli’s equation directly.
- Why is it okay to use this general formula for *any* primary flow element based on differential pressure? There are many different types of flow elements (venturis, orifices, nozzles, Pitot tubes, segmented wedge tubes, etc.), each with its own unique design. What is common to all these elements that the same basic equation form may be used to describe the operation of them all?

[file i00474](#)

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### Oppgave 12

Suppose a 6 inch V-cone flow element is sized to generate a  $\Delta P$  of 30 kPa at a flow rate of  $160 \text{ m}^3/\text{h}$ . Determine the new differential pressure instrument calibration ranges if this same flow element will now be used to measure the following water flow ranges:

- $Q$  range = 0 to  $110 \text{ m}^3/\text{h}$  ;  $\Delta P$  range = \_\_\_\_\_
- $Q$  range = 0 to  $140 \text{ m}^3/\text{h}$  ;  $\Delta P$  range = \_\_\_\_\_
- $Q$  range = 0 to  $180 \text{ m}^3/\text{h}$  ;  $\Delta P$  range = \_\_\_\_\_
- $Q$  range = 0 to  $230 \text{ m}^3/\text{h}$  ;  $\Delta P$  range = \_\_\_\_\_

#### Suggestions for Socratic discussion

- If the density of the fluid being measured by this flowmeter were to suddenly change, would it affect the *zero*, the *span*, or the *linearity* of the flowmeter's calibration?

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### Oppgave 13

A horizontal venturi tube at a seawater desalinization plant is sized to produce 37.25 kPa while flowing at  $1400 \text{ m}^3/\text{h}$  of sea water (at a density of 1.025 grams per cubic centimeter).

Calculate the differential pressure produced by this same venturi tube at a flow rate of  $740 \text{ m}^3/\text{h}$ , and at a lighter density of  $1.01 \text{ g}/\text{cm}^3$ .

Assuming a water density of  $1.03 \text{ g}/\text{cm}^3$  and a measured differential pressure of 3.1 PSID, calculate the volumetric flow rate through the venturi tube.

Assuming a water density of  $1.02 \text{ g}/\text{cm}^3$  and a measured differential pressure of 12 kPaD, calculate the volumetric flow rate through the venturi tube.

#### Suggestions for Socratic discussion

- What is the purpose of a “desalinization” plant, and where might you expect to find one?

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Oppgave 14

A Foxboro pneumatic square root extractor has a calibrated range of 3 to 15 PSI for both input and output. Complete the following table of values for this relay, assuming perfect calibration (no error). Be sure to show your work!

| Input signal (PSI) | Percent of input span (%) | Percent of output span (%) | Output signal (PSI) |
|--------------------|---------------------------|----------------------------|---------------------|
| 5                  |                           |                            |                     |
| 13                 |                           |                            |                     |
|                    | 50                        |                            |                     |
|                    | 30                        |                            |                     |
|                    |                           | 80                         |                     |
|                    |                           | 15                         |                     |
|                    |                           |                            | 7                   |
|                    |                           |                            | 12                  |

**Suggestions for Socratic discussion**

- Why are pneumatic square-root extractors all but obsolete in modern industry? What has replaced their functionality?
- Share problem-solving techniques for obtaining answers to this problem.

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Oppgave 15

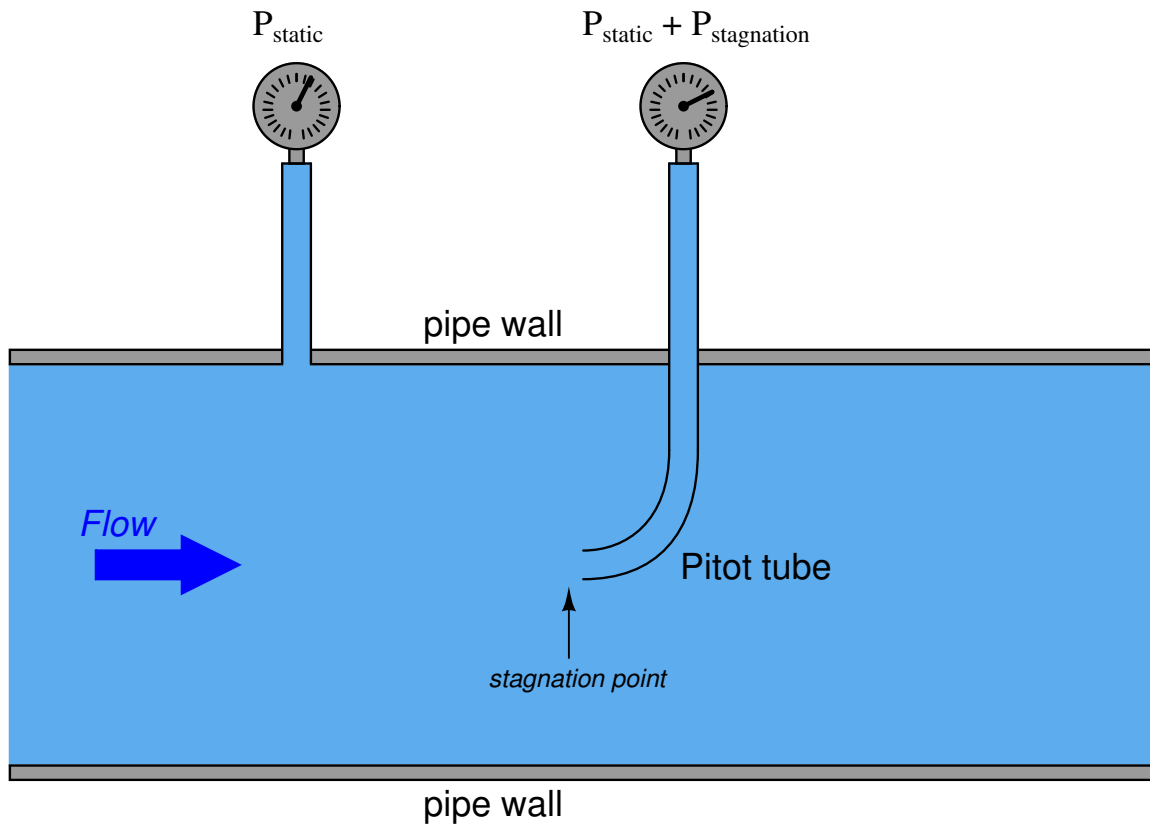
Calculate the volumetric flow rate (in units of cubic meters per minute) for water flowing out of the 25.4 cm diameter (ID) discharge pipe of a centrifugal pump at a velocity of 7.62 meter per second. Then, convert that flow rate into units of gallons per minute.

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Oppgave 16

As fluid flows past a stationary object such as a *Pitot tube*, the fluid immediately in front of the tube comes to a full stop. This is called a *stagnation point*, and the pressure resulting from the complete loss of velocity at the stagnation point is called the *stagnation pressure*.



Manipulate Bernoulli's equation to show how this stagnation pressure is determined by fluid velocity ( $v$ ).

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Oppgave 17

Calculate the pressure developed by a Pitot tube measuring air speed at 80 km/h, at sea level ( $\rho_{\text{air}} = 1.21114 \text{ kg/m}^3$ ).

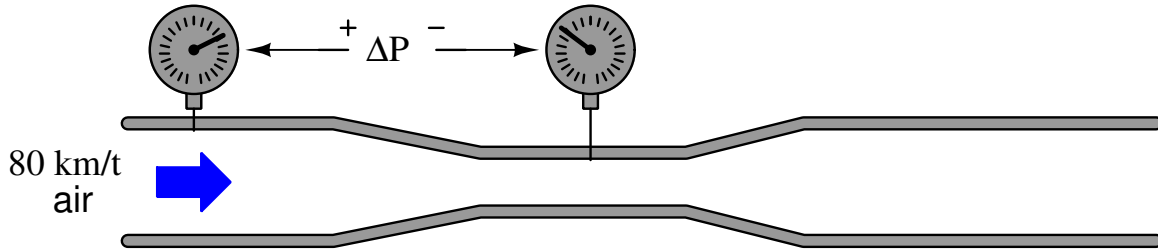
Also, how much pressure will the Pitot tube develop at twice the air speed (160 km/h)?

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### Oppgave 18

Calculate the differential pressure developed by an open venturi tube measuring air speed at 80 km/h, at sea level ( $\rho_{air} = 1.21114 \text{ kg/m}^3$ , where the throat diameter is one-half that of the entrance diameter:

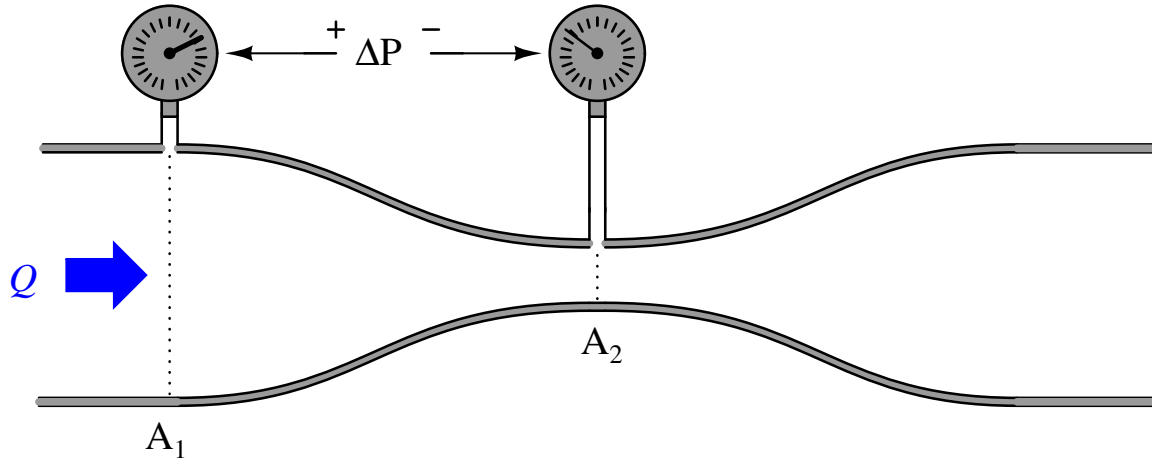


Also, how much pressure will the venturi tube develop at twice the air speed (160 km/h)?  
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### Oppgave 19

From Bernoulli's equation, develop a formula for calculating volumetric flow rate ( $Q$ ) given differential pressure drop  $\Delta P$  between two flow streams with differing cross-sectional areas ( $A_1$  and  $A_2$ ). Assume an incompressible fluid ( $\rho = \text{constant}$ ) flowing along a level path ( $z_1 = z_2$ ), and recall that volumetric flow rate is equal to the product of cross-sectional area and fluid velocity ( $Q = Av$ ).



**Bernoulli's equation:**

$$z_1 \rho g + \frac{v_1^2 \rho}{2} + P_1 = z_2 \rho g + \frac{v_2^2 \rho}{2} + P_2$$

[file i02983](#)

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## Oppgave 20

Two flow-indicating instruments employ a common orifice plate to measure the flow of water through a pipe. The full differential pressure generated by this orifice plate at its rated flow of 800 GPM is 120 inches water column (120 "WC):

- Receiver gauge (3-15 PSI input) connected to the output of a pneumatic DP transmitter connected across the orifice, registering 385 GPM on a 0-800 GPM square-root scale
- Panel-mounted indicator (3-15 PSI) connected to the output of the same pneumatic DP transmitter, registering 403 GPM on a 0-800 GPM square-root scale

Based on this information, where do you think the calibration error is located? If there isn't enough information yet to pinpoint the location of the error, devise a test to reveal where the error is.

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## Oppgave 21

Suppose a turbine flowmeter used to measure the flow of natural gas has a “K factor” equal to 0.02688 SL per pulse. Calculate the following:

The total amount of gas volume passed through the flowmeter after a digital counter circuit records 2,594,620 pulses.

The flow rate through the meter (i SLM) with the pulse signal having a frequency of 94 Hz.

The amount of time required (in units of hours and minutes) to accumulate 525,000 pulses (on a digital counter circuit) give a steady flow rate of 170 SLM.

Suppose someone entered the wrong K factor value into the digital electronic transmitter connected to the turbine meter’s pickup coil. Would this cause a *zero shift*, a *span shift*, a *linearity error*, or a *hysteresis error*? Explain your reasoning.

### Suggestions for Socratic discussion

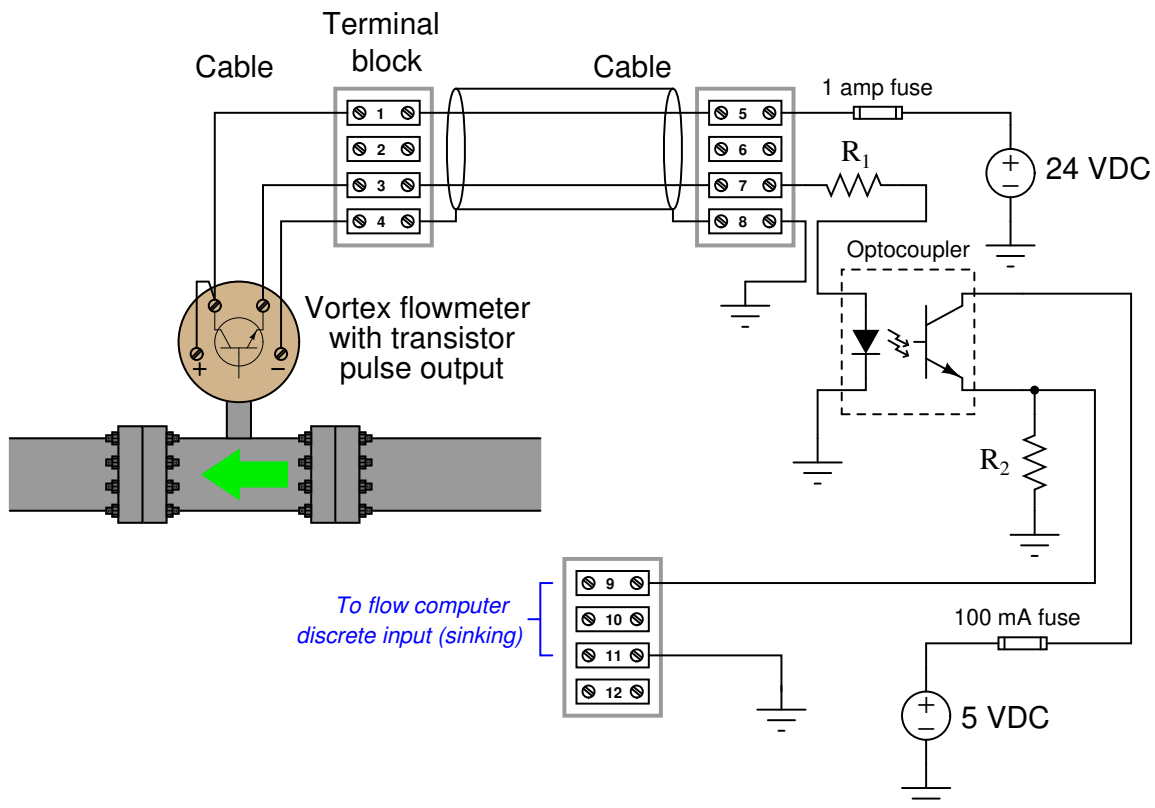
- The label “Standard Cubic Feet” means one cubic foot of volume with the gas at room temperature and atmospheric (sea-level) pressure. Explain why we might use the unit of “Standard Cubic Feet” to express the flow of a gas through a pipe rather than simple “Cubic Feet”.
- What advantages does a turbine meter have for measuring natural gas flow that make it well-suited for this application?
- Explain what would be necessary to make a turbine flowmeter register the true *mass flow rate* of the fluid rather than just the volumetric flow rate.
- Demonstrate how to *estimate* numerical answers for this problem without using a calculator.

file i04057



Oppgave 22

Contractors install this vortex flowmeter, equipped with a pulse output (1 pulse per 25 gallons), to totalize flow through a pipe:



Unfortunately, the flow computer connected to this circuit is not registering any accumulated flow, even though an operator has verified flow through the pipe at approximately 370 gallons per minute. Your first step is to disconnect the flow computer input from this circuit (so it is wired exactly as shown) then to take your DC voltmeter and measure voltage between terminals 1 and 4: there, your meter registers 23.1 volts DC. Your next step is to measure DC voltage across the collector and emitter terminals of the optocoupler's transistor: there your meter registers 0 volts.

Identify the likelihood of each specified fault for this circuit. Consider each fault one at a time (i.e. no coincidental faults), determining whether or not each fault could independently account for *all* measurements and symptoms in this circuit.

| Fault                   | Possible | Impossible |
|-------------------------|----------|------------|
| $R_1$ failed open       |          |            |
| $R_2$ failed open       |          |            |
| $R_1$ failed shorted    |          |            |
| $R_2$ failed shorted    |          |            |
| 1 amp fuse blown        |          |            |
| 100 milliamp fuse blown |          |            |
| 24 VDC source dead      |          |            |
| 5 VDC source dead       |          |            |

Finally, identify the *next* diagnostic test or measurement you would make on this system. Explain how the result(s) of this next test or measurement help further identify the

location and/or nature of the fault.

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### Oppgave 23

Suppose a vortex flowmeter is used to measure the flow rate of fuel oil into a large combustion boiler. The vortex meter has a “K factor” equal to 0.09667 liter per pulse. Calculate the following:

The sensor frequency at a fuel oil flow rate of 8510 liter per hour.

The total amount of fuel consumed by the boiler after a digital counter circuit records 800,000 pulses.

The fuel oil flow rate (in cubic feet per minute) at a sensor frequency of 35 Hz.

Suppose someone entered the wrong K factor value into the digital electronic transmitter connected to the vortex meter’s sensor. Would this cause a *zero shift*, a *span shift*, a *linearity error*, or a *hysteresis error*? Explain your reasoning.

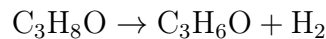
#### Suggestions for Socratic discussion

- Identify how we could set up this vortex flowmeter to record the total amount of fuel oil consumed by the boiler every 24 hours, and then log those values in records for operator reference.
- Explain how you could use simple test equipment to measure the frequency of the signal output by the vortex shedding sensor while the flowmeter was in operation. Note: some vortex flowmeters provide test points for you to connect electronic test equipment directly to the sensor inside the pipe!
- If the temperature of the fuel oil were to increase slightly, would it affect the vortex flowmeter’s measurement accuracy? Explain why or why not.
- Explain what would be necessary to make a vortex flowmeter register the true *mass flow rate* of the fluid rather than just the volumetric flow rate.
- Demonstrate how to *estimate* numerical answers for this problem without using a calculator.

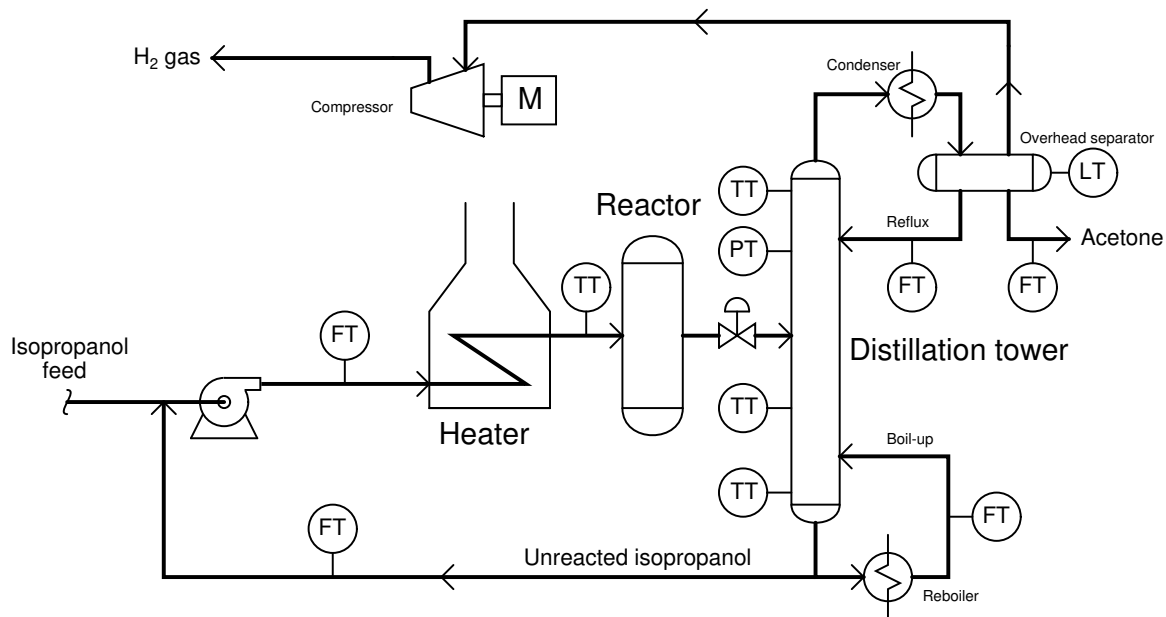
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## Oppgave 24

Acetone – a valuable industrial solvent (chemical formula  $C_3H_6O$ ) – may be manufactured from isopropyl alcohol (chemical formula  $C_3H_8O$ ) in a chemical reaction that breaks two atoms of hydrogen away from each molecule of alcohol, leaving acetone and hydrogen gas ( $H_2$ ) as byproducts:



A simplified flow diagram for this process is shown here:



Suppose the decision is made to use a vortex flowmeter to measure acetone reflux flow into the distillation tower. This particular vortex flowmeter has a minimum Reynolds number value of 10,000 as specified by the manufacturer. Calculate the minimum flow rate of acetone at 20 °C this vortex meter will be able to measure given a schedule-40 pipe size of DN40 (ID=40.94). Assume a density of 790 kg/m<sup>3</sup> and an absolute viscosity of 36 mPa s for acetone at this temperature.

### Suggestions for Socratic discussion

- Why would you as a technician (not an engineer) need to know anything about *minimum flow cutoff* for a vortex flowmeter? Identify a practical scenario where this knowledge might become important for you to do your job.
- Explain what the *Reynolds number* of a flowing fluid means in your own words. Specifically, what effects are manifest from different Reynolds number values?
- What is the purpose of a *distillation tower* in this particular process and how does it work?
- If you are familiar with distillation tower operation, identify which substance has the lower boiling point: acetone or isopropyl alcohol.

[file i04060](#)

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## Oppgave 25

Read pages 2-3 through 2-5 of the “Rosemount Model 8800C and Model 8800A Smart Vortex Flowmeter” reference manual (publication 00809-0100-4003 Revision JA), and answer the following questions:

Explain why a vertical pipe orientation is preferred for this type of flowmeter, identifying the proper direction(s) of flow for different process fluids.

Figure 2-2 shows preferred mounting positions for hot pipes – explain why these positions are preferred to other alternative positions.

Identify the minimum upstream and downstream straight-pipe lengths for this flowmeter.

Figure 2-9 on page 2-12 shows the bolt-tightening sequence recommended for flange-mounted flowmeter installations. Examine each of the sequences shown, and explain why the sequence of bolt-tightening matters. Hint: the exact same principle is involved when tightening lug nuts on a car wheel, and it is called *cross-torquing*.

### Suggestions for Socratic discussion

- Explain why the manual recommends you “install valves downstream of the meter when possible”.
- This manual mentions the option of pressure and temperature compensation for the vortex flowmeter. Explain why one might choose to apply this type of compensation in a specific process application. Also, explain why compensating pressure and temperature sensors should be located downstream of the vortex flowmeter rather than upstream.
- Suppose you needed to “cross-torque” the bolts on a machine component, but did not have a manual to specify which bolts to torque in what order. Explain how you could apply a general cross-torquing procedure to *any* multi-bolt application.
- Suppose you were asked to build a circuit to interpret the pulse output from this model of vortex flowmeter, blinking an LED on and off with the pulse frequency. Sketch this circuit, being sure to note which screw terminals on the flowmeter to connect your circuit to.

[file i04063](#)

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## Oppgave 26

*Turbine* flow meters are almost self-explanatory in their operation. Compare and contrast the turbine flow meter against the standard orifice plate flow meter as a flow-measuring device. What are some of the advantages of turbine meters over orifice plates? Are there any significant disadvantages?

Also, compare signal linearity between the two flow measurement technologies: we know that orifice plates require square-root characterization to obtain a linear response to flow rate. Is the same true for turbine meters? Why or why not?

