Venturi Example

Given: A venturi is to be used to measure a 250 gpm flow of 70°F water in a 4-in ID pipe.

Find: Select a throat diameter that provides $Re_d > 200{,}000$ in the throat, and determine what differential pressure must be measured.

Water Properties:

$\mu = 6.58 \times 10^{-4}$ lbm/ft-s = 2.37 lbm/ft-hr

$\rho = 62.3$ lbm/ft^3

Venturi Example (Cont'd)

<u>Sol'n</u>: $Re_d = \rho Vd/\mu$ and $\dot{m} = \rho \cdot Q$, or:

$$\dot{m} = 62.3\frac{\text{lbm}}{\text{ft}^3}\times 250\frac{\text{gal}}{\text{min}}\times 60\frac{\text{min}}{\text{hr}}\times 0.13368\frac{\text{ft}^3}{\text{gal}}$$

$$\dot{m} = 125{,}000\ \text{lbm}/\text{hr}$$

Next, want Re in terms of mass flow rate:

$$\dot{m} = \rho \cdot V \cdot \pi d^2 / 4 \qquad V = \frac{4\dot{m}}{\rho \cdot \pi \cdot d^2}$$

Venturi Example (Cont'd)

Putting Re_d in terms of mass flow rate...

$$Re_d = \frac{\rho \cdot \left(\frac{4\,\dot{m}}{\rho \cdot \pi \cdot d^2} \right) \cdot d}{\mu} = \frac{4\,\dot{m}}{\pi \cdot d \cdot \mu}$$

Now can find d for various Re_d (at highest mass flow rate):

$$d = \frac{4\,\dot{m}}{\pi \cdot Re_d \cdot \mu}$$

Venturi Example (Cont'd)

For Re_d = 200,000:

$$d = \frac{4 \times 125{,}000 \dfrac{\text{lbm}}{\text{hr}}}{200{,}000\,\pi \times 2.37 \dfrac{\text{lbm}}{\text{ft} \cdot \text{hr}}} = 0.336\,\text{ft} = 4.03\,\text{in}$$

Since D = 4.00 in, we need a smaller d and should have no problem with Re_d > 200,000.

Choose d = 2 inches for convenience.

Venturi Example (Cont'd)

$$\mathrm{Re_d} = \frac{4\,\dot{m}}{\pi \cdot d \cdot \mu} = \frac{4 \times 125{,}000\,\frac{\mathrm{lbm}}{\mathrm{hr}}}{\pi \cdot \frac{2}{12}\,\mathrm{ft} \times 2.37\,\frac{\mathrm{lbm}}{\mathrm{ft} \cdot \mathrm{hr}}} = 403{,}000$$

Next we rearrange the YMCA Equation:

$$Q = Y \cdot M \cdot C \cdot A_2 \cdot \sqrt{\frac{2\left(P_1 - P_2\right)}{\rho}}$$

Venturi Example (Cont'd)

Solving for $\Delta P = P_1 - P_2$:

$$\Delta P = \frac{\rho \cdot Q^2}{2\,Y^2 \cdot M^2 \cdot C^2 \cdot A_2^2}$$

For incompressible fluid (water), Y = 1.

$$A_2 = \frac{\pi \left(\frac{2}{12}\,\text{ft} \right)^2}{4} = 0.02181\ \text{ft}^2$$

Venturi Example (Cont'd)

$$A_1 = \frac{\pi\left(\frac{4}{12}\text{ ft}\right)^2}{4} = 0.08727\text{ ft}^2$$

$$M = \frac{1}{\sqrt{1-\left(A_2 / A_1\right)^2}} = \frac{1}{\sqrt{1-\left(0.02181 / 0.08727\right)^2}} = 1.033$$

Venturi Example (Cont'd)

- Correction factor C can be obtained from the obstruction meter handout or from text Table 10.1 (p. 280).
- Use Table 10.1 for a machined entrance, note we have β = d/D = 2 in/4 in = 0.5, and Re_D = 201,000 (calculation not shown).
- β, D and $Re_D > 2 \times 10^5$ fall within the given ranges, so the value C = 0.995 applies.