[file i00497](#)

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### Oppgave 27

A turbine flowmeter measuring cooling water for a large power generator uses an electronic circuit to convert its pickup coil pulses into a 4-20 mA analog current signal. The “K factor” for the turbine element is 0.0101 liter per pulse, and the 4-20 mA analog output is ranged from 0 to 500 l/m flow. Complete the following table of values for this transmitter, assuming perfect calibration (no error). Be sure to show your work!

| Measured flow<br>(l/m) | Pickup signal<br>frequency (Hz) | Percent of output<br>span (%) | Output signal<br>(mA) |
|------------------------|---------------------------------|-------------------------------|-----------------------|
| 250                    |                                 |                               |                       |
| 412                    |                                 |                               |                       |
|                        | 305                             |                               |                       |
|                        | 780                             |                               |                       |
|                        |                                 | 63                            |                       |
|                        |                                 | 49                            |                       |
|                        |                                 |                               | 10                    |
|                        |                                 |                               | 16                    |

#### Suggestions for Socratic discussion

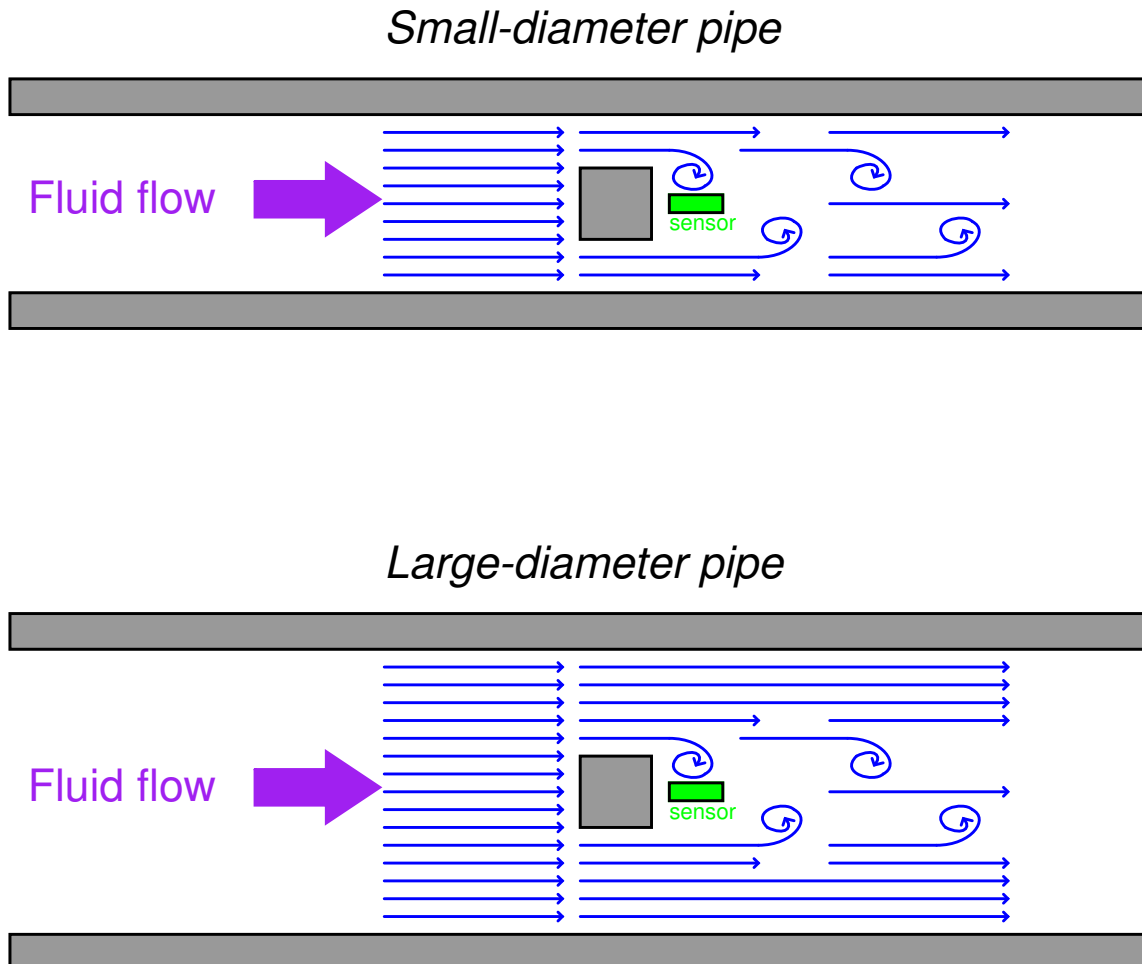
- Demonstrate how to *estimate* numerical answers for this problem without using a calculator.
- Suppose you were asked to check the accuracy of the frequency-to-current converter circuit for this flowmeter. What sort of test equipment would you use, and how could you perform the test with the flowmeter still installed in the cooling water pipe?
- Could the pulse output of the pickup coil be used directly as a flow signal, or is the converter circuit absolutely necessary?
- Explain how a PLC could be used to *totalize* the water flow through this flowmeter, to provide total usage values at the end of each day.

file i00101

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Oppgave 28

Suppose two water pipes of different diameter both have blunt objects (“bluff bodies”) in the paths of their respective water flows. A pressure sensor device located near each of the bluff bodies measures the frequency of the vortices produced:



If the bluff bodies in both pipes have the same physical dimensions, and the vortex shedding frequencies are the same in both scenarios, which pipe carries a greater volumetric flow rate of water? Or, do they carry the same amount of flow? Why or why not??

[file i00495](#)

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Oppgave 29

Compare and contrast the vortex-shedding flow meter against the standard orifice plate flow meter. What are some of the advantages of vortex meters over orifice plates? Are there any significant disadvantages?

Also, compare signal linearity between the two flow measurement technologies: we know that orifice plates require square-root characterization to obtain a linear response to flow rate. Is the same true for vortex meters? Why or why not?

[file i00494](#)

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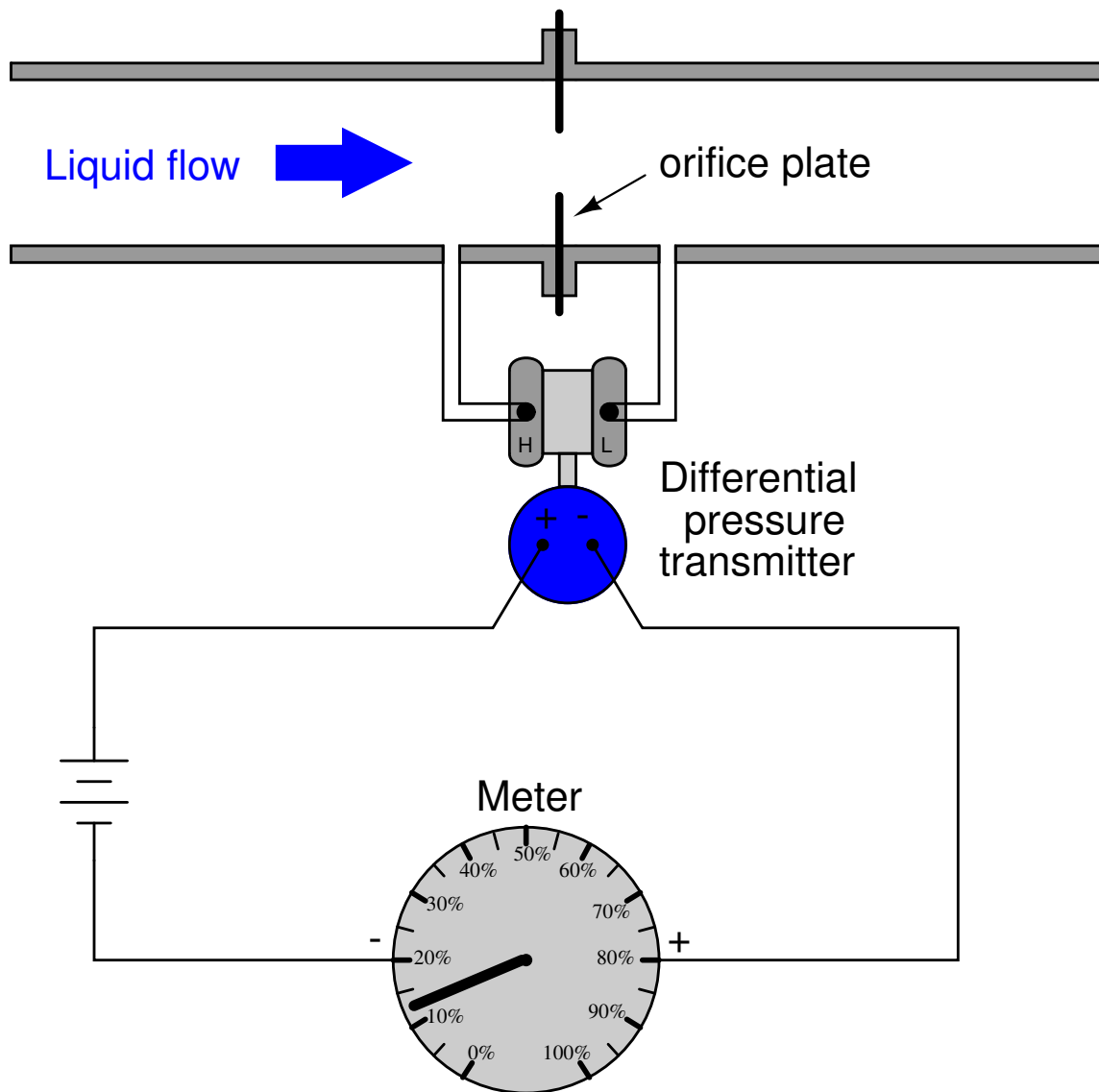
Oppgave 30

Research the necessary upstream and downstream straight-pipe requirements for vortex and turbine meters, and identify how these requirements compare against the typical requirements of orifice plates. For review's sake, why do we need a certain minimum length of straight pipe length upstream and downstream of a flow-measuring device?  
[file i00501](#)

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Oppgave 31

What will be wrong with this measurement system if we connect a linear-scale indicator (an electrical meter movement responding to the transmitter's current signal) to the transmitter's output, and try to measure fluid flow along this scale? Assume the transmitter has been properly calibrated to output full current (typically 20 mA) at full flow through the orifice plate.



Hint: what will the meter indicate when the actual flow rate is at 0%, 50%, and 100%?  
[file i00483](#)



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## Oppgave 32

Read pages 2-2 through 2-18 of the “Rosemount Series 8700 Magnetic Flowmeter Flowtubes” reference manual (publication 00809-0100-4727 Revision DA), and answer the following questions:

Identify the minimum upstream and downstream straight-pipe runs necessary for reliable flow measurement using one of these magnetic flowmeters.

Two cables connect the remotely-mounted transmitter (“head”) unit to the flowtube. Identify the purpose of each cable; specifically, what each one connects to inside the flowtube.

Identify the proper direction of process liquid flow when the flowtube is mounted vertically or at an angle, and explain why this is the preferred direction.

### **Suggestions for Socratic discussion**

- Explain why it is important to not run cables from two different magnetic flow transmitters to their respective flowtube assemblies through the same electrical conduit.
- Explain why cable termination procedures must be strictly adhered to, including not stripping back the cable shield more than half an inch, and also bonding the shield conductors (only) to the flowtube case.
- Comment on the flange bolt torquing sequences shown on page 2-7. Are these sequences arbitrary, or is there some general principle we should recognize here?

file i04066

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### Oppgave 33

Magnetic flowmeters exhibit special advantages and disadvantages when compared to other flow-measuring technologies. For each of the following strengths and weaknesses, explain *why* it is this way for a magnetic flowmeter:

#### Strengths:

- Short upstream/downstream straight-pipe requirements: 5 up and 3 down (typically)
- Output is linearly related to volumetric flow rate – no square root characterization required
- Good rangeability
- Bidirectional measurement possible

#### Weaknesses:

- Does not work with nonconducting fluids
- Excellent electrical grounding of the flowmeter is *essential*
- Coating of electrodes may affect performance
- Needs to be installed in pipe with electrodes horizontal, never vertical

Suppose a magflow meter is operating with a partially-filled pipe, with both electrodes still fully contacting the liquid. Will this operating condition cause a *zero shift*, a *span shift*, a *linearity error*, or a *hysteresis error*? Explain your reasoning.

Suppose the flowstream through a magflow meter contains some non-conductive solids in addition to conductive liquid. Will this affect the accuracy or reliability of the flowmeter? Explain why or why not.

file i00525

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## Oppgave 34

Read selected portions of the “Daniel Ultrasonic Gas Flowmeter” manual for the 3400 series SeniorSonic and JuniorSonic flowmeters (part number 3-9000-740 Revision H), and answer the following questions:

Read page 3-22 and identify the minimum straight-pipe lengths upstream and downstream required for proper operation of the flowmeter.

Read page 3-22 and identify how closely the diameter of the meter flowtube must match the inside diameter of the pipe it connects to.

Read page 3-22 and identify how closely a temperature-sensing probe (i.e. thermowell with RTD) may be installed to the meter flowtube, and which side (upstream or downstream) it should be on.

Read pages 5-1 through 5-5 and identify the operating principle (Doppler or transit-time) used in both the SeniorSonic and JuniorSonic gas flowmeters.

### **Suggestions for Socratic discussion**

- Why should the Senior flowmeter be installed with chords oriented horizontally?
- Why should the Junior flowmeter be installed with chords 45 degrees off vertical?
- How many paths (chords) are used in the Senior versus the Junior models?
- How does the general design of the Senior model differ from that of the Junior model?

file i04070

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### Oppgave 35

Transit-time (“counterpropagation”) ultrasonic flowmeters infer the flow rate of a gas or a liquid by measuring the time it takes for sound waves to travel both upstream and downstream through a moving fluid:

$$Q = k \frac{t_{up} - t_{down}}{(t_{up})(t_{down})}$$

Where,

$Q$  = Volumetric flow rate

$k$  = Constant of proportionality

$t_{up}$  = Time for sound pulse to travel upstream (against the flow)

$t_{down}$  = Time for sound pulse to travel downstream (with the flow)

Perform a “thought experiment” where the fluid inside an ultrasonic flowmeter is standing still, and demonstrate how this equation gives a value of zero for  $Q$ .

#### **Suggestions for Socratic discussion**

- A strong emphasis is placed on performing “thought experiments” in this course. Explain why this is. What practical benefits might students realize from regular mental exercises such as this?
- Perform a thought experiment demonstrating how the speed of sound is irrelevant for this type of flowmeter, based on an analysis of the formula shown above. Use the substitutions  $t_{up} = \frac{L}{c-v}$  and  $t_{down} = \frac{L}{c+v}$  to define travel time in terms of path length ( $L$ ), fluid velocity ( $v$ ), and speed of sound ( $c$ ).

[file i04071](#)

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### Oppgave 36

Ultrasonic flowmeters exhibit special advantages and disadvantages when compared to other flow-measuring technologies. For each of the following strengths and weaknesses, explain *why* it is this way for an ultrasonic flowmeter:

#### Strengths:

- May be attached to the *outside* of a pipe
- Relatively inexpensive on large pipes
- Work on liquids, gases, and some vapors
- Output is linearly related to volumetric flow rate – no square root characterization required
- Good rangeability
- Bidirectional measurement possible

#### Weaknesses:

- Calibration varies with speed of sound in fluid for some types (which?)
- Efficiently coupling sensors to pipe can be challenging
- May require long straight-pipe lengths to condition flow
- May suffer false readings from sound waves “ringing around the pipe” instead of going through the fluid

[file i00529](#)

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### Oppgave 37

Magnetic flowmeters only function when measuring the flow of *electrically conductive* fluids. First, explain why electrical conductivity is an essential property of the fluid. Second, identify common fluids that *cannot* be detected by a magnetic flowmeter. Third, determine whether slight changes in conductivity have any effect on the accuracy of a magnetic flowmeter (e.g. if the conductivity of the fluid decreased by a factor of two, would the output voltage similarly decrease by the same factor?).

[file i00523](#)

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### Oppgave 38

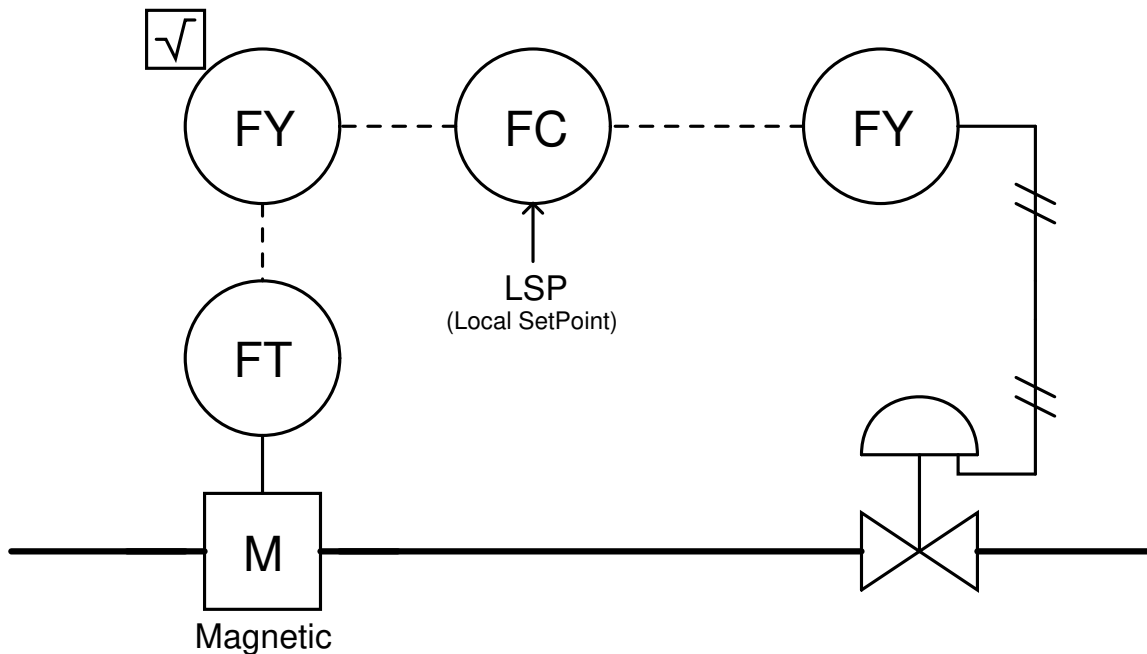
Explain the difference(s) between an *AC* magnetic flowmeter and a *DC* magnetic flowmeter. Also, describe why there are two types (i.e. what advantages do each type of magnetic flowmeter enjoy?)

[file i00524](#)

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### Oppgave 39

The following flow control system (as built) refuses to maintain process flow at a steady setpoint. It seems “sluggish” to respond to changes at high flow rates, and control at low flow rates is very erratic (rapid cycling in the measured flow). From the control scheme shown here, can you determine the problem?



[file i00526](#)

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### Oppgave 40

Noen dyr bruker ekkolokasjon for å finne veien i mørket. Ubåter bruker sonar til det samme. Forklar hvordan dette prinsippet kan brukes til å akustisk måle avstanden til et objekt. Hvordan kan vi bruke dette til å måle hastigheten til et objekt?

[file i00528](#)

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### Oppgave 41

Describe the operational principles of two types of *ultrasonic* flowmeter technologies: *Doppler* and *transit-time*. What physical properties of the fluid stream affect an ultrasonic flowmeter’s calibration?

[file i00527](#)

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### Oppgave 42

The two major types of ultrasonic flowmeters work best in different fluid streams. One type “prefers” a clean fluid stream, while the other “prefers” a flow stream containing particulate matter or bubbles. Identify which ultrasonic flowmeter type is best suited to which type of flow stream, and explain why.

[file i00530](#)

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Oppgave 43

Read the whitepaper published by Rosemount on the topic of top-mounting DP flowmeters on steam lines (“Top Mount Installation for DP Flowmeters in Steam Service”, document 00870-0200-4809, copyright August 2009) and answer the following questions:

Why has the traditional recommendation for DP flow transmitter on steam lines been to locate the transmitter *below* the line?

What kind(s) of problem(s) are typically experienced with below-pipe mounting of DP flow transmitters in steam line applications?

Can DP flowmeters *always* be top-mounted? If not, what limitations dictate whether or not to top-mount?

Why shouldn't Annubar-style flow elements be mounted *vertically* in a steam pipe, but rather should be canted at least 15 degrees from vertical?

file i03488

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## Oppgave 44

Refer to pages 4 and 5 of the “Micro Motion ‘ELITE’ Coriolis Flow and Density Meters” product datasheet (publication PS-00374 Revision L), and answer the following questions:

Compare the turndown performance of a Coriolis flowmeter against that of a typical orifice plate flowmeter, and identify which one has better performance. Explain *why* one has better performance than the other.

Examine the graph of accuracy versus flow rate on page 4 and explain the meaning of the “turndown ratio” limits shown on the graph (e.g. 100:1, 20:1, 2:1). Explain what *turndown* means for any measuring instrument.

Select an appropriate model of flowmeter for measuring the flow rate of water up to 25 GPM.

Select an appropriate model of flowmeter for measuring the flow rate of natural gas up to 400 SCFM (at a line pressure of 500 PSI).

### **Suggestions for Socratic discussion**

- Page 10 contains tables showing the effect of process temperature and process pressure on measurement accuracy, both for flow rate and for density. Explain why changes in process pressure and/or process temperature would have this effect on a Coriolis flowmeter.
- Pages 17 through 22 show illustrations of these Coriolis flowmeters. For each of the given drawings, identify where the two vibrating tubes are located, and what shape those tubes take.

file i04076



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### Oppgave 45

Suppose we are measuring the flow rate of a liquid using a Coriolis flowmeter, and the volumetric flow rate of the liquid increases (with liquid density remaining the same). Will the amplitude of the meter tubes' "undulating" motion increase, decrease, or remain the same given this change in flow? Will the meter tubes' resonant frequency of vibration increase, decrease, or remain the same? Explain your answers.

Now suppose we are using the same Coriolis flowmeter to measure liquid flow, but this time the liquid's density becomes greater (i.e. the liquid becomes denser) with no change in volumetric flow. Again, qualitatively identify the change in undulation amplitude, and also in resonant frequency, for the flowmeter's metal tubes, and explain your answers.

Finally, suppose the flow through this Coriolis meter stops completely. How will changes in fluid density affect the tubes' motion, given a condition of zero flow? Again, explain your answers.

#### Suggestions for Socratic discussion

- A strong emphasis is placed on performing "thought experiments" in this course. Explain why this is. What practical benefits might students realize from regular mental exercises such as this?

[file i00728](#)

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### Oppgave 46

Calculate the mass flow rate of a liquid having a density of  $950 \text{ kg/m}^3$  flowing through a pipe at a volumetric rate ( $Q$ ) of  $250 \text{ m}^3/\text{h}$ .

$$W = \text{_____ kg/m}$$

$$W = \text{_____ kg/sec}$$

#### Suggestions for Socratic discussion

- Demonstrate how to *estimate* numerical answers for this problem without using a calculator.
- Which unit of measurement do you think is best for *custody transfer* applications: GPM or lb/min? Explain your reasoning.
- When expressing mass flow in Imperial measurements, the unit of "lbm" is often used. Why is the letter "m" appended to the symbol for pound? Is there another Imperial unit for mass other than "lbm"??

[file i04081](#)

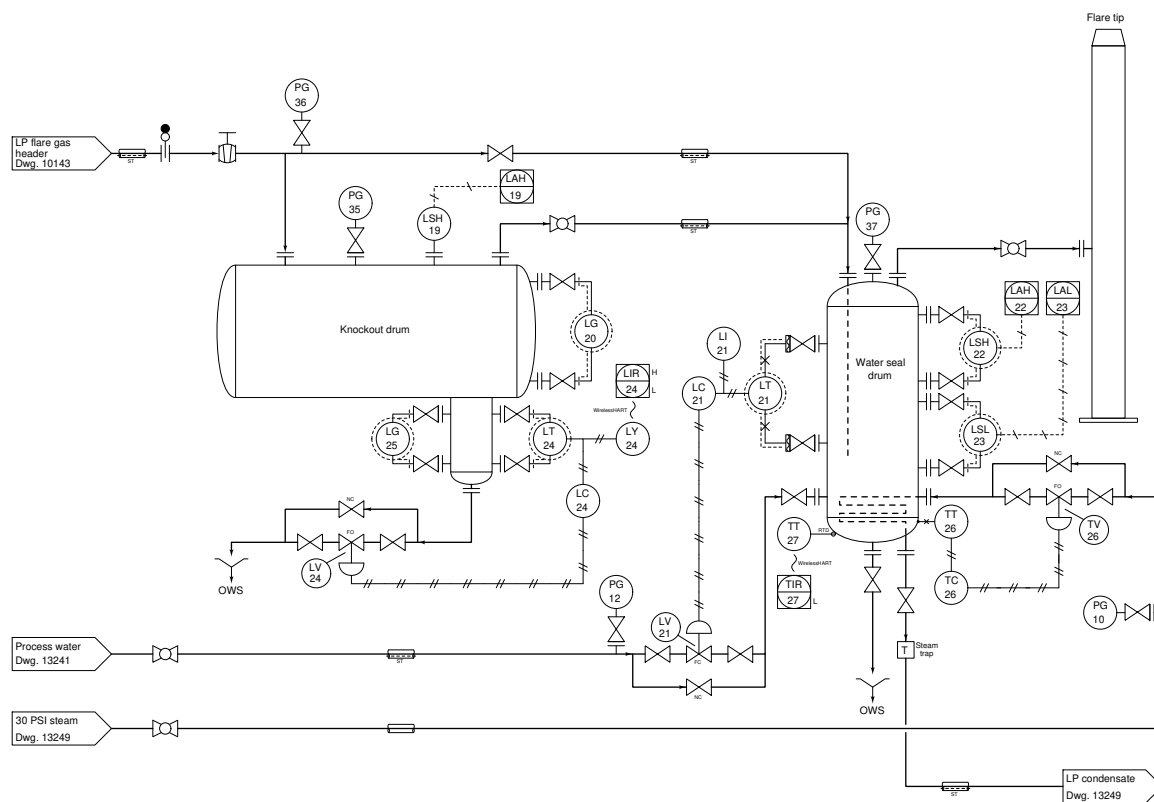
### Oppgave 47

Coriolis massestrømningsmålere har flere fordeler over andre strømningsmålere. Dette gjør at det ofte er verdt den høye kostnaden som er forbundet med anskaffelse. List opp noen av fordelene og eventuelt ulemper med denne teknologien.