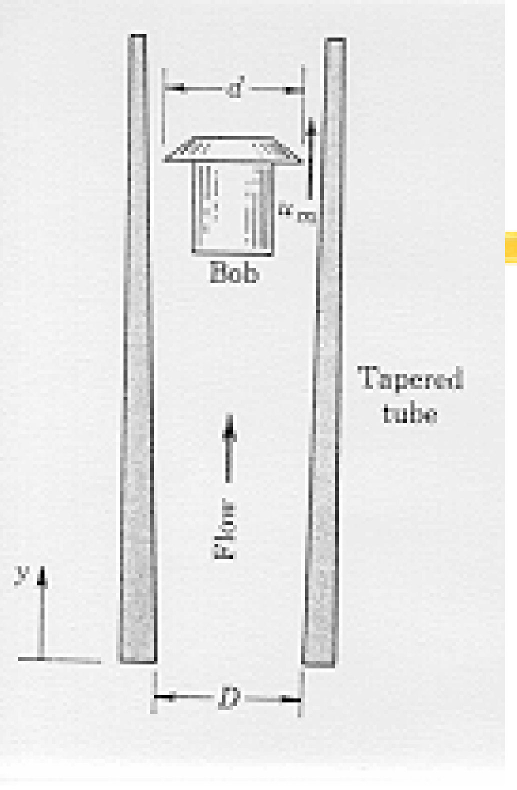
Venturi Example (Cont'd)

Inserting these values into the equation for ΔP:

$$\Delta P = \frac{62.3\,\frac{\text{lbm}}{\text{ft}^3} \times \left(250\,\frac{\text{gal}}{\text{min}} \times \frac{0.13368\ \text{ft}^3}{\text{gal}} \times \frac{1\,\text{min}}{60\,\text{s}}\right)^2}{2 \times 1 \times 1.033^2 \times 0.995^2 \times \left(0.02181\ \text{ft}^2\right)^2 \times 32.2\,\frac{\text{ft}\cdot\text{lbm}}{\text{lbf}\cdot\text{s}^2}}$$

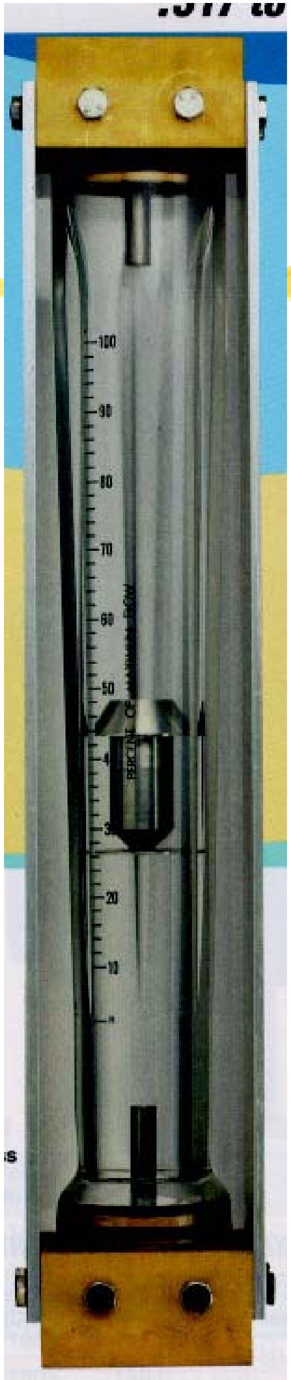
$$\Delta P = 597\,\frac{\text{lbf}}{\text{ft}^2} = 4.15\ \text{psi}$$