[file i00539](#)

### Oppgave 48

The “flare” at an oil refinery functions as a safe way to quickly dispose of pressurized hydrocarbon compounds, by burning them far away from anything else that might be flammable. In this system, as with most flare systems, a “knockout drum” exists to separate vapors from liquid, so that only vapors are sent to the flare tip to be burned. Any captured liquid is drained to the Oily Water Sewer (OWS) system:



As with most flare systems, the exact composition of material sent to the flare to be burned is both highly variable and unknown from moment to moment. In a typical refinery, anything from hydrogen gas to diesel fuel might get sent to the flare during a “depressurization” event.

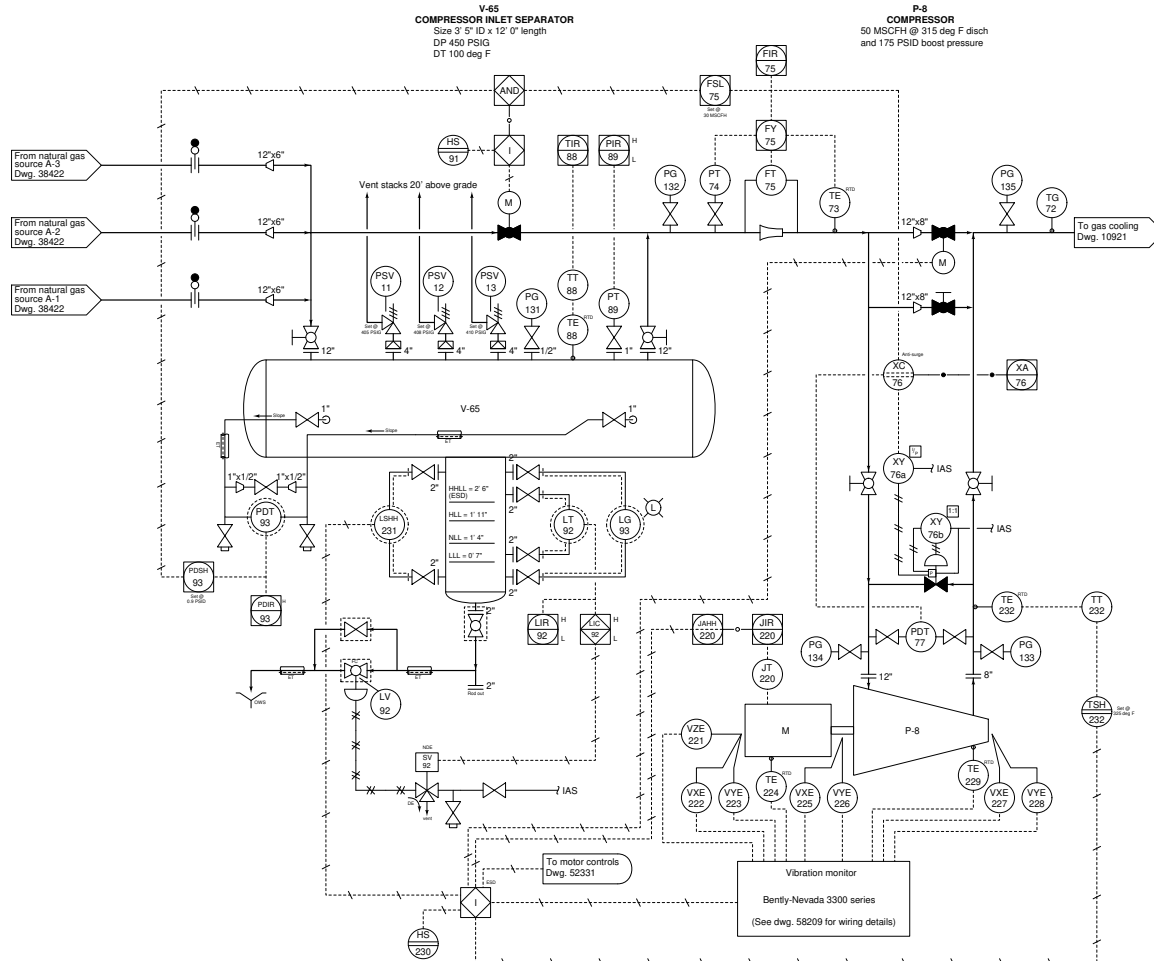
Suppose operations personnel at this refinery wish to monitor the total flow rate of hydrocarbon material burned at the flare. Engineers are debating what type(s) of flowmeter might be used for this task, and where exactly it should be placed in the piping system.

Brainstorm some different flow-sensing technologies, and then determine whether or not each one of them could be applied to this problem.

[file i00977](#)

## Oppgave 49

A large natural gas compressor takes in gas from three different sources, “knocks out” any liquid that might be entrained in the gas, and then boosts the pressure of that gas for transport through miles of piping:



Flowmeter FT-75 has been in service for many years, but unfortunately does not provide good enough turndown for operations’ needs when the compressor is operated at a fraction of its rated capacity. Engineers are debating what type(s) of flowmeter might be used to replace FT-75.

First, explain what “turndown” means in the context of this flowmeter, and explain why this particular type of flowmeter might not provide good enough turndown.

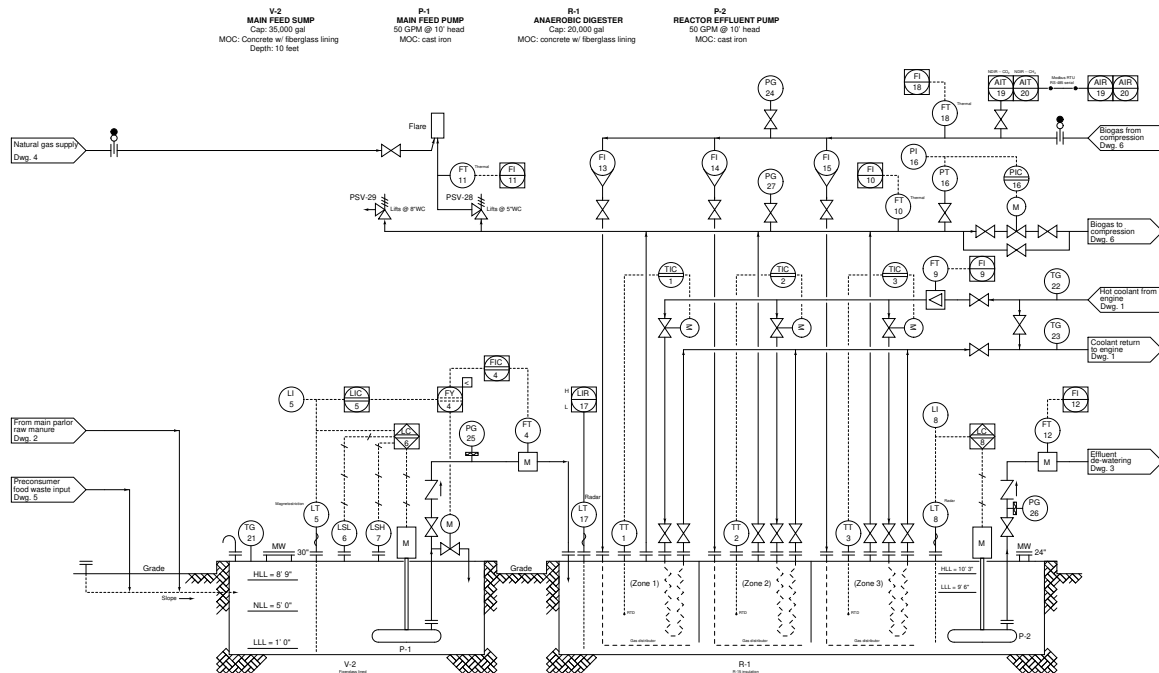
Brainstorm some different flow-sensing technologies, and then determine whether or not each one of them could be applied here.

[file i00978](#)

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## Oppgave 50

In this process, liquefied manure from a dairy farm is mixed with pre-consumer food waste for anaerobic digestion, the purpose of which being to produce “biogas” which is largely methane and burns similarly to natural gas. This biogas is used as fuel for a large engine, which turns a generator to make electricity. The heated coolant from this engine is piped back to the digester vessel to maintain the organic matter at a temperature similar to the internal temperature of a cow’s digestive tract. Some of the biogas is recycled back into the digester as a means of stirring the liquefied mixture to prevent solids from settling at the bottom and clogging the system:



Identify the following flowmeter types and comment on why those types are particularly well-suited to the fluid stream they’re measuring:

- FT-4 (influent to digester)
- FT-9 (coolant flow from engine)
- FT-10 and FT-18 (biogas flow)
- FT-12 (effluent flow to de-watering)

file i02146

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Oppgave 51

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Oppgave 52

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Oppgave 53

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#### Oppgave 54

Read and outline the “Weirs and Flumes” subsection of the “Variable-Area Flowmeters” section of the “Continuous Fluid Flow Measurement” chapter in your *Lessons In Industrial Instrumentation* textbook. Note the page numbers where important illustrations, photographs, equations, tables, and other relevant details are found. Prepare to thoughtfully discuss with your instructor and classmates the concepts and examples explored in this reading.

[file i04082](#)

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#### Oppgave 55

Calculate the electrical resistance of a 100 ohm RTD ( $\alpha = 0.00385$ ) at the following temperatures:

- $T = 120\text{ }^{\circ}\text{C}$  ;  $R = \underline{\hspace{2cm}}$
- $T = 390\text{ }^{\circ}\text{F}$  ;  $R = \underline{\hspace{2cm}}$

Calculate the temperature of a 100 ohm RTD ( $\alpha = 0.00392$ ) at the following resistances:

- $R = 115\ \Omega$  ;  $T = \underline{\hspace{2cm}}$
- $R = 180\ \Omega$  ;  $T = \underline{\hspace{2cm}}$

#### **Suggestions for Socratic discussion**

- Identify some advantages RTDs hold over thermocouples.
- Identify some advantages thermocouples hold over RTDs.

[file i04079](#)

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#### Oppgave 56

What is a flow *prover*, and why is it periodically necessary to use one to re-calibrate positive-displacement flowmeters?

[file i00546](#)

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#### Oppgave 57

There are several different types of flow meter devices broadly grouped under the classification of *positive displacement*. Describe the operational principle of a positive displacement flowmeter. Also, describe what physical properties of the fluid stream affect a positive displacement flowmeter’s calibration.

[file i00544](#)

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### Oppgave 58

Suppose both a thermal mass flowmeter and a Coriolis mass flowmeter monitor gas flow going through the exact same pipe. Normally, the gas flowing through this pipe is pure helium (specific heat  $c = 1.24$  cal/g-K), and the thermal mass flowmeter has been calibrated for helium gas. Then one fine day an operator places a few shutoff valves in the wrong positions and sends hydrogen gas (specific heat = 3.41 cal/g-K) down the line instead of helium.

Not knowing that the wrong gas is now flowing through this pipe, the operator adjusts a manual flow control valve to stabilize the flow rate at its normal value, looking at the thermal mass flowmeter's indication as the process variable.

First, explain why the two flowmeters no longer agree with each other (assuming they registered in perfect agreement while sensing the flow of helium gas).

Second, identify whether the Coriolis flowmeter registers *more* mass flow than the thermal flowmeter or *less* mass flow than the thermal flowmeter.

Finally, identify which of the two flowmeters (if any!) still registers the true mass flow rate with hydrogen going down the line instead of helium.

#### Suggestions for Socratic discussion

- Explain what *specific heat* means, and give a practical example from everyday life.
- What does this “thought experiment” tell us about Coriolis versus thermal mass flowmeters in general? Which of these flowmeter types do you think costs less?
- Thermal mass flow measurement is used almost universally for intake air flow measurement on automobile engines with electronic controls. Do you think the same type of problem exists in this application that we saw in our “thought experiment”?
- Suppose the gas composition does not change (i.e. it is still pure helium), but the line pressure increases. How will each of these mass flowmeters respond to this one process condition change?
- Suppose the thermal mass flowmeter were replaced with an orifice plate and DP sensor. Would this solve the problem of discrepancies between flowmeters resulting from fluid composition changes? Explain why or why not.

[file i04080](#)

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### Oppgave 59

Read and outline the “Thermal Flowmeters” subsection of the “True Mass Flowmeters” section of the “Continuous Fluid Flow Measurement” chapter in your *Lessons In Industrial Instrumentation* textbook. Note the page numbers where important illustrations, photographs, equations, tables, and other relevant details are found. Prepare to thoughtfully discuss with your instructor and classmates the concepts and examples explored in this reading.

[file i04077](#)

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## Oppgave 60

Perform a “thought experiment” where natural gas moves through a thermal mass flowmeter having just one (heated) RTD temperature sensing element. Explain what happens to the temperature of this element as the gas flow rate increases and decreases, and how the flowmeter’s electronics would interpret this temperature change as a change in flow.

Now, perform another “thought experiment” where a constant flow of natural gas changes temperature as it moves through a thermal mass flowmeter having just one (heated) RTD temperature sensing element. Explain what happens to the temperature of this element as the incoming gas increases and decreases in temperature, and how the flowmeter’s electronics would interpret this temperature change as a change in flow.

Finally, explain why all thermal flowmeters are built with *two* temperature sensors, one heated and one unheated.

### **Suggestions for Socratic discussion**

- A strong emphasis is placed on performing “thought experiments” in this course. Explain why this is. What practical benefits might students realize from regular mental exercises such as this?
- Do you think a thermal mass flowmeter would be a good candidate technology for *natural gas* flow metering? Explain why or why not.

file i04078

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## Oppgave 61

Identify any area(s) of your study in which you would like to become stronger. Examples include technical reading, electrical circuit analysis, solving particular types of problems, time management, and/or skills applied in the lab. Cite specific examples if possible, and bring these to your instructor's attention so that together you may target them for improvement. As a starting point, try consulting the list of topics on the first page of the worksheet for the upcoming mastery exam, as well as the "General Values and Expectations" list near the beginning of the worksheet identifying the habits and qualities necessary for success in this career.

Next, identify practical strategies you will use to strengthen these areas. Examples include focusing on specific types of problem-solving whenever those types appear in the homework, working through practice problems for a particular subject, and/or coordinating with your lab team to give you more practice on specific skills.

### **Suggestions for Socratic discussion**

- One useful strategy is to maintain a *journal* of all you've learned in a course of study. Explore ways you could take the work you're already doing to prepare for homework (daily discussions with your instructor) and turn this into a journal or even a weblog ("blog") for your own reflection and eventual use as a portfolio to showcase your capabilities to employers.
- Where exactly are the practice problem worksheets located on the *Socratic Instrumentation* website?
- Peruse the "feedback questions" for this (and/or past) course sections to identify any questions related to areas you would like to strengthen.

file i00999



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### Oppgave 62

An ecological survey team installs a Cippoletti weir in a small stream to measure water flow through it. Calculate the amount of water flow (in units of  $\text{ft}^3/\text{sec}$ ) represented by a crest height (“head”) of 5 inches. Assume the weir has a crest width of 4 feet and that the crest height is being measured by a level sensor located 3 feet upstream of the weir.

Also, convert this flow value into units of gallons per minute.

#### **Suggestions for Socratic discussion**

- Why do you think a weir would be a good candidate technology for measuring the flow rate of water down a small stream?
- Do you see any ways that a Cippoletti weir could experience problems measuring water flow down a natural stream? If so, can you think of a better flowmeter technology for this application?

[file i04084](#)

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### Oppgave 63

A municipal wastewater treatment plant uses a 6-foot-wide Parshall flume to measure the flow of effluent (treated water leaving the facility, also called “outfall”). Calculate the head (height of water) immediately upstream of this flume at an effluent flow rate of 5,460 GPM.

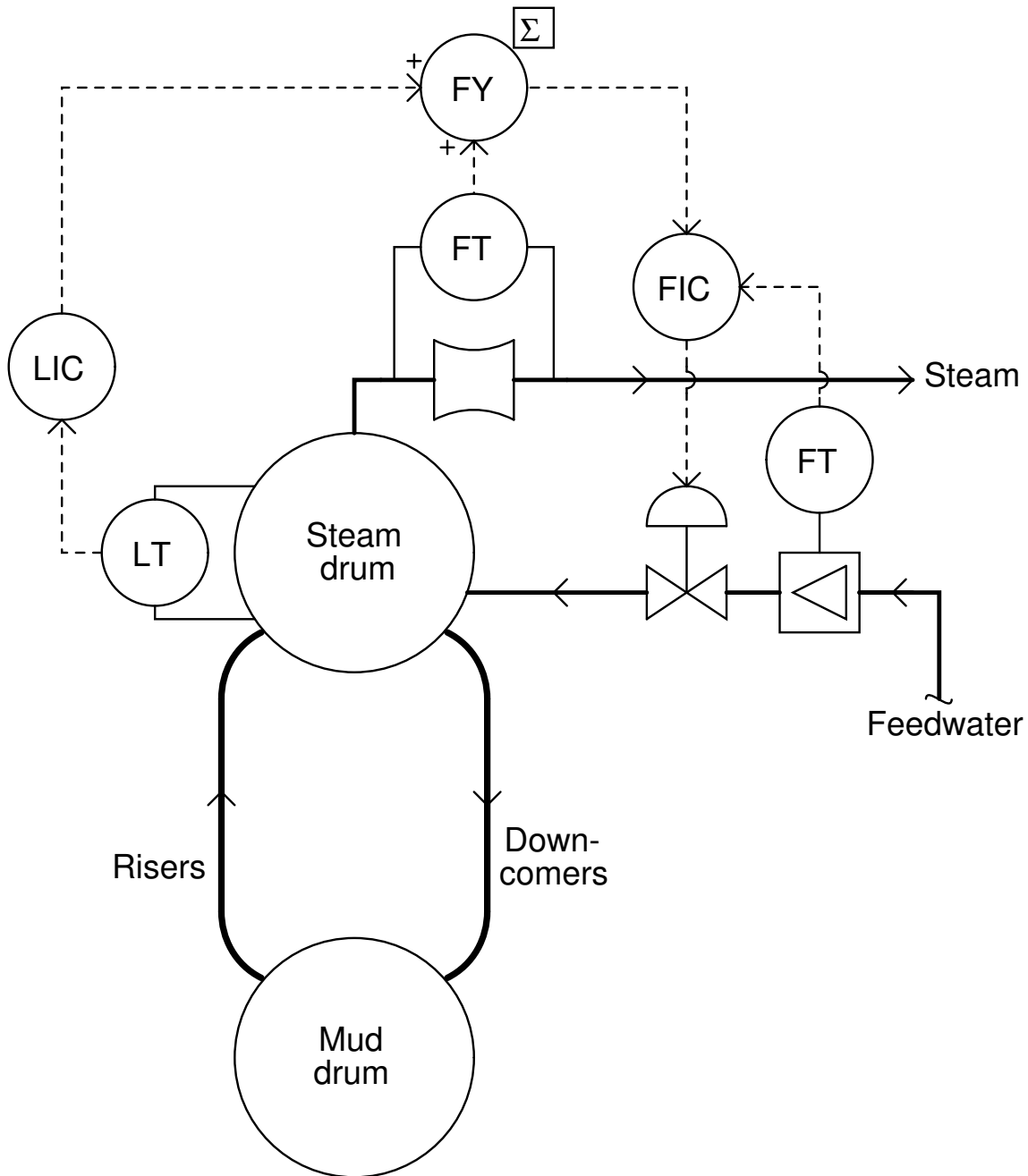
#### **Suggestions for Socratic discussion**

- Why do you think a flume is a good candidate technology for measuring the flow rate of wastewater?
- How did you need to apply *algebra* to solve for the height of water in this flume?

[file i04085](#)

Oppgave 64

A venturi tube is used to measure the flow rate of steam exiting a power boiler:



Supposing this venturi tube normally develops a differential pressure of 100 inches water column at a flow rate of 970 pounds per minute with a steam density of  $\rho = 1.33 \text{ lbm/ft}^3$ , calculate the following:

- Differential pressure at 700 lbm/min mass flow = \_\_\_\_\_
- Differential pressure at 550 lbm/min mass flow and  $\rho = 1.30 \text{ lbm/ft}^3$  = \_\_\_\_\_
- Mass flow rate at 90 "W.C. = \_\_\_\_\_
- Mass flow rate at 43 "W.C. and  $\rho = 1.35 \text{ lbm/ft}^3$  = \_\_\_\_\_

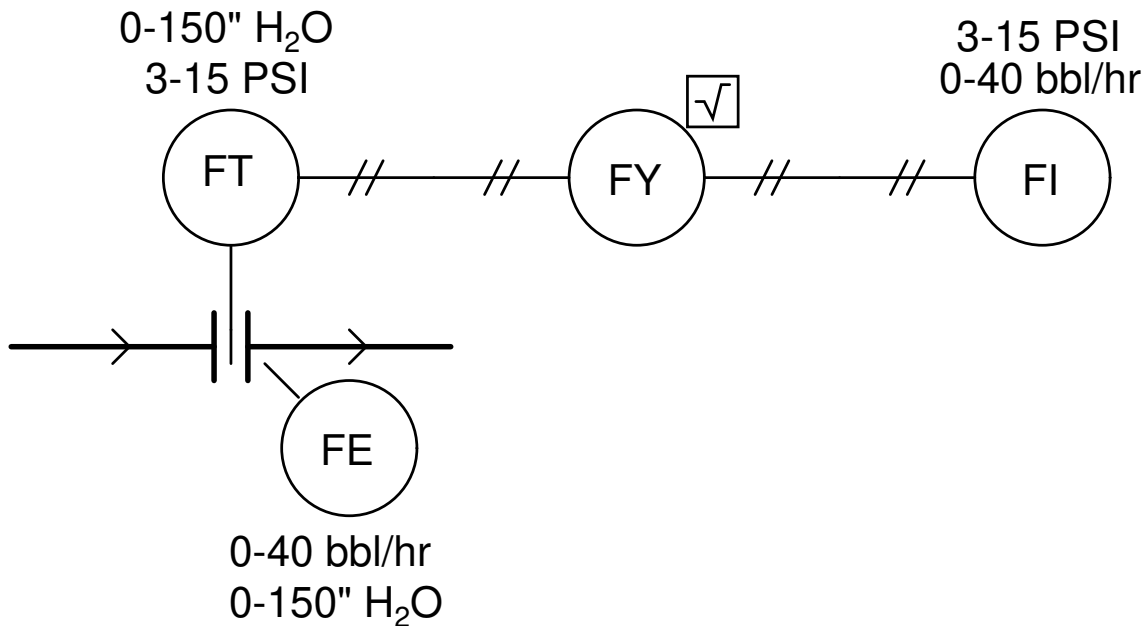
### Suggestions for Socratic discussion

- Explain why both steam flow and water flow are best measured in *mass* units rather than volumetric in this process application.
- Identify some factors that could realistically cause the steam's density to change.

file i04087

Opgave 65

An orifice plate is used to measure the flow rate of diesel fuel exiting the processing unit at an oil refinery where the customary unit for liquid flow measurement within refineries is “barrels per hour” (bbl/hr). Calculate the following parameters in this flow measurement loop, at two different flow rates (10 bbl/hr and 31 bbl/hr):



- **At a flow rate of 10 bbl/hr:**
- Orifice plate  $\Delta P = \underline{\hspace{2cm}}$  " H<sub>2</sub>O
- Differential pressure transmitter output signal =  $\underline{\hspace{2cm}}$  PSI
- Square root extractor output signal =  $\underline{\hspace{2cm}}$  PSI
- Flow indicator reading =  $\underline{\hspace{2cm}}$  bbl/hr
  
- **At a flow rate of 31 bbl/hr:**
- Orifice plate  $\Delta P = \underline{\hspace{2cm}}$  " H<sub>2</sub>O
- Differential pressure transmitter output signal =  $\underline{\hspace{2cm}}$  PSI
- Square root extractor output signal =  $\underline{\hspace{2cm}}$  PSI
- Flow indicator reading =  $\underline{\hspace{2cm}}$  bbl/hr

file i00725

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### Oppgave 66

Suppose we need to measure the volumetric flow rate of deionized water (purified by triple-distillation) used as “make-up” water for a chemical experiment in a laboratory, from a maximum flow rate of 20 GPM down to a minimum flow rate of 1 GPM. Identify the most appropriate technologies from this list, and explain why they others will not work:

- Magnetic
- Coriolis
- Pitot tube
- Ultrasonic
- Orifice plate
- Thermal
- Vortex
- Positive displacement
- Pipe elbow

#### **Suggestions for Socratic discussion**

- If we needed to measure mass flow rather than volumetric flow, would this change our selection of flowmeter? Explain why or why not.
- Identify which of these flowmeters are bidirectional, and explain why based on their principles of operation.