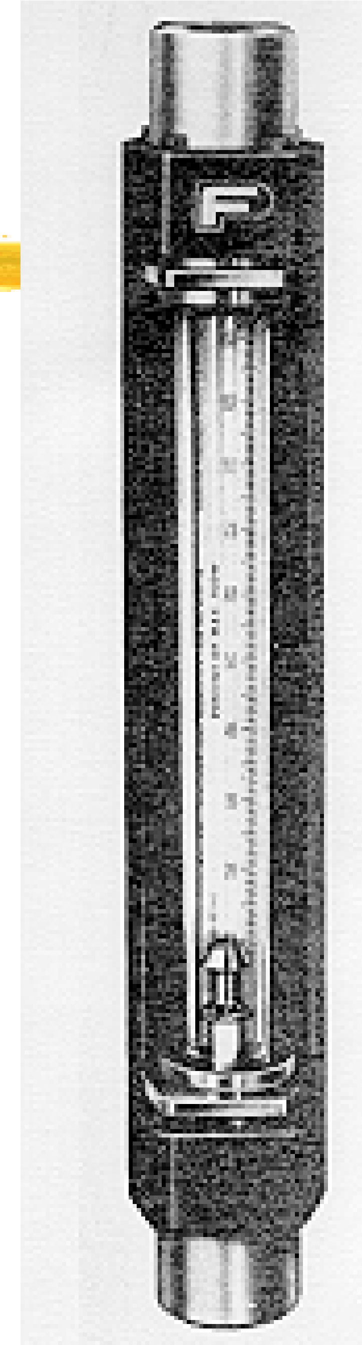
Rotameter



- Simple device for liquid and gas flow measurement
- This is a variable area meter- the rotameter uses a tapered tube with ball or float.
- As flow increases, float moves upward until fluid lift balances weight of float.
- Rotameter scale indicates fluid for which it is calibrated. Other fluids need correction.

Typical Rotameters





Rotameter Correction

- Rotameters are calibrated for only one fluid at given T and P (P not important for liquids).
- When the fluid is different or the conditions are different, the rotameter reading must be corrected to obtain the correct flow rate.
- Significant changes in use of rotameter yield loss in accuracy.

Rotameter Correction- Liquids

- For liquids, the correction equation is:

$$\frac{Q_{act}}{Q_{gage}} = \left(\frac{\rho_b - \rho_{act}}{\rho_b - \rho_{gage}} \right)^{1/2} \left(\frac{\rho_{gage}}{\rho_{act}} \right)^{1/2}$$

where Q_{gage} is gage flow rate reading, Q_{act} is corrected (actual) flow rate, ρ is density, subscript "gage" indicates fluid and conditions for which gage was calibrated, subscript "act" indicates actual fluid and conditions measured, and ρ_b is the float density.

Rotameter Correction- Gases

- The correction equation for gases is:

$$\frac{Q_{act}}{Q_{gage}} = \left(\frac{P_{gage}}{P_{act}} \cdot \frac{T_{act}}{T_{gage}} \cdot \frac{M_{gage}}{M_{act}} \right)^{1/2}$$

where Q_{gage} is gage flow rate reading, Q_{act} is corrected flow rate, P is *absolute* pressure, T is *absolute* temperature, M is molecular weight, subscript "gage" refers to conditions for which rotameter was calibrated, and subscript "act" refers to actual measured conditions and fluid.

Spring-Loaded Rotameter

- The conventional rotameter uses the gravitational force, consequently it must be oriented vertically.
- Rotameters should be installed using a level to assure correct vertical orientation.
- Rotameters are available that oppose the flow drag force on the bob with a spring force. These can be oriented in any direction, but typically are less accurate.

Spring-Loaded Rotameter

Wet Test Meter

- A positive displacement gas flow meter.
- Meter is water filled. It counts the number of times a fixed water volume is displaced by gas.
- To get flow rate, meter is timed for some number of displaced volumes.
- Gas is exposed to liquid, so corrections must be made for water evaporation into the gas.
- Normally assume gas is *saturated* with water vapor before exiting the meter.

Wet Test Meter Correction

- Gas volume is measured at some T and P (T, P also must be measured), but rate is desired at *standard* T, P (standards vary...)
- Use ideal gas law:

$$\dot{m} = \frac{P\dot{V}}{RT} = \frac{P}{RT} \cdot Q$$

- The *dry* gas flow rate is desired:

$$\dot{m}_{dry\,gas} = \frac{P_{std}}{RT_{std}} \cdot Q_{std} = \frac{P_{dry,m}}{RT_m} \cdot Q_m$$

Wet Test Meter Correction

- Thus, the standard dry gas volumetric flow rate is:

$$Q_{std} = \frac{P_{dry,m} \cdot T_{std}}{P_{std} \cdot T_m} \cdot Q_m$$

- Total measured pressure, P_m is the sum of the dry gas partial pressure, $P_{dry,m}$, and H_2O partial pressure, which is P_{sat} at T_m, so:

$$P_{dry,m} = P_m - P_{sat@T_m}$$

Wet Test Meter Correction

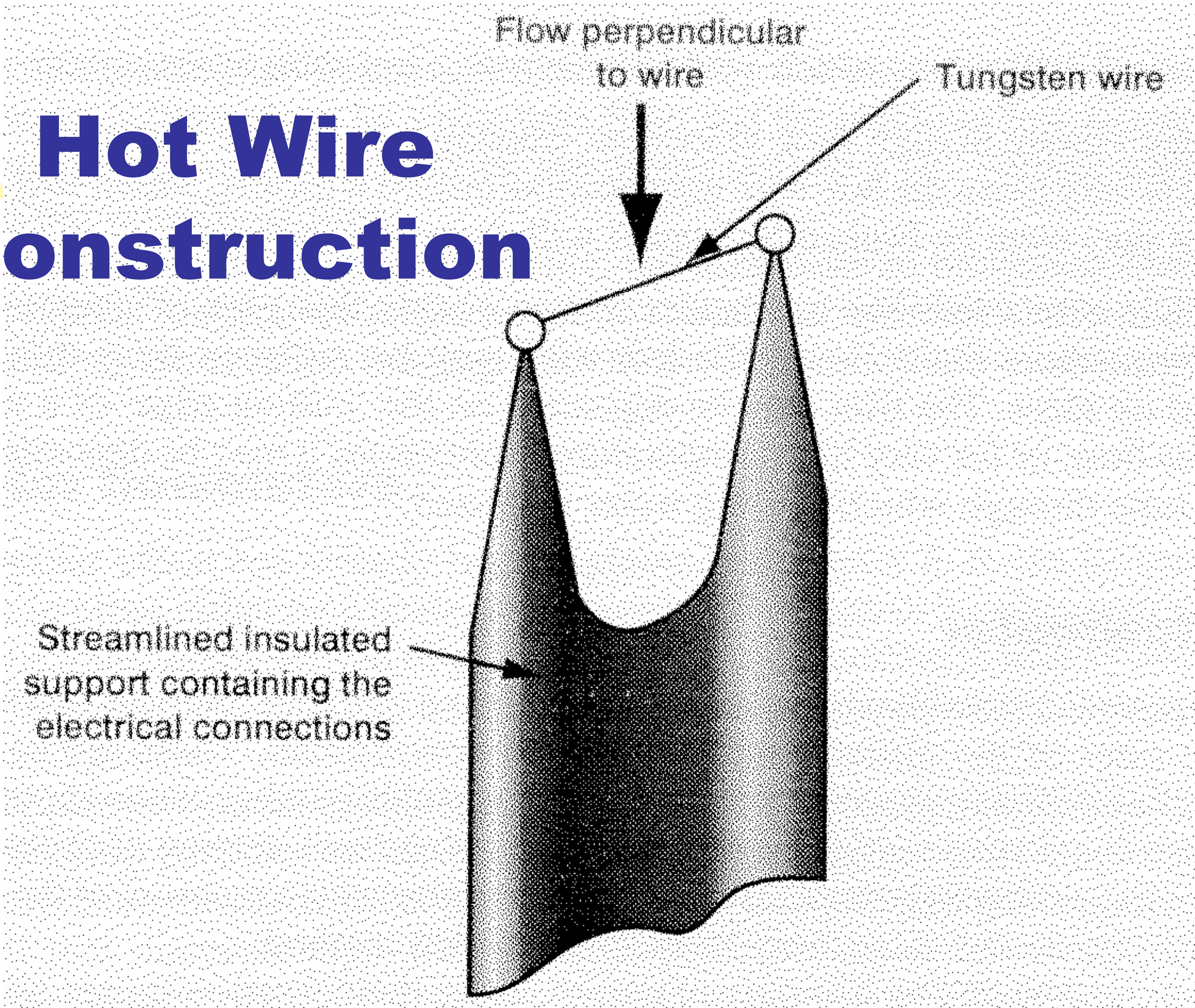
- Putting this all together, the standard dry gas volumetric flow rate is:

$$Q_{std} = \frac{\left(P_m - P_{sat@T_m}\right) \cdot T_{std}}{P_{std} \cdot T_m} \cdot Q_m$$

Hot Wire Anemometer

- A hot wire anemometer is a probe used to measure local velocity (like a pitot tube).
- It's a small, resistance wire, often platinum or tungsten, held at constant T by electric current.
- Heat loss from wire is proportional to both $hA\Delta T$ and I^2R, and h is proportional to velocity, so measurement of I can be used to obtain velocity.