[file i04088](#)

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### Oppgave 67

Suppose we need to install a flowmeter in a location where there is plenty of upstream straight-length pipe, but no downstream straight-length pipe (i.e. the flowmeter immediately discharges into an elbow). Identify the most appropriate technologies from this list, and explain why they others will not work:

- Magnetic
- Coriolis
- Ultrasonic
- Vortex
- Positive displacement
- Venturi tube

[file i04089](#)

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### Oppgave 68

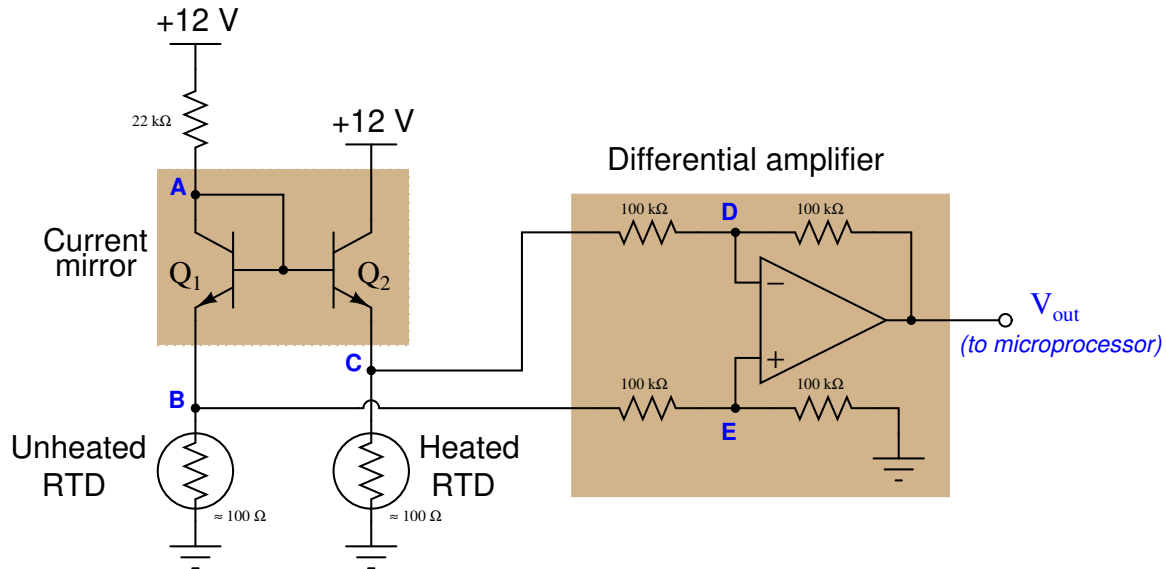
Suppose we are measuring the flow rate of a gas using a turbine flowmeter. This is a simple turbine flowmeter, with one turbine spinning freely, generating electronic pulses via a “pick-up” coil sensing the passing of turbine blades.

If the density of this gas suddenly increases with no change in volumetric flow, will the turbine speed increase, decrease, or stay the same?

[file i00730](#)

## Opggave 69

A thermal mass flowmeter uses two RTD sensing elements (one heated, one unheated) to infer mass flow rate through a pipe. The following circuit converts the difference in RTD temperatures into a voltage signal for a microprocessor to interpret:



A *current mirror* works to keep current through both RTDs equal, while a differential amplifier measures the difference in voltage drops across the two RTDs.

Unfortunately, this flowmeter is not functioning as it should. The microprocessor reports an over-ranged flow measurement even when the flowmeter has been “blocked in” by closing block valves both upstream and downstream in the pipe. You are summoned to troubleshoot this circuit, and you begin by measuring the output voltage from the amplifier – you read 0 volts DC with your voltmeter. Next, you measure voltage between test points **C** and **B**, again measuring 0 volts DC.

Identify the likelihood of each specified fault for this circuit. Consider each fault one at a time (i.e. no coincidental faults), determining whether or not each fault could independently account for *all* measurements and symptoms in this circuit.

| Fault  | Possible | Impossible |
|--|----------|------------|
| 22 kΩ resistor failed open                   |          |            |
| Unheated RTD failed open                     |          |            |
| Heated RTD failed open                       |          |            |
| Unheated RTD failed shorted                  |          |            |
| Heated RTD failed shorted                    |          |            |
| Transistor Q <sub>1</sub> failed shorted C-E |          |            |
| Transistor Q <sub>2</sub> failed shorted C-E |          |            |
| 12 VDC source dead                           |          |            |

Also, explain why these initial voltage measurements made sense to take. In other words, explain what each measurement told you about the nature of the fault.

Finally, identify the *next* diagnostic test or measurement you would make on this system. Explain how the result(s) of this next test or measurement help further identify the location and/or nature of the fault.

file i02946



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## Oppgave 70

In this question, you will be asked to research several different types of flowmeters and determine their specifications with regard to piping geometry (minimum upstream and downstream straight-pipe lengths), minimum or maximum Reynolds number, fluid types, and any other special advantages or disadvantages. This will require a significant amount of research on your part, but the exercise is well worth the effort, because it will educate you on the proper applications of each flowmeter type. This will enable you to make educated decisions on the type of flowmeter to choose for a wide range of fluid flow measurement applications.

Shown here is the standard “form” you should use in researching each flowmeter type:

- **Principle of operation:** *A one-sentence description of what physical phenomenon is used to detect or infer flow rate.*
- **Fluid type(s):** *Gas, liquid, or either.*
- **Minimum straight-run piping lengths (in units of “pipe diameters”):**
- **Reynolds number range:** *Minimum or maximum Reynolds number for pipe flow (not flow through the throat of the device).*
- **Typical accuracy (in percent of full-flow value):**
- **Bidirectional flow measurement:** *Yes or no.*
- **Inherently measures true mass flow:** *Yes or no.*
- **Special advantages:** *Brief description of any peculiar advantages of this device over other flowmeter devices.*
- **Special disadvantages:** *Brief description of any peculiar disadvantages of this device as compared to other flowmeter devices.*

Research these aspects for the following flowmeter types:

- **Orifice plate**
- 
- Principle of operation:
- 
- Fluid type(s):
- 
- Minimum straight-run piping lengths (in units of “pipe diameters”):
- 
- Reynolds number range:
-

- Typical accuracy (in percent of full-flow value):

- 

- Bidirectional flow measurement:

- 

- Inherently measures true mass flow:

- 

- Special advantages:

- 

- Special disadvantages:

- **Venturi tube**

- 

- Principle of operation:

- 

- Fluid type(s):

- 

- Minimum straight-run piping lengths (in units of “pipe diameters”):

- 

- Reynolds number range:

- 

- Typical accuracy (in percent of full-flow value):

- 

- Bidirectional flow measurement:

- 

- Inherently measures true mass flow:

- 

- Special advantages:

- 

- Special disadvantages:

- **Pitot tube or Annubar**

- 

- Principle of operation:

- 

- Fluid type(s):

- 

- Minimum straight-run piping lengths (in units of “pipe diameters”):

- 

- Reynolds number range:

- 

- Typical accuracy (in percent of full-flow value):

- 

- Bidirectional flow measurement:

- 

- Inherently measures true mass flow:

- 

- Special advantages:

- 

- Special disadvantages:

- **Vortex**

- 

- Principle of operation:

- 

- Fluid type(s):

- 

- Minimum straight-run piping lengths (in units of “pipe diameters”):

- 

- Reynolds number range:

- 

- Typical accuracy (in percent of full-flow value):

- 
- Bidirectional flow measurement:
- 
- Inherently measures true mass flow:
- 
- Special advantages:
- 
- Special disadvantages:
  
- V-cone
- 
- Principle of operation:
- 
- Fluid type(s):
- 
- Minimum straight-run piping lengths (in units of “pipe diameters”):
- 
- Reynolds number range:
- 
- Typical accuracy (in percent of full-flow value):
- 
- Bidirectional flow measurement:
- 
- Inherently measures true mass flow:
- 
- Special advantages:
- 
- Special disadvantages:

- **Segmental wedge**
- 
- Principle of operation:
- 
- Fluid type(s):
- 
- Minimum straight-run piping lengths (in units of “pipe diameters”):
- 
- Reynolds number range:
- 
- Typical accuracy (in percent of full-flow value):
- 
- Bidirectional flow measurement:
- 
- Inherently measures true mass flow:
- 
- Special advantages:
- 
- Special disadvantages:
  
- **Magnetic**
- 
- Principle of operation:
- 
- Fluid type(s):
- 
- Minimum straight-run piping lengths (in units of “pipe diameters”):
- 
- Reynolds number range:
- 
- Typical accuracy (in percent of full-flow value):

- 
- Bidirectional flow measurement:
- 
- Inherently measures true mass flow:
- 
- Special advantages:
- 
- Special disadvantages:
  
- Coriolis
- 
- Principle of operation:
- 
- Fluid type(s):
- 
- Minimum straight-run piping lengths (in units of “pipe diameters”):
- 
- Reynolds number range:
- 
- Typical accuracy (in percent of full-flow value):
- 
- Bidirectional flow measurement:
- 
- Inherently measures true mass flow:
- 
- Special advantages:
- 
- Special disadvantages:

- **Weir**
- 
- Principle of operation:
- 
- Fluid type(s):
- 
- Minimum straight-run piping lengths (in units of “pipe diameters”):
- 
- Reynolds number range:
- 
- Typical accuracy (in percent of full-flow value):
- 
- Bidirectional flow measurement:
- 
- Inherently measures true mass flow:
- 
- Special advantages:
- 
- Special disadvantages:

- **Thermal**
- 
- Principle of operation:
- 
- Fluid type(s):
- 
- Minimum straight-run piping lengths (in units of “pipe diameters”):
- 
- Reynolds number range:
- 
- Typical accuracy (in percent of full-flow value):

- 
- Bidirectional flow measurement:
- 
- Inherently measures true mass flow:
- 
- Special advantages:
- 
- Special disadvantages:
  
- **Ultrasonic**
- 
- Principle of operation:
- 
- Fluid type(s):
- 
- Minimum straight-run piping lengths (in units of “pipe diameters”):
- 
- Reynolds number range:
- 
- Typical accuracy (in percent of full-flow value):
- 
- Bidirectional flow measurement:
- 
- Inherently measures true mass flow:
- 
- Special advantages:
- 
- Special disadvantages:



- **Turbine**
- 
- Principle of operation:
- 
- Fluid type(s):
- 
- Minimum straight-run piping lengths (in units of “pipe diameters”):
- 
- Reynolds number range:
- 
- Typical accuracy (in percent of full-flow value):
- 
- Bidirectional flow measurement:
- 
- Inherently measures true mass flow:
- 
- Special advantages:
- 
- Special disadvantages:

- **Positive displacement**

- 
- Principle of operation:
- 
- Fluid type(s):
- 
- Minimum straight-run piping lengths (in units of “pipe diameters”):
- 
- Reynolds number range:
- 
- Typical accuracy (in percent of full-flow value):

- 
- Bidirectional flow measurement:
- 
- Inherently measures true mass flow:
- 
- Special advantages:
- 
- Special disadvantages:

- **Rotameter**

- 
- Principle of operation:
- 
- Fluid type(s):
- 
- Minimum straight-run piping lengths (in units of “pipe diameters”):
- 
- Reynolds number range:
- 
- Typical accuracy (in percent of full-flow value):
- 
- Bidirectional flow measurement:
- 
- Inherently measures true mass flow:
- 
- Special advantages:
- 
- Special disadvantages:

- **Pipe elbow**

- 

- Principle of operation:

- 

- Fluid type(s):

- 

- Minimum straight-run piping lengths (in units of “pipe diameters”):

- 

- Reynolds number range:

- 

- Typical accuracy (in percent of full-flow value):

- 

- Bidirectional flow measurement:

- 

- Inherently measures true mass flow:

- 

- Special advantages:

- 

- Special disadvantages:

- **Target**

- 

- Principle of operation:

- 

- Fluid type(s):

- 

- Minimum straight-run piping lengths (in units of “pipe diameters”):

- 

- Reynolds number range:

- 

- Typical accuracy (in percent of full-flow value):

- 
- Bidirectional flow measurement:
- 
- Inherently measures true mass flow:
- 
- Special advantages:
- 
- Special disadvantages:

- **Flume**

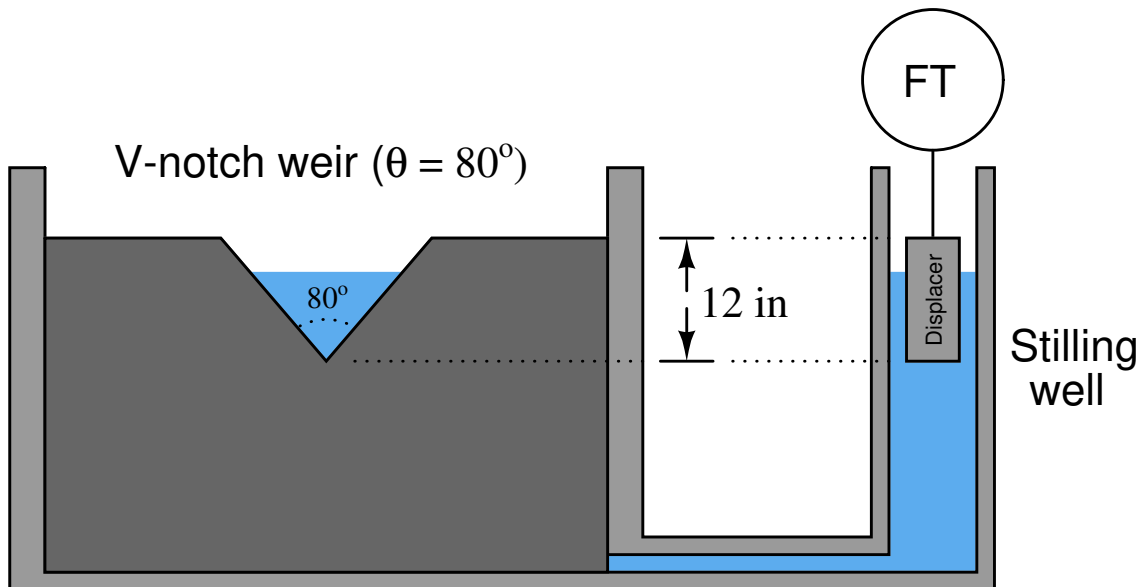
- 
- Principle of operation:
- 
- Fluid type(s):
- 
- Minimum straight-run piping lengths (in units of “pipe diameters”):
- 
- Reynolds number range:
- 
- Typical accuracy (in percent of full-flow value):
- 
- Bidirectional flow measurement:
- 
- Inherently measures true mass flow:
- 
- Special advantages:
- 
- Special disadvantages:

file i00541

---

Oppgave 71

Calculate values for the following calibration table, for a displacer-style transmitter measuring water flow through a V-notch weir. The displacer is cylindrical in shape, has a length of 12 inches (matching the weir's V-notch depth), and a diameter of 2 inches. The percentage in the calibration table refers to percent of the weir's flow range, not the percentage of displacer submergence:



Be sure to show your work!

| Water flow rate (ft <sup>3</sup> /s) | Percent of flow span (%) | Depth that displacer is submerged (in) | Buoyant force (lb) |
|--------------------------------------|--------------------------|--|--------------------|
|                                      | 0                        |  |                    |
|                                      | 10                       |  |                    |
|                                      | 25                       |  |                    |
|                                      | 50                       |  |                    |
|                                      | 75                       |  |                    |
|                                      | 90                       |  |                    |
|                                      | 100                      |  |                    |

[file i00684](#)

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Oppgave 72

Convert the volumetric flow rate of 35 gallons per minute (35 GPM) into a *mass* flow rate in pounds per minute, assuming the fluid in question is water.

[file i00724](#)

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Oppgave 73

A turbine flowmeter with a *k* factor of 53 pulses per gallon generates a pulse signal with a frequency of 381 Hz. Calculate the volumetric flow rate.

[file i03050](#)

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#### Oppgave 74

Suppose we are measuring the flow rate of a weak acid solution using a magnetic flowmeter. The conductivity of the acid is well within the acceptable range for this meter, and so it works just fine.

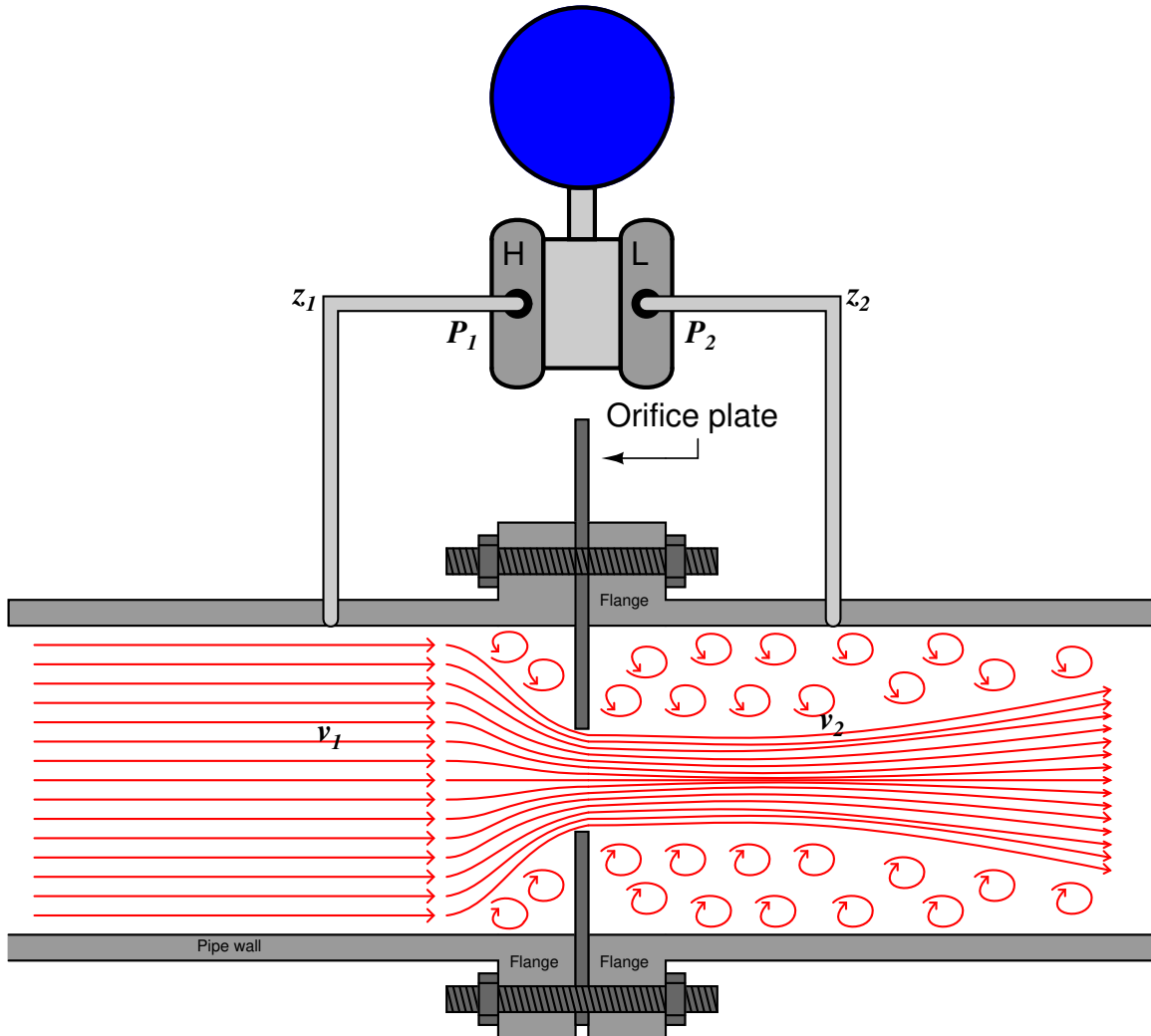
Now suppose the acid solution grows in strength (greater acid concentration). This will increase the conductivity of the solution, because there are now more ions available to carry an electric current. What effect will this have on the magnetic flowmeter's calibration? Will someone have to re-calibrate the flowmeter in order for it to properly measure the acid flow again? If so, will this be a zero or a span shift? Which way will the zero and/or span shift, higher or lower? Explain your answer(s)!

file i00729

Oppgave 75

The fundamental equation for an orifice plate is based on Bernoulli's Law:

$$z_1 \rho g + \frac{v_1^2 \rho}{2} + P_1 = z_2 \rho g + \frac{v_2^2 \rho}{2} + P_2$$



Assuming the same height at both measuring points  $z_1$  and  $z_2$ , Bernoulli's equation simplifies to this:

$$\frac{v_1^2 \rho}{2} + P_1 = \frac{v_2^2 \rho}{2} + P_2$$

Collecting like terms to either side of the equation:

$$P_1 - P_2 = \frac{v_2^2 \rho}{2} - \frac{v_1^2 \rho}{2}$$

$$\Delta P = \frac{\rho}{2} (v_2^2 - v_1^2)$$

$$\frac{2\Delta P}{\rho} = v_2^2 - v_1^2$$

If we know that the vena contracta velocity is substantially greater than the full-diameter pipe velocity, we may express the equation as an approximation:

$$\frac{2\Delta P}{\rho} \approx v_2^2$$
$$v_2 \approx \sqrt{\frac{2\Delta P}{\rho}}$$

We know that  $v_2$ , in turn, directly relates to flow ( $Q$ ), and so we may write this as an equation once more using a proportionality constant  $k$  to incorporate all sizing variables and coefficients:

$$Q = k\sqrt{\frac{\Delta P}{\rho}}$$

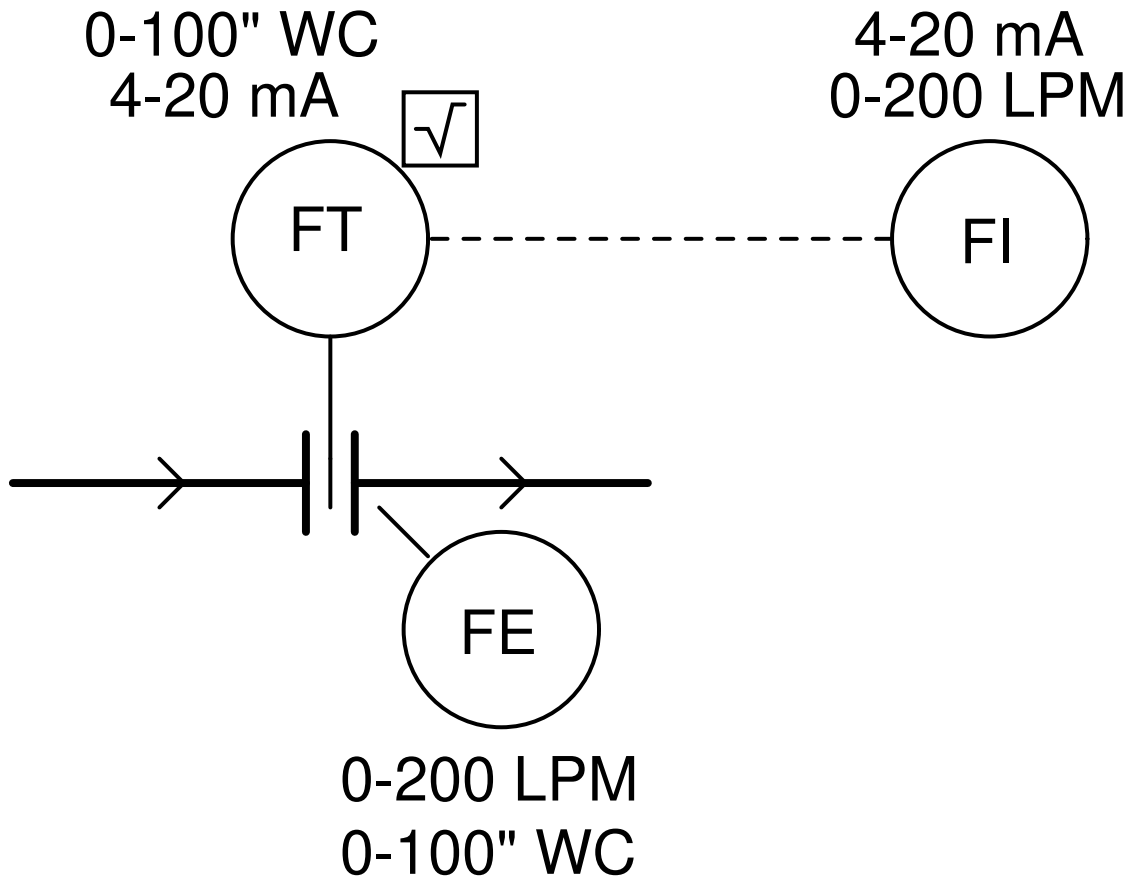
Based on this equation, determine what a differential pressure transmitter will do if the fluid going through an orifice plate suddenly becomes *denser* without changing volumetric flowrate (i.e. the velocity  $v$  through the pipe remains the same while  $\rho$  increases).

file i00731



Opgave 76

An orifice plate is used to measure the flow rate of ultra-pure water at a pharmaceuticals processing facility where the customary unit for liquid flow measurement is “liters per minute” (LPM). Calculate the following parameters in this flow measurement loop, at two different flow rates (78 LPM and 120 LPM):



Note that the transmitter is equipped with internal square root characterization, so that no external square root computer is required.

- **At a flow rate of 78 LPM:**
  - Orifice plate  $\Delta P = \underline{\hspace{2cm}}$  " H<sub>2</sub>O
  - Differential pressure transmitter output signal =  $\underline{\hspace{2cm}}$  mA
  - Flow indicator reading =  $\underline{\hspace{2cm}}$  LPM
- **At a flow rate of 120 LPM:**
  - Orifice plate  $\Delta P = \underline{\hspace{2cm}}$  " H<sub>2</sub>O
  - Differential pressure transmitter output signal =  $\underline{\hspace{2cm}}$  mA
  - Flow indicator reading =  $\underline{\hspace{2cm}}$  LPM

Suggestions for Socratic discussion

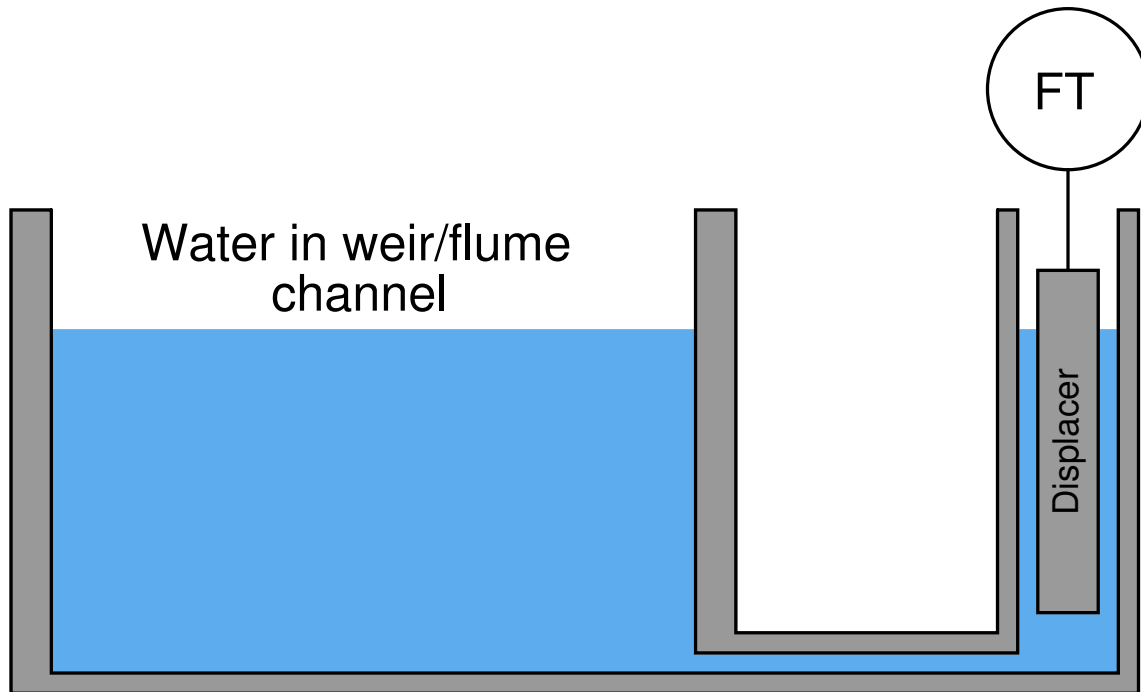
- A poor choice of flowmeters for this particular application would be *magnetic*. Explain why

file i00726

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## Oppgave 77

Weirs and flumes are frequently equipped with stilling wells to provide a “quiet” liquid height for an instrument to measure, usually an ultrasonic or displacer sensor such as the type used to measure liquid level in a closed vessel:

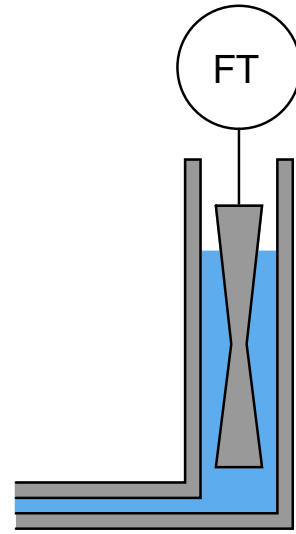
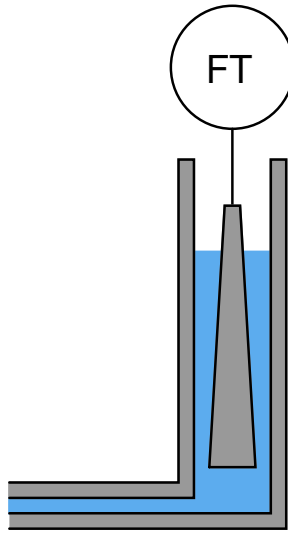
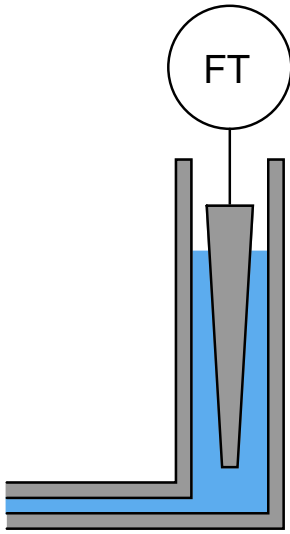


This level-sensing instrument usually provides the characterization necessary to linearize the weir or flume’s nonlinear flow/height response. If the level-sensing instrument is ultrasonic, the flow characterization may be done in the same digital computer that calculates liquid level by timing the sound echoes.

However, there is a low-technology way to do the same thing. If we use a displacer rather than a digital ultrasonic sensor, we may perform this same characterization by carefully choosing the correct non-cylindrical displacer shape, so that liquid height in the stilling well does not linearly translate to buoyant force felt by the transmitter unit.

Suppose we are setting up a transmitter on a Cippoletti weir, whose flow rate varies with the 1.5 power of liquid height in the stilling well ( $Q \propto H^{1.5}$ ). Choose the correct profile of displacer for this application, to properly linearize the liquid height into a flow signal that we may read directly:

*Which displacer has the correct profile?*

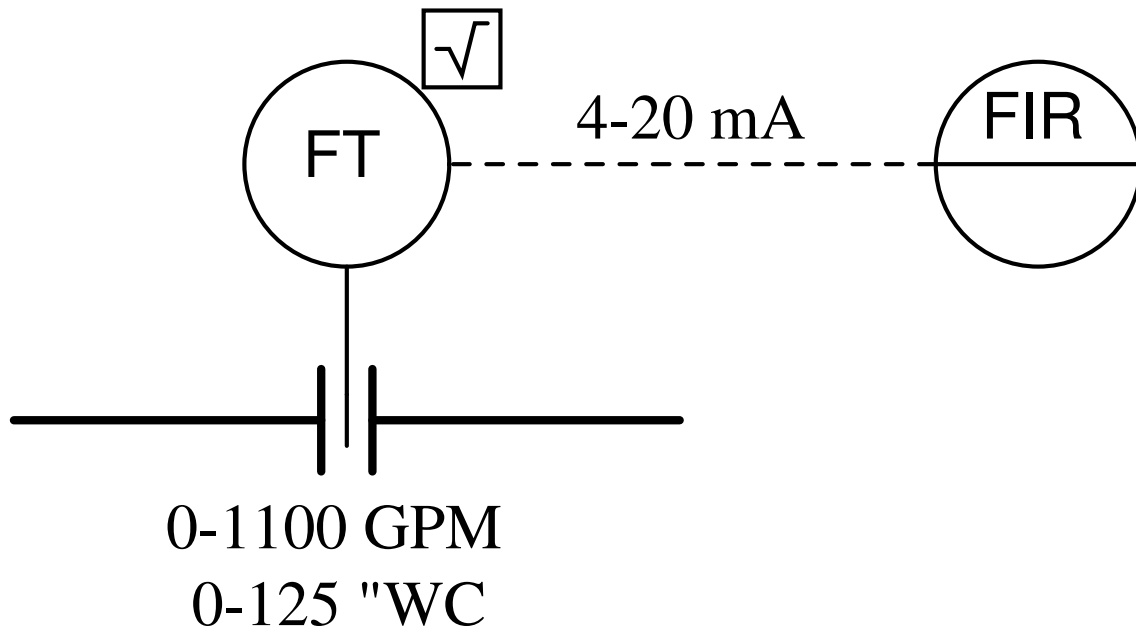


file i00624

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Oppgave 78

A “smart” differential pressure transmitter is configured to measure the differential pressure created by an orifice plate, and also to perform the square-root function necessary to linearize the orifice plate’s signal:



Calculate the following:

- Loop current at 350 GPM = \_\_\_\_\_ mA
- Differential pressure at 600 GPM = \_\_\_\_\_ "WC

file i00708

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Oppgave 79

Suppose an old orifice plate is replaced by a new orifice plate with a larger hole. What effect will this change have on the differential pressure generated by the plate at any given flow rate? What effect will this change have on the amount of flow it can measure with the same  $\Delta P$  range?

file i00727

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### Oppgave 80

An industrial cooling tower uses a vortex flowmeter to measure the flow rate of water through an 8-inch pipe (bore size = 7.981 inches). Calculate the *minimum* water flow rate measurable by this flowmeter, assuming a minimum necessary Reynolds number value of 20,000.

#### Suggestions for Socratic discussion

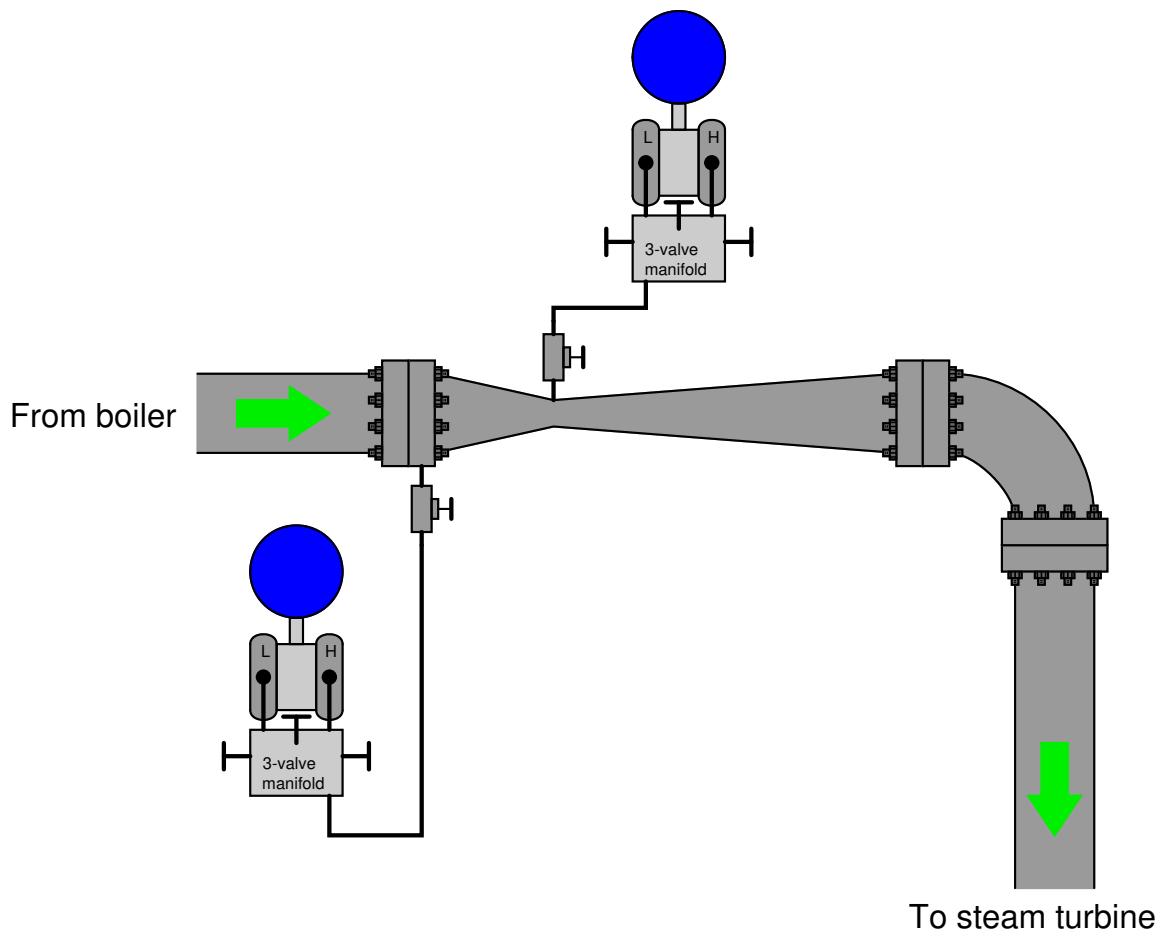
- Why do vortex flowmeters suffer from *low-flow cutoff*?
- Supposing we needed better low-flow measurement capability in this cooling water flow measurement application than what this flowmeter can deliver, what alternative(s) do you suggest? Keep in mind that we need to minimize cost while making our choices!

[file i04086](#)

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### Oppgave 81

Suppose a venturi tube is installed on a steam line to measure the flow of high-pressure steam coming from a powerhouse boiler and going to a steam turbine (to generate electricity). The contractors who installed the flowmeter left you with this mess:

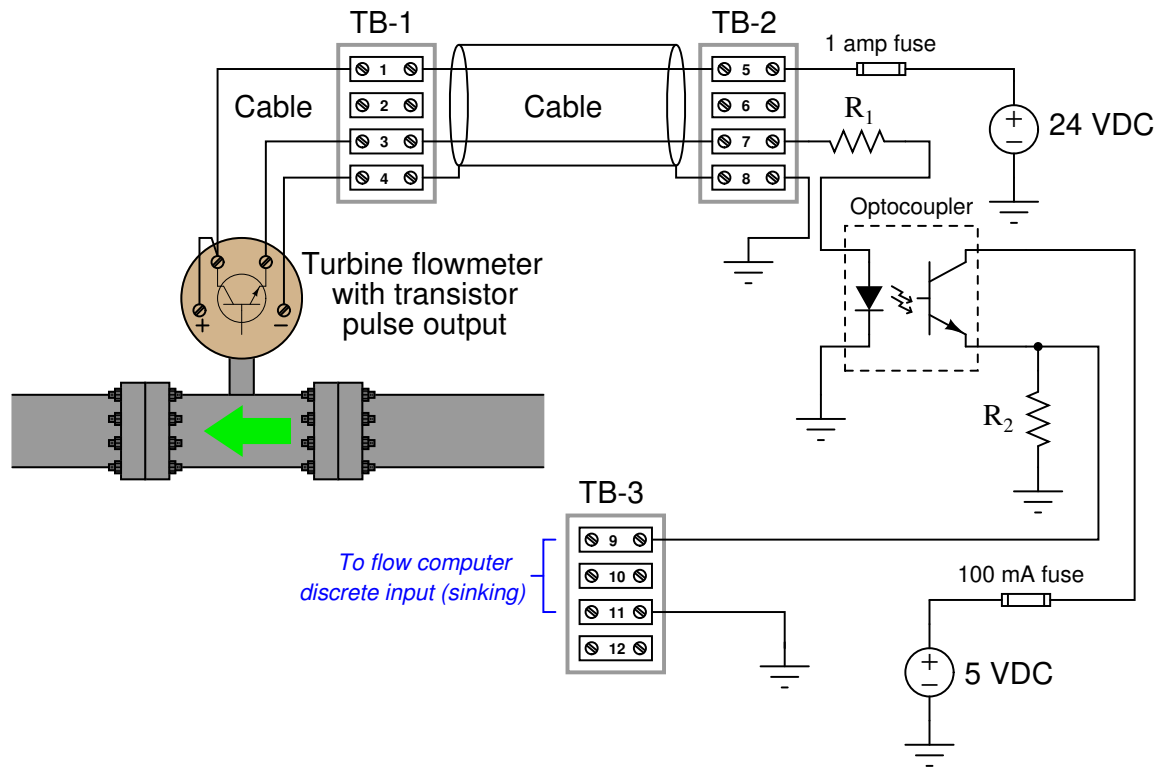


Explain what is wrong with this installation, and what must be done to fix it.

[file i00054](#)

Opggave 82

The flow computer connected to this turbine flowmeter (with electronic pick-up) does not register any flow, even though we know there to be fluid flowing through the pipe. A voltmeter connected between terminals TB1-1 and TB1-3 registers approximately 11.0 volts DC, and 10.8 volts AC at a frequency of 86 Hz:



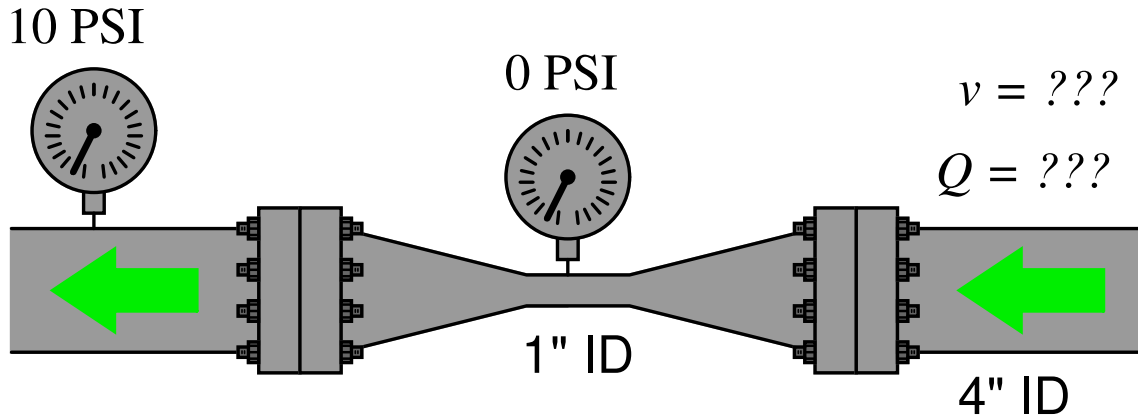
Determine the diagnostic value of each of the following tests. Assume only one fault in the system, including any single component or any single wire/cable/tube connecting components together. If a proposed test could provide new information to help you identify the location and/or nature of the one fault, mark “yes.” Otherwise, if a proposed test would not reveal anything relevant to identifying the fault (already discernible from the measurements and symptoms given so far), mark “no.”

| Diagnostic test   | Yes | No |
|---|-----|----|
| Measure DC voltage between terminals TB2-5 and TB2-8                  |     |    |
| Measure resistance between TB2-7 and TB2-8 with the 1 amp fuse pulled |     |    |
| Measure DC voltage across 100 mA fuse                                 |     |    |
| Measure DC voltage across 1 amp fuse                                  |     |    |
| Measure AC voltage between terminals TB3-9 and TB3-11                 |     |    |
| Measure continuity of conductor connecting terminals TB1-4 and TB2-8  |     |    |

---

Opggave 83

Calculate the required fluid velocity in order to reduce the pressure at the narrow throat to 0 PSIG, then also calculate the volumetric flow rate corresponding to this velocity in units of GPM:



The inside diameter (ID) of the throat is 1 inch, while the inside diameter of the wide pipe is 4 inches. Assume the fluid to be water ( $\rho = 1.94 \text{ slugs/ft}^3$ ) at a constant downstream pressure of 10 PSIG:

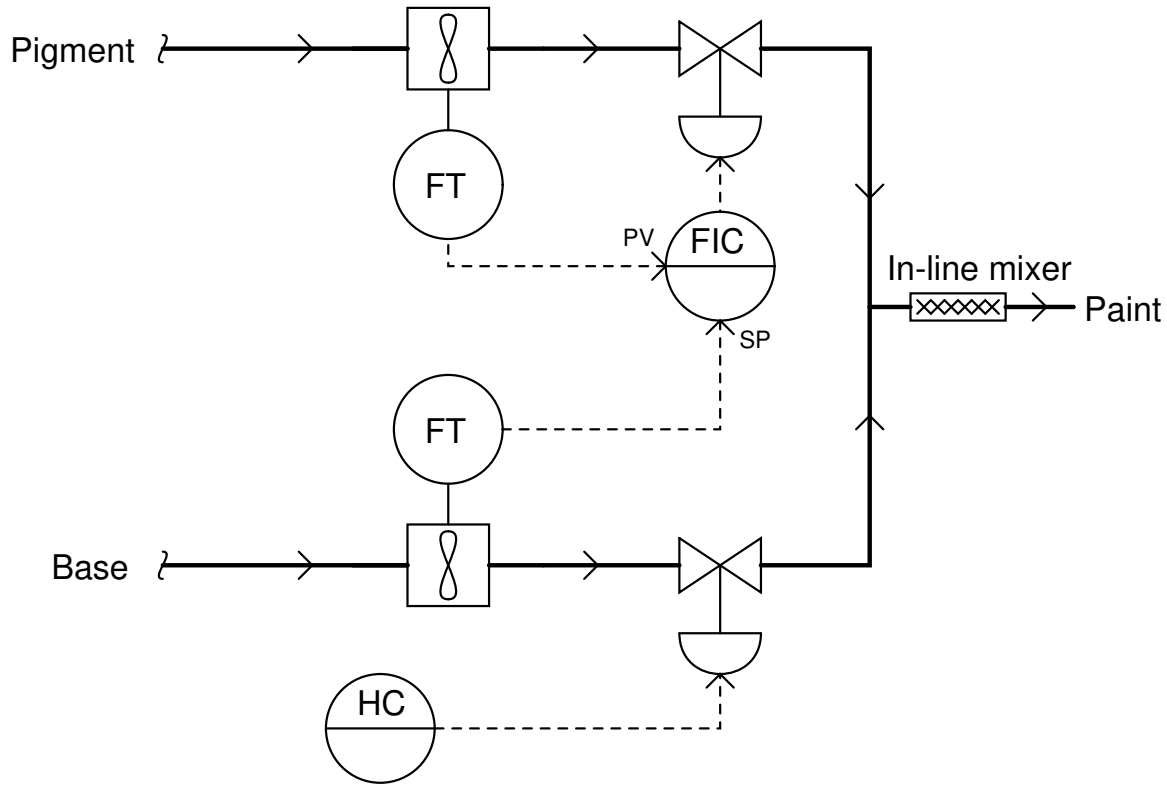
Hint: the trick to solving for velocity ( $v$ ) is to reduce Bernoulli's equation so that it contains just that one unknown variable. In other words, you need to be able to express the velocity at the 1-inch throat in terms of the velocity at the 4-inch pipe, so you will have just one  $v$  in the equation rather than a  $v_1$  and a  $v_2$ .

[file i00052](#)



Oppgave 84

In this paint mixing system, clear *base* and dark *pigment* are mixed together to form a paint with the desired coloring. A control valve positioned by hand (the human operator) throttles the flow of base, and that amount of flow is matched by pigment automatically throttled by a flow controller, to achieve a set ratio of pigment to base flow:



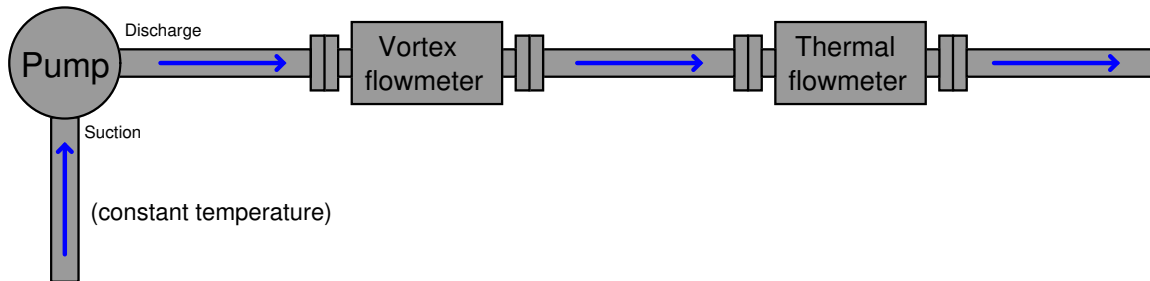
After a couple of years of successful operation, the system begins to output paint that is “paler” in color than it should be. Identify the likelihood of each specified fault for this control system. Consider each fault one at a time (i.e. no coincidental faults), determining whether or not each fault could independently account for the pale-colored paint.

| Fault                                       | Possible | Impossible |
|---|----------|------------|
| Base flowmeter registering reading too low  |          |            |
| Pigment flowmeter registering too low       |          |            |
| Base flowmeter registering reading too high |          |            |
| Pigment flowmeter registering too high      |          |            |
| Base control valve leaking by               |          |            |
| Pigment control valve leaking by            |          |            |
| Mixer plugged                               |          |            |
| Controller in manual mode                   |          |            |

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### Opggave 85

Two flowmeters are used to simultaneously measure the flow rate of a liquid through a pipe coming from a positive displacement pump:



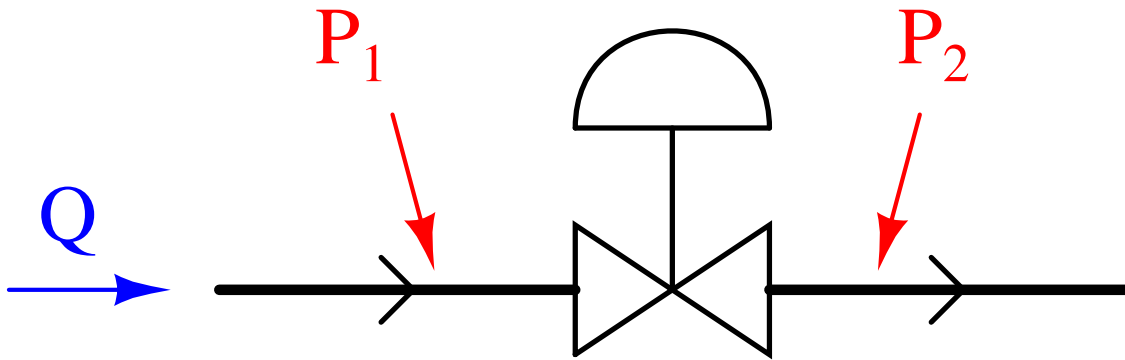
Suppose the positive displacement pump continues to turn at a constant speed, with the temperature of the incoming liquid constant. Suddenly, a steam pipe located near the pump breaks open, directing hot steam at the discharge pipe of the pump, heating the fluid as it exits the pump.

Determine the effect this change in fluid discharge temperature will have on the output signals coming from both flowmeters (vortex and thermal), then explain your answer in detail.

---

Opggave 86

The equation for determine volumetric flow rate ( $Q$ ) of a liquid with a certain specific gravity ( $G_f$ ) through a control valve given the upstream and downstream liquid pressures ( $P_1$  and  $P_2$ , respectively) is as follows:



$$Q = C_v \sqrt{\frac{P_1 - P_2}{G_f}}$$

The variable  $C_v$  is called the *flow coefficient* of the control valve, and it varies from zero at full-closed to a certain maximum value (depending on valve size and type) at wide-open.

Manipulate this equation to solve for downstream pressure ( $P_2$ ) in terms of the other variables. Be sure to show all your work!

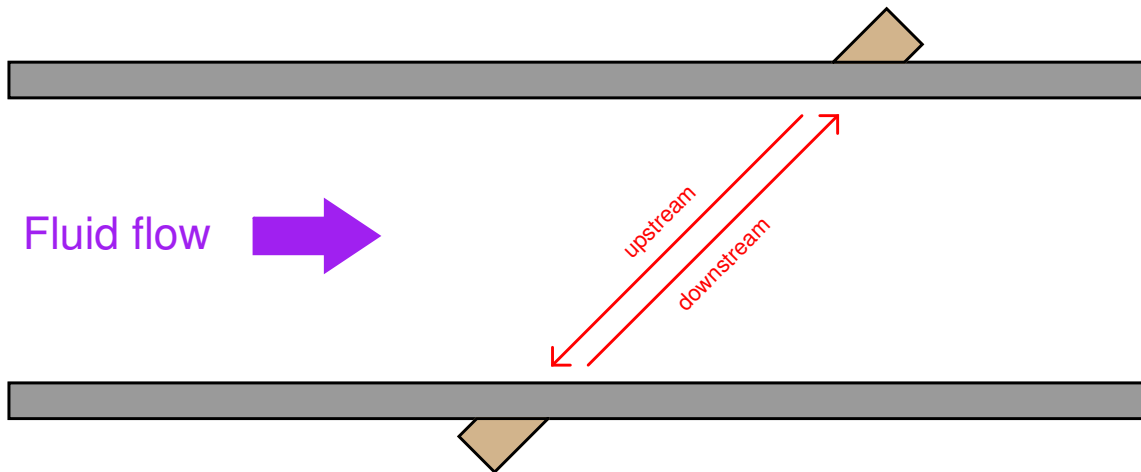
$P_2 =$

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Oppgave 87

The flow rate of a fluid measured by a *counterpropagation* (“transit-time”) ultrasonic flowmeter is given by the following formula:

$$Q = k \frac{t_{up} - t_{down}}{(t_{up})(t_{down})}$$



Knowing that the time for a sound wave to propagation upstream is equal to the length of the travel path divided by the difference in sound wave and fluid velocities ( $t_{up} = \frac{L}{c-v}$ ) and that the time for a sound wave to propagation downstream is equal to the length of the travel path divided by the sum of sound wave and fluid velocities ( $t_{down} = \frac{L}{c+v}$ ), prove that the flow rate measurement ( $Q$ ) does not depend on the speed of sound through the fluid ( $c$ ). In other words, substitute these mathematical definitions for  $t_{up}$  and  $t_{down}$  into the flowmeter equation and simplify to show that  $c$  is eliminated (canceled out) in the end.

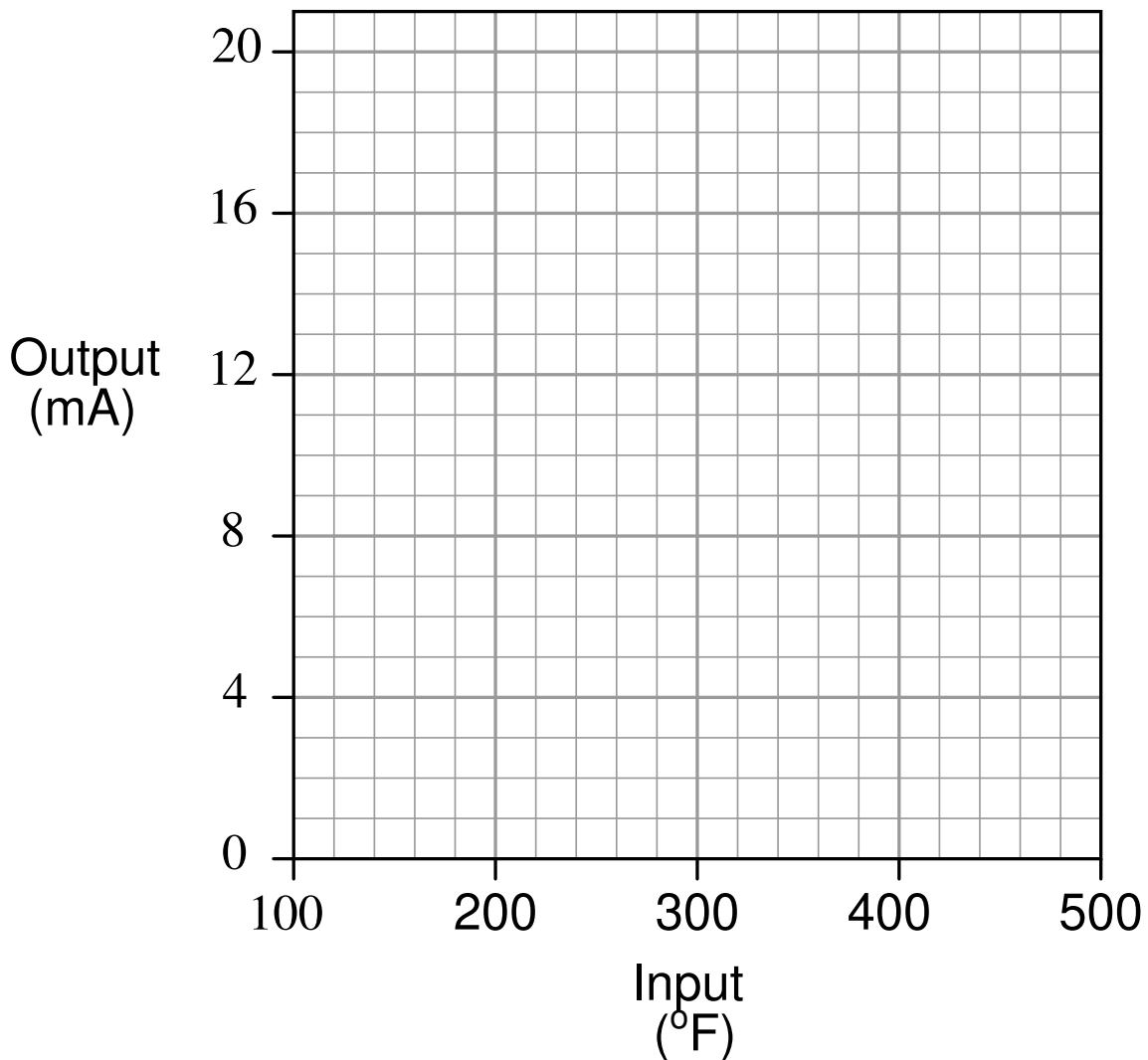
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Oppgave 88

An electronic temperature transmitter has an input range of 100 to 500 degrees Fahrenheit (type J thermocouple) and an output range of 4 to 20 mA. When subjected to a series of simulated temperatures (5-point up/down test), it responds as such:

| Simulated temperature (deg F) | Output signal (mA) |
|-------------------------------|--------------------|
| 100                           | 4.1                |
| 200                           | 8.0                |
| 300                           | 11.75              |
| 400                           | 16.0               |
| 500                           | 20.2               |
| 400                           | 16.0               |
| 300                           | 11.75              |
| 200                           | 8.0                |
| 100                           | 4.1                |

Graph this instrument's ideal transfer function on the graph below, along with its *actual* transfer function graph based on the measured values recorded above. Then, determine what kind of calibration error it has (*zero shift*, *span shift*, *linearity*, and/or *hysteresis*).

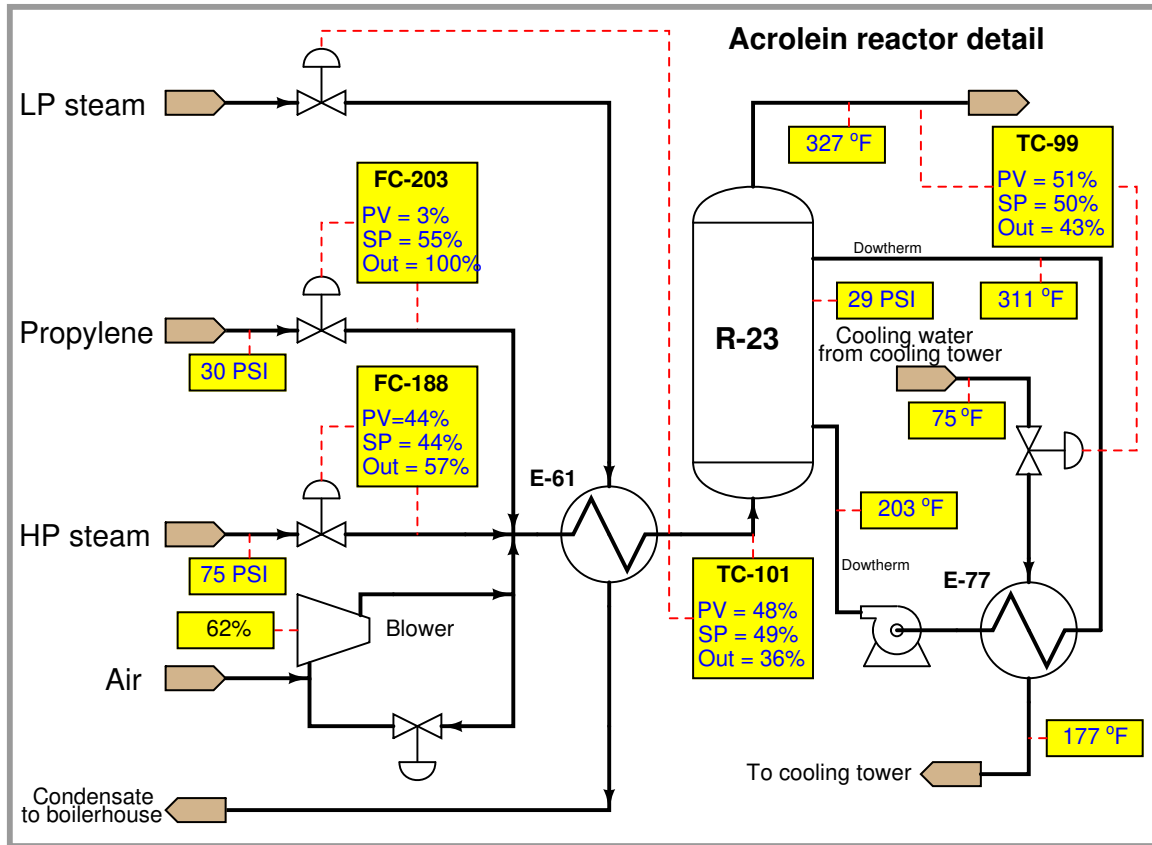


Hint: a computer spreadsheet program might be a useful tool in graphing this instrument's response. Feel free to attach a printed copy of a spreadsheet graph instead of hand-sketching one on this page.

file i03489

Oppgave 89

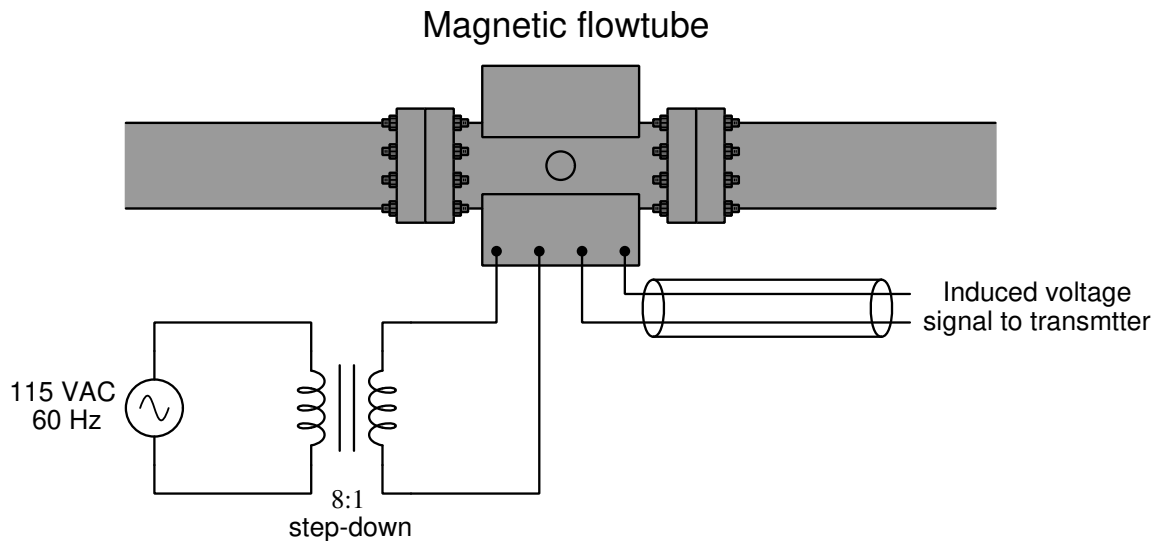
An antimicrobial agent called *acrolein* used to protect diesel fuel from fungal growth may be manufactured by reacting propylene with steam and air in a reactor vessel:



Suppose operators call you to troubleshoot a problem they are having with this process, and to help you start they show you this graphic display on one of their DCS workstations. Identify the problem in this process, suggest at least two possible causes for it, and identify the next diagnostic step you would take to confirm the cause(s).

## Opggave 90

The field coil of this AC magnetic flowmeter is energized by 60 Hz line AC power, the coil exhibiting a known quantity of inductance as well as wire resistance:



The *magnitude* of the induced voltage signal is a function of the field coil's magnetic flux density ( $B$ ), the velocity of the fluid moving through the flowtube ( $v$ ), and the diameter of the flowtube ( $d$ ). The *phase angle* of the induced voltage signal will be the same as the phase angle of the current through the field coil, relative to the source voltage.

Calculate the magnitude and phase angle of the induced voltage signal, given the following parameters:

- Flowtube diameter = 14 centimeters
- Magnetic flux density = 1.0 millitesla, RMS
- Field coil resistance = 11 ohms
- Field coil inductance = 4.1 millihenrys
- Fluid velocity = 6.3 meters per second



## Svar

---

Svar 1

**Partial answer:**

$\bar{v}$  through the 8-inch pipe = 201.49 feet per minute.

---

Svar 2

**Partial answer:**

$Q$  (minimum) = 2900.1 GPM

$$\text{Re} = \frac{3160G_fQ}{D\mu}$$

Where,

Re = Reynolds number (unitless)

$G_f$  = Specific gravity of liquid (unitless)

$Q$  = Flow rate (gallons per minute)

$D$  = Diameter of pipe (inches)

$\mu$  = Absolute viscosity of fluid (centipoise)

3160 = Conversion factor for British units

$$Q = \frac{\text{Re}D\mu}{3160G_f}$$

$$Q = \frac{(12500)(6.065)(111)}{(3160)\left(\frac{57.3}{62.4}\right)} = 2900.1 \text{ GPM}$$

$Q$  (minimum) = 2900.1 GPM = 387.7 ft<sup>3</sup>/min (*which is an extraordinarily high flow rate for a 6-inch pipe!*)

$$Q = A\bar{v}$$

$$\bar{v} = \frac{Q}{A} = \frac{387.7 \text{ ft}^3/\text{min}}{0.2006 \text{ ft}^2} = 1932.35 \text{ ft}/\text{min}$$

Based on these large figures (over 32 feet per second velocity!), this might not be the best flowmeter technology to use on olive oil! The relatively high viscosity of the oil makes it difficult to achieve the requisite Reynolds number for good operation.

---

Svar 3

---

Svar 4

$P_2 = 0.43 \text{ MPa}$

Follow-up question: calculate the *differential* pressure between either  $P_1$  or  $P_3$  and  $P_2$ .

---

Svar 5

The *Reynolds number* for a fluid flow is the ratio of a fluid's inertial (motion) forces as compared to its friction (viscous) forces.

To calculate Reynolds number given metric units:

$$\text{Re} = \frac{D\bar{V}\rho}{\mu}$$

Where,

Re = Reynolds number (unitless)

$D$  = Diameter of pipe, in meters (m)

$\bar{V}$  = Average velocity of fluid, in meters per second (m/s)

$\rho$  = Mass density of fluid, in kilograms per cubic meter ( $\text{kg}/\text{m}^3$ )

$\mu$  = Absolute viscosity of fluid, in Pascal-seconds ( $\text{Pa} \cdot \text{s}$ )

$$\text{Re} = 184903$$

---

Svar 6

$$\text{Re} \approx 13581 = \textit{turbulent}$$

Reynolds numbers less than 2,000 usually correspond to laminar flows, while Reynolds numbers above 10,000 usually correspond to turbulent flows. Reynolds numbers between 2,000 and 10,000 usually represent conditions of mild turbulence called “transitional flow.” Bear in mind these cutoff points are *very approximate*, and depend on many factors including pipe geometry and wall smoothness.

Examples of Reynolds number thresholds for laminar vs. turbulent flows are given here, from different sources:

- $\text{Re} < 2,000$  = “Laminar”
- $2,000 < \text{Re} < 10,000$  = “Transitional”
- $\text{Re} > 10,000$  = “Fully developed turbulent”
- Source: R. Siev, J.B. Arant, B.G. Lipták; Chapter 2.8: Laminar Flowmeters; *Instrument Engineer's Handbook, Process Measurement and Analysis, Third Edition*; pg. 105
- $\text{Re} > 10,000$  = “Definitely turbulent”
- Source: W.H. Howe, J.B. Arant, B.G. Lipták; Chapter 2.14: Orifices; *Instrument Engineer's Handbook, Process Measurement and Analysis, Third Edition*; pg. 153

- $Re < 2,000 = \text{“Laminar”}$
- $2,000 < Re < 4,000 = \text{“Transitional”}$
- $Re > 4,000 = \text{“Turbulent”}$
- Source: Instrument Society of America; Chapter 2: Fluid Properties – Part II; *ISA Industrial Measurement Series – Flow*; pg. 11

- $Re < 2,100 = \text{“Laminar”}$
- $Re > 3,000 = \text{“Turbulent”}$
- Source: Tyler G. Hicks, P.E.; Laminar Flow in a Pipe; *Standard Handbook of Engineering Calculations*; pg. 1-202

- $Re < 1,200 = \text{“Laminar”}$
- $Re > 2,500 = \text{“Turbulent”}$
- Source: Tyler G. Hicks, P.E.; Piping and Fluid Flow; *Standard Handbook of Engineering Calculations*; pg. 3-384

You’ve got to laugh when you see such vastly different threshold values given in the exact same reference book!

- $Re < (\text{about}) 2,000 = \text{“Laminar”}$
- $Re > 2,000 = \text{“Turbulent”}$
- Source: Douglas C. Giancoli; Chapter 10: Fluids; *Physics (Third Edition)*; pg. 11

- $Re < (\text{about}) 2,000 = \text{“Laminar”}$
- $2,000 < Re < 4,000 = \text{“Transitional”}$
- $Re > 4,000 = \text{“Turbulent”}$
- Source: Schoolcraft Publishing; Chapter 20: Properties of Fluid Flow; *Process Instrumentation – Volume I*; pg. 258

Another source, laughable in its attempt to precisely demarcate the threshold of turbulence, gives these figures:

- $Re < 2,320 = \text{“Laminar”}$
- $Re > 2,320 = \text{“Turbulent”}$
- Source: Website (<http://flow.netfirms.com/reynolds/theory.htm>)

It should be noted that laminar flow can be sustained at Reynolds numbers significantly in excess of 10,000 under very special circumstances. For example, in certain coiled capillary tubes, laminar flow may be sustained all the way up to  $Re = 15,000$ , due to something known as the *Dean effect*!

---

Svar 7

$$P_2 = 31.39 \text{ kPa}$$

It is tempting to alter Bernoulli's Equation to handle measurements in inches rather than feet (especially the annoying unit of pressure measurement: pounds per square *foot*, rather than PSI). However, caution must be exercised when attempting this, because there is more to it than simply converting feet into inches every place you see “ft” in the equation.

$$z_1 \rho g + \frac{v_1^2 \rho}{2} + P_1 = z_2 \rho g + \frac{v_2^2 \rho}{2} + P_2$$

There is the unit of “feet” lurking inside the unit of “slugs” which must also be accounted for. Here is the standard weight-mass-gravity equation relating slugs to pounds:

$$W = mg$$

$$[\text{lb}] = [\text{slug}] \left[ \frac{\text{ft}}{\text{s}^2} \right]$$

If we re-write the unit analysis equation to show slugs as a compound unit, we see that “feet” lurks within:

$$[\text{lb}] = \left[ \frac{\text{lb} \cdot \text{s}^2}{\text{ft}} \right] \left[ \frac{\text{ft}}{\text{s}^2} \right]$$

Thus, expressing  $g$  in inches per second squared would require us to invent a new unit of mass ( $\text{lb} \cdot \text{s}^2$  per in) instead of slugs ( $\text{lb} \cdot \text{s}^2$  per ft).

---

Svar 8

$$P_1 = 296.77 \text{ PSI} \quad P_2 = 293.27 \text{ PSI}$$

Bernoulli's equation assumes no gain or loss of energy between the two locations compared, and so it *cannot* be used to contrast the pump's suction and discharge pressures. The pump is a machine that adds energy to the fluid going through it, and so the assumption of equal (total) energy between the incoming and outgoing flow streams is not correct.

---

Svar 9

$$P_2 = 0.776 \text{ MPa}$$

---

Svar 10

$$P_{out} = 0.359 \text{ MPa}$$

Note: with a pipe diameter ratio of 4:1 (out:in), the exit velocity will be *16 times* slower than the inlet velocity  $(1:4)^2 = (1:16)$ .

---

Svar 11

**Partial answer:**

- $Q = 110 \text{ m}^3/\text{h}$  ;  $\Delta P = 4.15 \text{ kPa}$
  - $Q = 55 \text{ m}^3/\text{h}$  ;  $\Delta P = 1.04 \text{ kPa}$
  - $Q = 140 \text{ m}^3/\text{h}$  ;  $\Delta P = 6.75 \text{ kPa}$
  - $Q = 215 \text{ m}^3/\text{h}$  ;  $\Delta P = 15.85 \text{ kPa}$
- 

Svar 12

**Partial answer:**

- $Q$  range = 0 to  $110 \text{ m}^3/\text{h}$  ;  $\Delta P$  range = 0-14.18 kPa
  - $Q$  range = 0 to  $140 \text{ m}^3/\text{h}$  ;  $\Delta P$  range = 0-22.97 kPa
  - $Q$  range = 0 to  $180 \text{ m}^3/\text{h}$  ;  $\Delta P$  range = 0-37.97 kPa
  - $Q$  range = 0 to  $230 \text{ m}^3/\text{h}$  ;  $\Delta P$  range = 0-62.00 kPa
- 

Svar 13

**Partial answer:**

$$\Delta P = 10.25 \text{ kPa at } 740 \text{ m}^3/\text{h} \text{ and } 1.01 \text{ g/cm}^3$$

$$Q = 1058 \text{ m}^3/\text{h} \text{ flow rate at } 3.1 \text{ PSID and } 1.03 \text{ g/cm}^3$$

$$Q = 796.6 \text{ m}^3/\text{h} \text{ flow rate at } 12 \text{ kPaD and } 1.02 \text{ g/cm}^3$$

---

Svar 14

| Input signal (PSI) | Percent of input span (%) | Percent of output span (%) | Output signal (PSI) |
|--------------------|---------------------------|----------------------------|---------------------|
| 5                  | 16.67                     | 40.82                      | 7.899               |
| 13                 | <b>83.33</b>              | <b>91.29</b>               | <b>13.95</b>        |
| 9                  | 50                        | 70.71                      | 11.49               |
| 6.6                | 30                        | 54.77                      | 9.573               |
| 10.68              | 64                        | 80                         | 12.6                |
| <b>3.27</b>        | <b>2.25</b>               | 15                         | <b>4.8</b>          |
| 4.333              | 11.11                     | 33.33                      | 7                   |
| 9.75               | 56.25                     | 75                         | 12                  |

Values shown in bold-faced type are those given to students in the "Answer" section.

---

Svar 15

$$Q = Av = \pi \left( \frac{0.254\text{m}}{2} \right)^2 \cdot 7.62 = 0.386 \text{ m}^3/\text{s} = 6120 \text{ GPM}$$

---

Svar 16

**Bernoulli's equation:**

$$z_1 \rho g + \frac{v_1^2 \rho}{2} + P_1 = z_2 \rho g + \frac{v_2^2 \rho}{2} + P_2$$

Assuming no change in height ( $z$ ) is involved:

$$\frac{v_1^2 \rho}{2} + P_1 = \frac{v_2^2 \rho}{2} + P_2$$

Knowing that  $P_1$  is the static pressure and that  $P_2$  is equal to  $P_{static} + P_{stagnation}$ :

$$\frac{v_1^2 \rho}{2} + P_{static} = \frac{v_2^2 \rho}{2} + P_{static} + P_{stagnation}$$

$$\frac{v_1^2 \rho}{2} = \frac{v_2^2 \rho}{2} + P_{stagnation}$$

Knowing that  $v_2$  is zero at the stagnation point:

$$\frac{v_1^2 \rho}{2} = P_{stagnation}$$

Therefore,  $P_{stagnation} = \frac{1}{2} v^2 \rho$

---

Svar 17

$$P \text{ at } 80 \text{ km/h} = 276.82 \text{ Pa}$$

$$P \text{ at } 160 \text{ km/h} = 1107.3 \text{ Pa}$$

---

Svar 18

Tar utgangspunkt i Bernoulli

$$z_1 \rho g + \frac{v_1^2 \rho}{2} + P_1 = z_2 \rho g + \frac{v_2^2 \rho}{2} + P_2$$

Samme høyde  $z$  ledd faller vekk

↓

$$\frac{v_1^2 \rho}{2} + P_1 = \frac{v_2^2 \rho}{2} + P_2$$

Snur med hensyn på  $\Delta P$

↓

$$P_1 - P_2 = \Delta P = \frac{v_2^2 \rho}{2} - \frac{v_1^2 \rho}{2} = \frac{\rho}{2} (v_2^2 - v_1^2) = \frac{\rho}{2} \left( \left( v_1 \left( \frac{D_1}{D_2} \right)^2 \right)^2 - v_1^2 \right) =$$

$$\frac{1.21114}{2} \left( \left( 22.22 \left( \frac{2}{1} \right)^2 \right)^2 - 22.22^2 \right) = 4485.6 \text{ Pa}$$

$\Delta P$  at 80 km/h = 4485.6 Pa

$\Delta P$  at 160 km/h = 17942 Pa

Assuming no difference in height ( $z$ ):

$$\frac{v_1^2 \rho}{2} + P_1 = \frac{v_2^2 \rho}{2} + P_2$$

$$P_1 - P_2 = \frac{v_2^2 \rho}{2} - \frac{v_1^2 \rho}{2}$$

$$\Delta P = \frac{\rho}{2} (v_2^2 - v_1^2)$$

$$\frac{2\Delta P}{\rho} = v_2^2 - v_1^2$$

$$\text{If } Q = Av \text{ then } v = \frac{Q}{A}$$

$$\frac{2\Delta P}{\rho} = \left(\frac{Q}{A_2}\right)^2 - \left(\frac{Q}{A_1}\right)^2$$

$$\frac{2\Delta P}{\rho} = \frac{Q^2}{A_2^2} - \frac{Q^2}{A_1^2}$$

$$\frac{2\Delta P}{\rho} = \frac{Q^2 A_1^2}{A_1^2 A_2^2} - \frac{Q^2 A_2^2}{A_1^2 A_2^2}$$

$$\frac{2\Delta P}{\rho} = Q^2 \frac{A_1^2 - A_2^2}{A_1^2 A_2^2}$$

$$Q^2 = \left(\frac{A_1^2 A_2^2}{A_1^2 - A_2^2}\right) \left(\frac{2\Delta P}{\rho}\right)$$

$$Q = \sqrt{\frac{A_1^2 A_2^2}{A_1^2 - A_2^2}} \sqrt{\frac{2\Delta P}{\rho}}$$

$$Q = \frac{A_1 A_2}{\sqrt{A_1^2 - A_2^2}} \sqrt{\frac{2\Delta P}{\rho}}$$

Where,

$Q$  = Volumetric flow rate (ft<sup>3</sup>/s)

$A_1$  = Large flow area (ft<sup>2</sup>)

$A_2$  = Small (throat) flow area (ft<sup>2</sup>)

$\Delta P$  = Differential pressure drop (lb/ft<sup>2</sup>)

$\rho$  = Mass density of fluid (slugs/ft<sup>3</sup>)



---

Svar 20

We cannot tell exactly where the problem is, but we know it must be either in the receiver gauge or in the panel-mounted indicator (assuming only one fault in the system).

One test would be to block and equalize the DP transmitter's manifold, to see which indicator goes closest to zero. Chances are, the error is (at least) a zero shift, and as such should reveal itself in this test. Whichever indicator goes exactly to zero during this test is good; whichever one reads some non-zero value during this test is in error.

Another test would be to use a pressure gauge to measure the 3-15 PSI pneumatic signal coming from the transmitter. If the pressure is 5.78 PSI, the receiver gauge is good and the panel-mounted indicator must be in error. If the pressure is 6.05 PSI, the receiver gauge is in error and the panel-mounted indicator is good.

---

Svar 21

**Partial answer:**

The amount of time required to accumulate 525,000 pulses (on a digital counter circuit) give a steady flow rate of 170 SLM = **1 hour, 23 minutes**

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Svar 22

---

Svar 23

**Partial answer:**

The total amount of fuel consumed by the boiler after a digital counter circuit records 800,000 pulses = **77,339.5 liter**

---

Svar 24

$$Re = \frac{Dv\rho}{\mu} \Rightarrow v = \frac{Re\mu}{D\rho} = \frac{10000 \cdot 36mPas}{40.94mm \cdot 790kg/m} = 0.099m/s$$
$$Q = Av = \pi\left(\frac{40.95mm}{2}\right) \cdot 0.099m/s = 0.13l/s = 7.81l/m$$

---

Svar 25

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Svar 26

- **Advantages of turbine meters over orifice plates**
- Very high accuracy
- Linear output requires no square-root characterization
- Better rangeability due to linear response to flow
- **Advantages of orifice plates over turbine meters**
- Typically cheaper
- Cleanliness of flow stream not as critical
- Turbine may become bound if viscous or fibrous solids are present in the flow stream
- Less wear over time (no bearings to wear out)

---

Svar 27

| Measured flow<br>(l/m) | Pickup signal<br>frequency (Hz) | Percent of output<br>span (%) | Output signal<br>(mA) |
|------------------------|---------------------------------|-------------------------------|-----------------------|
| 250                    | 412.5                           | 50                            | 12                    |
| 412                    | 679.8                           | 82.4                          | 17.18                 |
| 184.8                  | 305                             | 36.97                         | 9.915                 |
| 472.7                  | 780                             | 94.55                         | 19.13                 |
| 315                    | 519.8                           | 63                            | 14.08                 |
| 245                    | 404.3                           | 49                            | 11.84                 |
| 187.5                  | 309.4                           | 37.5                          | 10                    |
| 375                    | 618.8                           | 75                            | 16                    |

$$Q = kf$$

Where,

$f$  = Frequency in Hertz (pulses per second)

$k$  = Calibration factor in liter per pulse

$Q$  = Volumetric flow rate in liter per second

$$Q = \frac{kf}{60}$$

Where,

$f$  = Frequency in Hertz (pulses per second)

$k$  = Calibration factor in pulses per gallon

$Q$  = Volumetric flow rate in gallons per minute

---

Svar 28

The large pipe carries a greater volumetric rate of water flow than the small pipe.

Since the vortex shedding frequency is proportional to the fluid *velocity*, we know that the flow velocities in both cases must be the same (given identical bluff body geometries). However, since the larger pipe has a greater cross-sectional area, an identical velocity equates to a greater *volume* rate of water moving past the bluff body and sensor.

---

Svar 29

- **Advantages of vortex meters over orifice plates**
- Immune to changes in fluid density (and therefore temperature and pressure as well)
- Linear output requires no square-root characterization
- Better rangeability due to linear flow response (at least down to the “cut off” point)
- **Advantages of orifice plates over vortex meters**
- Cheaper for very large pipe sizes
- Orifice plates may be more tolerant of low-frequency pipe vibrations
- Some orifice plates may measure bidirectional flow
- Able to sense flow down to zero (vortex flowmeters will “cut off” at some low flow rate)

Low-flow cutoff is a problem unique to vortex flowmeters. At low flow rates, the Reynolds number drops below the turbulent threshold, at which point fluid viscosity prevents vortices from shedding. The vortex street simply ceases to exist at any flow rate below this critical point, meaning the flowmeter’s output goes to zero at any flow rate below the cutoff point.

---

Svar 30

Vortex meter and turbine meter both: 15 to 50 pipe diameters upstream; 5 pipe diameters downstream.

---

Svar 31

At 0% flow and 100% flow rates, the meter will indicate accurately. It will be very much in error at any point in between. At 50% true flow rate, for example, the meter will only indicate 25%, since the differential pressure drop generated by the orifice plate will only be that much at the half-flow rate.

Follow-up question: identify a way we may correct this system so that all the points along the indicator’s scale accurately reflect flow rate through the orifice.

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Svar 32

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Svar 33

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Svar 34

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Svar 35

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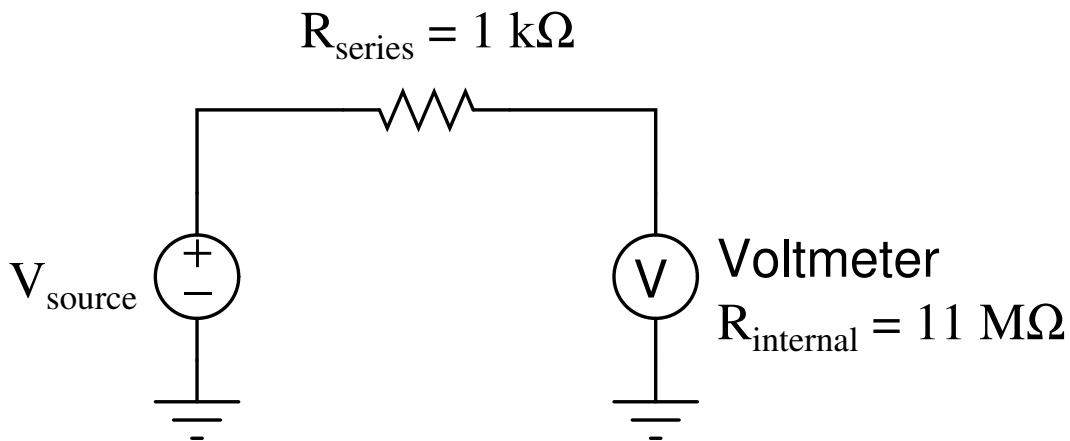
Svar 36

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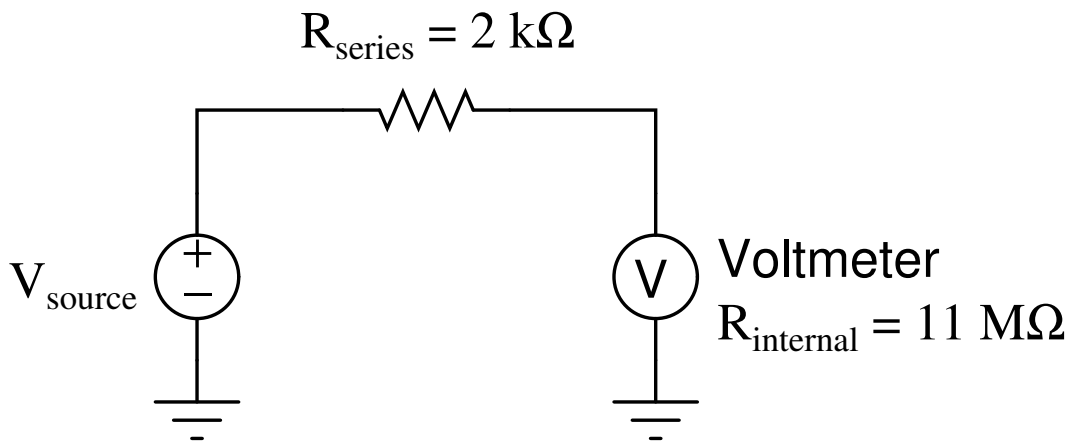
Svar 37

Answer to second question: most oils and concentrated alcohols have very low conductivity and thus cannot be measured by a magnetic flowmeter. Gases and vapors suffer the same problem.

In answer to the third question, I offer the following electrical “thought experiment.” Consider the effect of doubling the series resistance in this circuit:



*Does the voltmeter accurately measure  $V_{\text{source}}$  ?*



*Does the voltmeter accurately measure  $V_{\text{source}}$  ?*

---

Svar 38

“AC” flowmeters indeed use alternating current to energize their field windings, but “DC” meters do not use steady direct current. Rather, “DC” flowmeters use *pulsed* magnetic fields, sometimes of consistent polarity and other times with reversing polarity (making them “alternating” after all!).

Dual-frequency magflow meters attempt to capitalize on the best features of both DC and AC techniques, by employing specialized pulse waveforms.

DC magflow meters enjoy good rejection of “noise” voltages, while AC magflow meters typically exhibit faster response times.

---

Svar 39

Since the output of a magnetic flowmeter is linear with regard to flow, there is no need for square root extraction, as indicated by the first “FY” device in the loop. Square-rooting the flow signal will only cause problems if there is no need to do so!

---

Svar 40

The time elapsed between the generation of an acoustic pulse and the reception of its echo (reflected off the solid object) is directly proportional to the distance between the pulse source and the object. *Velocity* is simply the first derivative of distance with respect to time ( $v = \frac{dx}{dt}$ ).

---

Svar 41

Flow stream velocity may be measured via the use of sound waves transmitted and received through the liquid. One sonic technology, called *Doppler*, infers velocity by the change in sound frequency between the transmitted sound wave and the received sound wave.

Another sonic flowmeter technology, called *transit-time*, measures liquid velocity by measuring the difference between upstream and downstream velocities of sound waves transmitted through the fluid.

Doppler flowmeter calibration depends on the speed of sound through the process fluid. Transit-time flowmeter calibration does not. Ultrasonic flowmeters are not suitable for multiphase (vapor/liquid mixed) flows, and thus the pipe must be completely full of liquid (no gas pockets) or completely full of gas (no puddles or streams of liquid) in order to function properly.

---

Svar 42

Transit-time = clean flow streams ; Doppler = flow streams containing particulate and/or bubbles.

---

Svar 43

Why has the traditional recommendation for DP flow transmitter on steam lines been to locate the transmitter *below* the line? *Below-line mounting in steam service helps protect the transmitter against damage from high steam temperatures.*

What kind(s) of problem(s) are typically experienced with below-pipe mounting of DP flow transmitters in steam line applications? *Measurement errors at low DP values due to uneven water columns in “wet leg” impulse lines. The water in the wet impulse legs can also freeze in cold weather.*

Can DP flowmeters *always* be top-mounted? If not, what limitations dictate whether or not to top-mount? *Top-mounting is applicable only for certain limited temperature ranges. Otherwise, the pipe is simply too hot and the transmitter will be “cooked” to death.*

Why shouldn't Annubar-style flow elements be mounted *vertically* in a steam pipe, but rather should be canted at least 15 degrees from vertical? *To avoid measurement errors due to water running alongside the bottom of the steam line, impacting the lowest port on the Annubar element.*

---

Svar 44

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Svar 45

**Increased volumetric flow rate with constant density:** the undulating motion of the tubes will *increase* in amplitude due to the greater inertial forces, but the resonant frequency of the tubes will *remain the same* because the tubes' mass has not changed.

**Increased density with constant volumetric flow rate:** the undulating motion of the tubes will *increase* in amplitude due to the greater inertial forces resulting from an increased mass flow rate, and the resonant frequency of the tubes will *decrease* due to increased tube mass.

**Changes in fluid density at zero flow:** there will be no undulating motion, because there will be no Coriolis force with zero flow. The tubes' resonant frequency, however, will vary inversely with fluid density. One practical caveat is that there will need to be *some* flow in order to push a new fluid of different density into the flowmeter's vibrating tubes, in order to sense that new density.

---

Svar 46

$$W = \rho Q = 250m/h \cdot 950kg/m = 3958kg/m = 66.0kg/s$$

**Advantages:**

- Very high accuracy
- Immunity to upstream/downstream piping disturbances
- Provides real measurement of mass flow, fluid density, and fluid temperature
- Excellent rangeability
- Immunity to changes in density – this makes Coriolis flowmeters particularly well-suited for measuring non-Newtonian fluids
- Bidirectional

**Disadvantages:**

- Relatively low operating temperature limit (< 800° F)
- Difficulty measuring multi-phase flows (e.g. gas + liquid)
- Prohibitively expensive for large pipe sizes
- Cannot measure low-pressure gases very well (Coriolis forces too small)
- May suffer errors from external vibrations

Mass flow measurement is obtained by measuring the phase shift of the tube's oscillation between the two ends.

Density measurement is obtained by measuring the resonant frequency of the tubes. The basic equation for a mass-and-spring mechanical system is as follows:

$$f_r = \frac{1}{2\pi} \sqrt{\frac{k}{m}}$$

Where,

$f_r$  = Resonant frequency

$k$  = Spring constant

$m$  = Mass

Given a known tube mass and a known tube volume, knowing the resonant frequency of the tubes makes it quite easy to calculate the mass of the fluid filling the tubes, and thus the fluid density.

Temperature measurement comes from an RTD sensing fluid temperature as it enters the tube assembly.

First, the proper location of the vapor flowmeter: between the knockout drum and the water-seal drum, or between the water-seal drum and the flare tip. Proper straight-pipe lengths should be observed in order to achieve best measurement accuracy.

- **Orifice plate/venturi/etc.** – Probably not suitable, due to the unknown density ( $\rho$ ) of the vapors going through the pipe. If a gas density analyzer were added to the system, and its signal used along with absolute pressure and temperature compensation, accurate measurement of either volumetric or mass flow might be possible.
- **Positive displacement** – Probably not suitable, due to possible particulate matter in the gas stream, and rapid temperature changes. Most importantly, if this flowmeter ever jammed, it would “plug up” the flare and prevent its safe operation!
- **Turbine** – Possibly suitable. Pressure and temperature compensation would both be necessary to calculate true volumetric flow rate, however.
- **Vortex** – Probably not suitable, due to low-flow cutoff interfering with operation at low flare flow rates. Even if minimum flow could be ensured, pressure and temperature compensation would both be necessary to calculate true volumetric flow rate.
- **Magnetic** – Definitely unsuitable, due to non-conductivity of vapors in general.
- **Ultrasonic (Doppler)** – Definitely unsuitable, due to lack of objects in flow stream to reflect sound waves.
- **Ultrasonic (transit time)** – Possibly suitable. Pressure and temperature compensation would both be necessary to calculate true volumetric flow rate, however.
- **Coriolis** – Definitely suitable, but most likely too expensive to consider for this application.
- **Thermal mass** – Definitely unsuitable, due to the unknown and randomly changing specific heat of flare vapors.



Turndown refers to the ratio of minimum to maximum flow rate that may be accurately sensed by a particular flowmeter while remaining within acceptable limits of measurement error. Differential-pressure based flowmeters such as this venturi tube typically exhibit turndown ratios of only 4:1 (or sometimes worse) due to measurement uncertainties caused by uneven impulse line liquid heights, DP sensor calibration error, etc. The nonlinear nature of the flow/pressure relationship is the root of this problem.

- **Positive displacement** – Probably not suitable, due to possible particulate matter in the gas stream, and the high volume of flow expected. High volumes would require either a huge flowmeter, or would induce undue wear and tear in the fast-moving meter mechanism.
- **Turbine** – Possibly suitable. Pressure and temperature compensation would both be necessary to calculate true volumetric flow rate, however.
- **Vortex** – Possibly suitable, so long as the minimum flow rate exceeded the low-flow cutoff point for the flowmeter. If minimum flow could be ensured, pressure and temperature compensation would both be necessary to calculate true volumetric flow rate.
- **Magnetic** – Definitely unsuitable, due to non-conductivity of vapors in general.
- **Ultrasonic (Doppler)** – Definitely unsuitable, due to lack of objects in flow stream to reflect sound waves.
- **Ultrasonic (transit time)** – Possibly suitable. Pressure and temperature compensation would both be necessary to calculate true volumetric flow rate, however.
- **Coriolis** – Definitely suitable, but most likely too expensive to consider for this application.
- **Thermal mass** – Possibly suitable, so long as the specific heat of the natural gas was relatively stable over time. If not, compensation may be possible using a gas chromatograph to analyze the composition of the natural gas stream (gas chromatography is typically done anyway in the gas pipeline industry to determine the chemical heating value of the gas!).

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Svar 50

- **FT-4 (influent to digester):** This is a magnetic flowmeter, which is a good choice for this application because it is non-restrictive, linear, and handles entrained solids with ease.
- **FT-9 (coolant flow from engine):** This is a vortex flowmeter, which is a good choice for this application because it is linear-responding and senses a flow rate that is unlikely to drop below the meter’s low-flow cutoff point (because engine coolant flow is critically important and therefore will be at or near full flow at all times).
- **FT-10 and FT-18 (biogas flow):** These are thermal flowmeters, which is a good choice for this application because it is a technology yielding true mass flow rate (ideal for regulatory monitoring, for carbon credits), is linear, and is relatively inexpensive. The only potential problem in this application is the potential of the biogas composition to change with changes in biomass chemistry. Thermal mass flowmeters are dependent upon the fluid’s specific heat value remaining constant (or at least known), and in this case changes in biogas composition may effect specific heat and therefore introduce errors.
- **FT-12 (effluent flow to de-watering):** This is another magnetic flowmeter, which is a good choice for this application because it is non-restrictive, linear, and handles entrained solids with ease.

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Svar 51

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Svar 52

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Svar 53

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Svar 54

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Svar 55

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Svar 56

A “prover” is a precision device used to measure a flow rate for a short period of time. Provers are typically of the piston-and-cylinder design, measuring flow rate by timing how long it takes the piston to travel a certain distance (i.e. displace a certain volume of fluid).

Periodic re-calibration of positive-displacement flowmeters is necessary because they all suffer from internal friction and mechanical wear.

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Svar 57

*Positive displacement* flowmeters of all types use mechanisms to move specific volumes of fluid through with each rotation or other mechanism cycle. Many positive displacement meters resemble pump mechanisms in design.

Because positive displacement meters move specified volumes of fluid through them per cycle, they are immune to changes in viscosity, density, and other fluid parameters. However, it must be understood that the quantity being measured is actual volume, not *standardized* volume units. In other words, a positive displacement gas flowmeter inherently measures in units such as cubic feet per minute (CFM), not standard cubic feet per minute (SCFM).

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Svar 58

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Svar 59

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Svar 60

As flow increases, temperature decreases.

As incoming temperature increases, sensor temperature increases as well. This is interpreted to be *less* flow.

In order to compensate for the fluid's temperature entering the flowmeter and thus cancel any effects resulting from temperature change, we must have an unheated sensor that detects the fluid's "ambient" temperature.

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Svar 61

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Svar 62

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Svar 63

$H = 7.697$  inches

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Svar 64

**Partial answer:**

- Differential pressure at 550 lbm/min mass flow and  $\rho = 1.30$  lbm/ft<sup>3</sup> = **32.89 "W.C.**
- Mass flow rate at 90 "W.C. = **920 lbm/min**

---

Svar 65

**Partial answer:**

- **At a flow rate of 10 bbl/hr:**
  - Differential pressure transmitter output signal = 3.75 PSI
  - Square root extractor output signal = 6 PSI
  
- **At a flow rate of 31 bbl/hr:**
  - Orifice plate  $\Delta P = \underline{90.09}$  " H<sub>2</sub>O
  - Flow indicator reading = 31 bbl/hr

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Svar 66

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Svar 67

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Svar 68

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Svar 69

Note: All data obtained from the *Instrument Engineer's Handbook, Process Measurement and Analysis, Fourth Edition*, except where noted. Accuracy figures given here are conservative.

- **Orifice plate**

- 
- Principle of operation: *Differential pressure caused by energy exchange between kinetic and potential forms.*
- 
- Fluid type(s): *Gas or liquid.*
- 
- Minimum straight-run piping lengths (in units of "pipe diameters"): *Up to 50 D upstream, 5 D downstream ; 12 D up and 5 D down typical.*
- 
- Reynolds number range: *10,000 or greater for concentric, square-edge orifice plates ; special orifices may work well at lower Reynolds number values.*
- 
- Typical accuracy (in percent of full-flow value): *+/- 0.5%*
- 
- Bidirectional flow measurement: *Yes, with square-edged orifice plate and symmetrical upstream/downstream tap locations such as flange or corner.*
- 
- Inherently measures true mass flow: *No.*
- 
- Special advantages: *Relatively inexpensive and applicable to a wide range of fluids.*
- 
- Special disadvantages: *Square-edged orifice plates are particularly sensitive to wear, making them unsuitable for abrasive flow measurement.*

- **Venturi tube**

- 

- Principle of operation: *Differential pressure caused by energy exchange between kinetic and potential forms.*

- 

- Fluid type(s): *Gas or liquid.*

- 

- Minimum straight-run piping lengths (in units of “pipe diameters”): *Up to 26 D upstream, 2 D downstream ; 4 D up and 0 D down typical.*

- 

- Reynolds number range: *100,000 minimum.*

- 

- Typical accuracy (in percent of full-flow value): *+/- 0.75%*

- 

- Bidirectional flow measurement: *No.*

- 

- Inherently measures true mass flow: *No.*

- 

- Special advantages: *High pressure recovery.*

- 

- Special disadvantages: *Requires flowmeter spool – cannot sandwich between flanges or be inserted through a tap.*

- **Pitot tube or Annubar**

- 

- Principle of operation: *Differential pressure caused by energy exchange between kinetic and potential forms.*

- 

- Fluid type(s): *Gas or liquid.*

- 

- Minimum straight-run piping lengths (in units of “pipe diameters”): *Up to 30 D upstream, 5 D downstream.*

-

- Reynolds number range: *50,000 minimum.*
- 
- Typical accuracy (in percent of full-flow value): *+/- 5% typical ; +/- 1% possible with custom calibration.*
- 
- Bidirectional flow measurement: *No.*
- 
- Inherently measures true mass flow: *No.*
- 
- Special advantages: *May be inserted into pipe through tap.*
- 
- Special disadvantages: *Most pitot tubes sample flow profile at one point only, possibly leading to inaccurate measurements.*
- 
- **Vortex**
- 
- Principle of operation: *Von Kármán effect of vortices produced alternately from a blunt object in the flow path.*
- 
- Fluid type(s): *Gas or liquid.*
- 
- Minimum straight-run piping lengths (in units of “pipe diameters”): *Up to 50 D upstream, 5 D downstream ; 20 D up and 5 D down typical.*
- 
- Reynolds number range: *20,000 to 7,000,000 is where the Strouhal number remains constant at about 0.17.*
- 
- Typical accuracy (in percent of full-flow value): *+/- 2%*
- 
- Bidirectional flow measurement: *No.*
- 
- Inherently measures true mass flow: *No.*
-

- Special advantages: *High pressure recovery, easy integration of fluid volume (counting pulses), insertable elements possible.*
- 
- Special disadvantages: *Pipe vibrations may fool the vortex detector.*
- 
- V-cone
- 
- Principle of operation: *Differential pressure caused by energy exchange between kinetic and potential forms.*
- 
- Fluid type(s): *Gas or liquid.*
- 
- Minimum straight-run piping lengths (in units of “pipe diameters”): *2 D up (!) and 5 D down typical.*
- 
- Reynolds number range: *8,000 minimum (according to manufacturer).*
- 
- Typical accuracy (in percent of full-flow value): *+/- 0.25% if two  $\Delta P$  transmitters used.*
- 
- Bidirectional flow measurement: *No.*
- 
- Inherently measures true mass flow: *No.*
- 
- Special advantages: *Fewer upstream straight-pipe lengths required to condition flow compared to other head-based flow elements.*
- 
- Special disadvantages: *Requires flowmeter spool – cannot sandwich between flanges or be inserted through a tap.*



- **Segmental wedge**

- 

- Principle of operation: *Differential pressure caused by energy exchange between kinetic and potential forms.*

- 

- Fluid type(s): *Gas or liquid.*

- 

- Minimum straight-run piping lengths (in units of “pipe diameters”): *10 to 30 D upstream (Source: [http://www.flowmeterdirectory.com/flowmeter\\_artc/flowmeter\\_](http://www.flowmeterdirectory.com/flowmeter_artc/flowmeter_) and no downstream requirement specified. One manufacturer (ABB) claims that their wedge flow element requires “minimum upstream and downstream piping requirements” (Source: <http://www.abb.com>), whatever that means.*

- 

- Reynolds number range: *As low as 500 (!).*

- 

- Typical accuracy (in percent of full-flow value): *+/- 5% typical ; +/- 0.75% possible with custom calibration.*

- 

- Bidirectional flow measurement: *Yes.*

- 

- Inherently measures true mass flow: *No.*

- 

- Special advantages: *Well suited for viscous and slurry applications.*

- 

- Special disadvantages: *Requires flowmeter spool – cannot sandwich between flanges or be inserted through a tap.*

- **Magnetic**

- 

- Principle of operation: *Electromagnetic induction, as a conductive fluid flows perpendicular to a magnetic field.*

- 

- Fluid type(s): *Liquids only, that are electrically conductive (1  $\mu$ S/cm conductivity minimum).*

- 
- Minimum straight-run piping lengths (in units of “pipe diameters”): *Up to 5 D upstream, 3 D downstream ; 3 D up and 2 D down typical.*
- 
- Reynolds number range: *No minimum.*
- 
- Typical accuracy (in percent of full-flow value): *+/- 2% for AC ; +/- 1% for DC.*
- 
- Bidirectional flow measurement: *Yes.*
- 
- Inherently measures true mass flow: *No.*
- 
- Special advantages: *Obstructionless, work well with slurries.*
- 
- Special disadvantages: *Can be expensive for large pipe sizes, fouling of electrodes by insulating deposits such as minerals from “hard” water or oil residue may cause problems.*
- 
- **Coriolis**
- 
- Principle of operation: *Inertial force of a fluid flowing in a rotating reference frame (the “Coriolis” force).*
- 
- Fluid type(s): *Either gas or liquid, although liquid is easier due to greater density.*
- 
- Minimum straight-run piping lengths (in units of “pipe diameters”): *No special piping requirements.*
- 
- Reynolds number range: *No minimum.*
- 
- Typical accuracy (in percent of full-flow value): *+/- 0.1% (!)*
- 
- Bidirectional flow measurement: *Yes.*

- 
- Inherently measures true mass flow: *Yes!*
- 
- Special advantages: *High accuracy, offers fluid density and temperature measurements independent from mass flow measurement.*
- 
- Special disadvantages: *Sensitive to certain vibrations, cannot be used on temperatures above about 800° F, transmitter must be factory-matched to flow tube to be accurate.*
- 
- Weir
- 
- Principle of operation: *Differential pressure caused by energy exchange between kinetic and potential forms.*
- 
- Fluid type(s): *Liquid in an open channel.*
- 
- Minimum straight-run piping lengths (in units of “pipe diameters”): *No special piping requirements.*
- 
- Reynolds number range: *Liquid must be fairly low in viscosity.*
- 
- Typical accuracy (in percent of full-flow value): *+/- 10%*
- 
- Bidirectional flow measurement: *Theoretically possible, but seldom practiced.*
- 
- Inherently measures true mass flow: *No.*
- 
- Special advantages: *Simple and inexpensive.*
- 
- Special disadvantages: *Suitable only for open-channel flow.*

- **Thermal**

- 
- Principle of operation: *Cooling of a heated element by fluid convection.*
- 
- Fluid type(s): *Gas or liquid.*
- 
- Minimum straight-run piping lengths (in units of “pipe diameters”): *Up to 10 D upstream.*
- 
- Reynolds number range: *No minimum.*
- 
- Typical accuracy (in percent of full-flow value): *+/- 2%*
- 
- Bidirectional flow measurement: *Yes.*
- 
- Inherently measures true mass flow: *Yes!*
- 
- Special advantages: *Function better for low-flow gas streams than most other mass flowmeter technologies.*
- 
- Special disadvantages: *Usually practical only for low flow rates.*

- **Ultrasonic**

- 
- Principle of operation: *Time-of-flight for sound waves changing with fluid velocity, Doppler effect on reflected sound waves.*
- 
- Fluid type(s): *Gas or liquid.*
- 
- Minimum straight-run piping lengths (in units of “pipe diameters”): *20 D upstream, 5 D downstream ; possibly more upstream if disturbances are severe.*
-

- Reynolds number range: *No minimum, although meter calibration varies with Reynolds number.*
- 
- Typical accuracy (in percent of full-flow value): *+/- 1% for transit-time, +/- 5% for Doppler.*
- 
- Bidirectional flow measurement: *Yes.*
- 
- Inherently measures true mass flow: *No.*
- 
- Special advantages: *May be bolted to outside of pipe for non-intrusive flow measurement.*
- 
- Special disadvantages: *Sound waves may “ring around the pipe” without even going through the fluid, causing false readings.*

- **Turbine**

- 
- Principle of operation: *Windmill operation: fluid turns a bladed turbine at a speed dependent on the fluid’s velocity.*
- 
- Fluid type(s): *Gas or liquid.*
- 
- Minimum straight-run piping lengths (in units of “pipe diameters”): *Up to 50 D upstream, 5 D downstream ; 20 D up and 5 D down typical.*
- 
- Reynolds number range: *Liquid must be fairly low in viscosity, otherwise fluid drag on the turbine blades will affect low-flow accuracy.*
- 
- Typical accuracy (in percent of full-flow value): *+/- 1%*
- 
- Bidirectional flow measurement: *Yes.*
-

- Inherently measures true mass flow: *No.*
- 
- Special advantages: *High accuracy and repeatability, easy integration of fluid volume (counting pulses).*
- 
- Special disadvantages: *Moving parts will wear over time, can be damaged from overspeeding.*
- 
- **Positive displacement**
- 
- Principle of operation: *Measuring precise volumes of fluid passing through with a positive-displacement mechanism.*
- 
- Fluid type(s): *Gas or liquid.*
- 
- Minimum straight-run piping lengths (in units of “pipe diameters”): *No special piping requirements.*
- 
- Reynolds number range: *No minimum.*
- 
- Typical accuracy (in percent of full-flow value): *+/- 1% or better. Flow “provers” may attain extremely high accuracies.*
- 
- Bidirectional flow measurement: *Yes.*
- 
- Inherently measures true mass flow: *No.*
- 
- Special advantages: *Inherently totalizes (integrates) flow rate into a fluid volume quantity.*
- 
- Special disadvantages: *Greatest friction and mechanical wear of any flowmeter type.*

- **Rotameter**

- 

- Principle of operation: *Differential pressure caused by energy exchange between kinetic and potential forms.*

- 

- Fluid type(s): *Gas or liquid.*

- 

- Minimum straight-run piping lengths (in units of “pipe diameters”): *No special piping requirements.*

- 

- Reynolds number range: *No minimum.*

- 

- Typical accuracy (in percent of full-flow value): *+/- 5%*

- 

- Bidirectional flow measurement: *No.*

- 

- Inherently measures true mass flow: *No.*

- 

- Special advantages: *Inexpensive, reads out directly for people to see.*

- 

- Special disadvantages: *Not suitable for very high pressures, due to need for transparent viewing tube; fluid must be fairly clear; limited to relatively low flow rates.*

- **Pipe elbow**

- 

- Principle of operation: *Differential pressure caused by energy exchange between kinetic and potential forms.*

- 

- Fluid type(s): *Gas or liquid.*

- 

- Minimum straight-run piping lengths (in units of “pipe diameters”): *25 D upstream, 10 D downstream typical.*

-

- Reynolds number range: *10,000 minimum.*
- 
- Typical accuracy (in percent of full-flow value): *+/- 10%*
- 
- Bidirectional flow measurement: *Yes, if taps at 45° position.*
- 
- Inherently measures true mass flow: *No.*
- 
- Special advantages: *Pipe elbow is already there – cheap!*
- 
- Special disadvantages: *Poor accuracy.*
- 
- **Target**
- 
- Principle of operation: *Differential pressure caused by energy exchange between kinetic and potential forms.*
- 
- Fluid type(s): *Gas or liquid.*
- 
- Minimum straight-run piping lengths (in units of “pipe diameters”): *10 to 30 D upstream (Source: [http://www.geocities.com/ull\\_km1980/flowmeterselectionguide](http://www.geocities.com/ull_km1980/flowmeterselectionguide)) Downstream = 10 D (Source: <http://www.hersheymeasurement.com/specsheets/Target>)*
- 
- Reynolds number range: *No minimum with proper calibration.*
- 
- Typical accuracy (in percent of full-flow value): *+/- 0.5% for standard, +/- 5% for insertion.*
- 
- Bidirectional flow measurement: *Theoretically possible, but seldom practiced.*
- 
- Inherently measures true mass flow: *No.*
-



- Special advantages: *Insertion design is relatively easy to install in large pipes.*
- 
- Special disadvantages: *Difficult to calibrate.*
- 
- **Flume**
- 
- Principle of operation: *Differential pressure caused by energy exchange between kinetic and potential forms.*
- 
- Fluid type(s): *Liquid in an open channel.*
- 
- Minimum straight-run piping lengths (in units of “pipe diameters”): *No special piping requirements.*
- 
- Reynolds number range: *Liquid must be fairly low in viscosity.*
- 
- Typical accuracy (in percent of full-flow value): *+/- 10%*
- 
- Bidirectional flow measurement: *No.*
- 
- Inherently measures true mass flow: *No.*
- 
- Special advantages: *Simple and inexpensive, no pockets for solids to collect in (unlike a weir).*
- 
- Special disadvantages: *Suitable only for open-channel flow.*

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Svar 71

| Water flow rate (ft <sup>3</sup> /s) | Percent of flow span (%) | Depth that displacer is submerged (in) | Buoyant force (lb) |
|--------------------------------------|--------------------------|--|--------------------|
| 0                                    | 0                        | 0                                      | 0                  |
| 0.208                                | 10                       | 4.777                                  | 0.542              |
| 0.520                                | 25                       | 6.892                                  | 0.782              |
| 1.040                                | 50                       | 9.094                                  | 1.032              |
| 1.561                                | 75                       | 10.70                                  | 1.214              |
| 1.873                                | 90                       | 11.50                                  | 1.306              |
| 2.081                                | 100                      | 12                                     | 1.362              |

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Svar 72

35 GPM = 292.1 pounds per minute

Follow-up question: explain why it is essential to solving the problem to know what type of fluid this is.

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Svar 73

$Q = 431.3$  GPM (gallons per minute)

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Svar 74

There is negligible effect on the flowmeter's calibration with changes in liquid conductivity.

A common misunderstanding with magnetic flowmeters is the relationship between liquid conductivity and magnetic flowmeter calibration. So long as the conductivity stays within the acceptable range for the meter, changes in conductivity have negligible effect on calibration. The flowmeter's voltage-measuring circuitry has such vastly greater impedance than the electrical path through the liquid, that any changes in liquid conductivity are "swamped" by the much greater input impedance of the meter.

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Svar 75

If  $\rho$  increases without any change in  $v$ , the differential pressure  $\Delta P$  will increase.

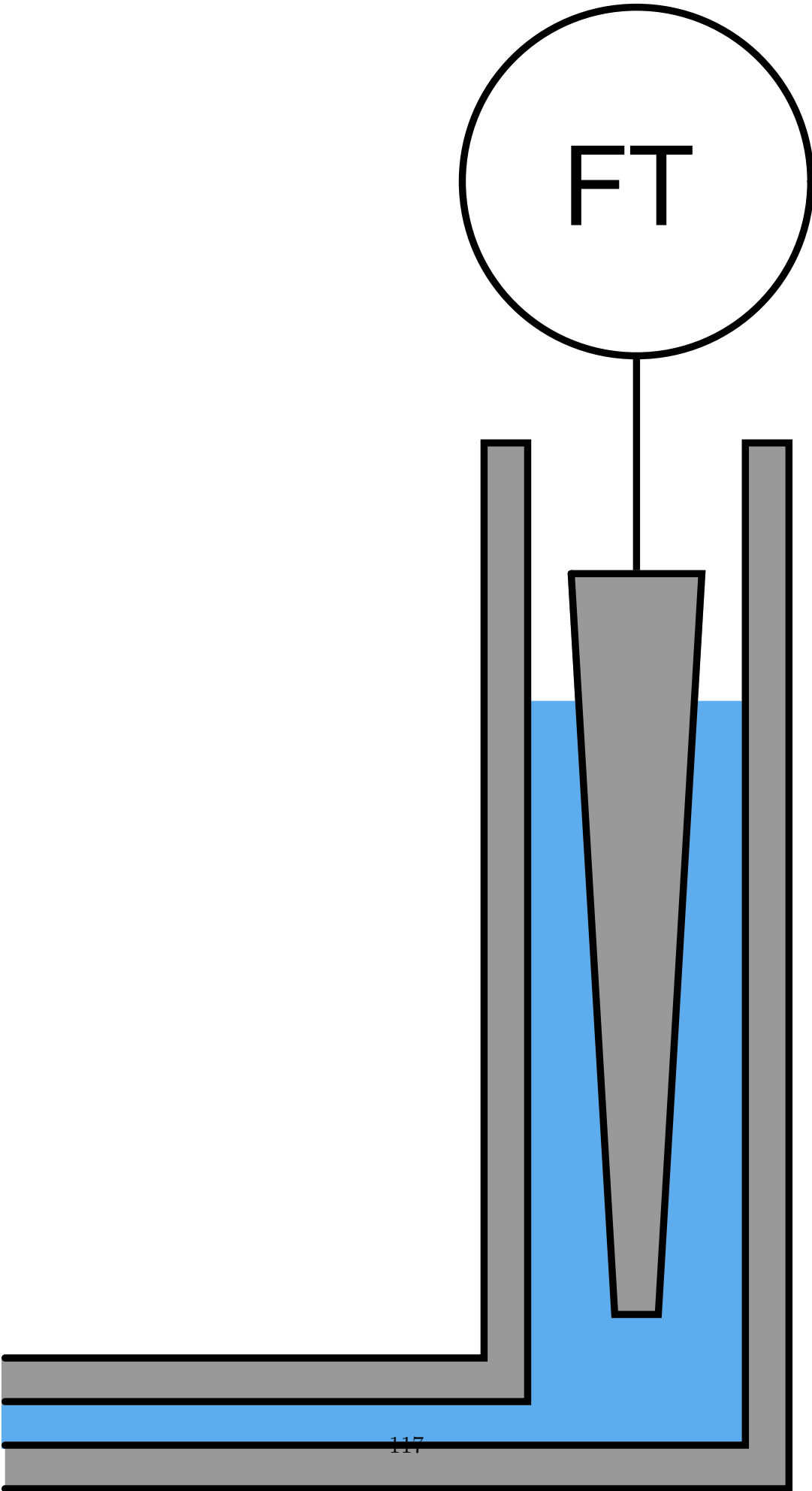
If  $\rho$  doubles,  $\Delta P$  will double as well. However, we would actually need the  $\Delta P$  to increase by a factor of *four* (4) in order to represent a doubling of flowrate, since the  $\Delta P$  is customarily square-rooted to linearize the nonlinear behavior of the orifice plate. As it is, a doubling of fluid density will only cause the indicated flow rate to increase by a factor of  $\sqrt{2}$ . "Close, but no cigar," as the saying goes.

$$Q = k\sqrt{\Delta P}$$

At a volumetric flow rate of 200 liters per minute and a corresponding differential pressure of 100 "WC, the value of  $k$  will be 20.

- **At a flow rate of 78 LPM:**
  - Orifice plate  $\Delta P = \underline{15.21}$  " H<sub>2</sub>O
  - Differential pressure transmitter output signal = 10.24 mA
  - Flow indicator reading = 78 LPM
  
- **At a flow rate of 120 LPM:**
  - Orifice plate  $\Delta P = \underline{36}$  " H<sub>2</sub>O
  - Differential pressure transmitter output signal = 13.6 mA
  - Flow indicator reading = 120 LPM





Now, explain *why* the displacer must have this kind of shape, and not one of the other shapes! Hint: sketch a graph of the weir's flow/height transfer function.

---

Svar 78

- Loop current at 350 GPM = **9.091** mA
- Differential pressure at 600 GPM = **37.19** "WC

---

Svar 79

A larger-hole orifice plate will generate *less*  $\Delta P$  for any given flow rate, and can measure *greater* flow rates with the same  $\Delta P$  range.

---

Svar 80

$$\text{Re} = \frac{(3160)G_f Q}{D\mu}$$

Where,

Re = Reynolds number (unitless)

$G_f$  = Specific gravity of liquid (unitless)

$Q$  = Flow rate (gallons per minute)

$D$  = Diameter of pipe (inches)

$\mu$  = Absolute viscosity of fluid (centipoise)

3160 = Conversion factor for British units

Since the process fluid in question here is *water*, we know that both  $G_f$  and  $\mu$  are equal to 1:

Solving for  $Q$ :

$$\text{Re} = \frac{(3160)G_f Q}{D\mu}$$

$$Q = \frac{(\text{Re})D\mu}{3160G_f}$$

$$Q = \frac{(20000)(7.981)(1)}{(3160)(1)}$$

$$Q = \frac{(20000)(7.981)(1)}{(3160)(1)}$$

$$Q = 50.51 \text{ GPM}$$

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Svar 81

This is a graded question – no answers or hints given!

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Svar 82

This is a graded question – no answers or hints given!

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Svar 83

This is a graded question – no answers or hints given!

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Svar 84

This is a graded question – no answers or hints given!

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Svar 85

This is a graded question – no answers or hints given!

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Svar 86

This is a graded question – no answers or hints given!

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Svar 87

This is a graded question – no answers or hints given!

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Svar 88

This is a graded question – no answers or hints given!

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Svar 89

This is a graded question – no answers or hints given!

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Svar 90

This is a graded question – no answers or hints given!

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