Hot Wire Construction



Hot Wire Anemometer

Turbine Meters

- A turbine meter is a small turbine inserted in a pipe so that all flow passes over it.
- The blade rotational frequency is sensed as a pulse rate by a magnetic pickup.
- Meter is calibrated so $Q = f/K$, where f is frequency and K is the flow coefficient.
- Typical K units: pulses/gal, pulses/liter, etc.
- Turbine meters have high accuracy, good transient response, and wide linear range.

Turbine Meter Assembly

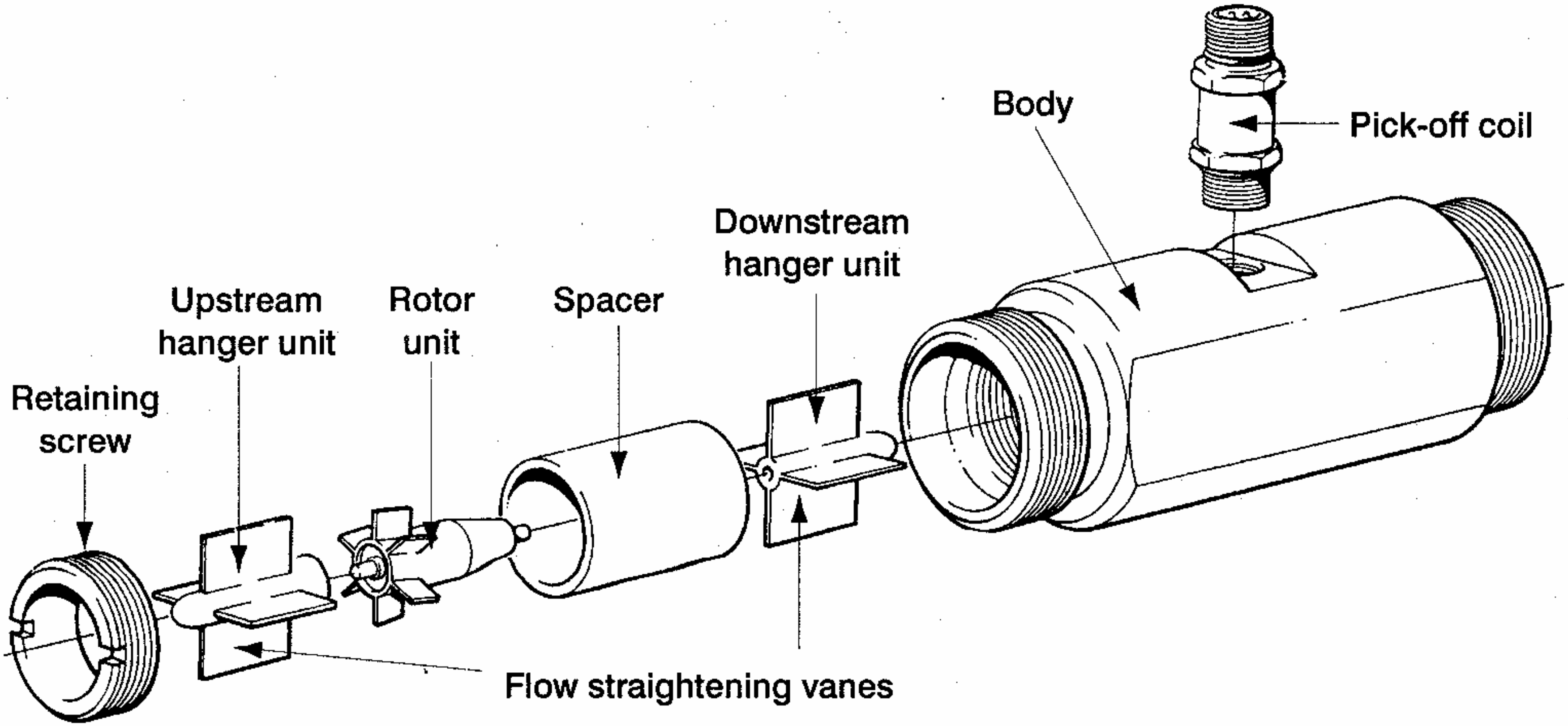
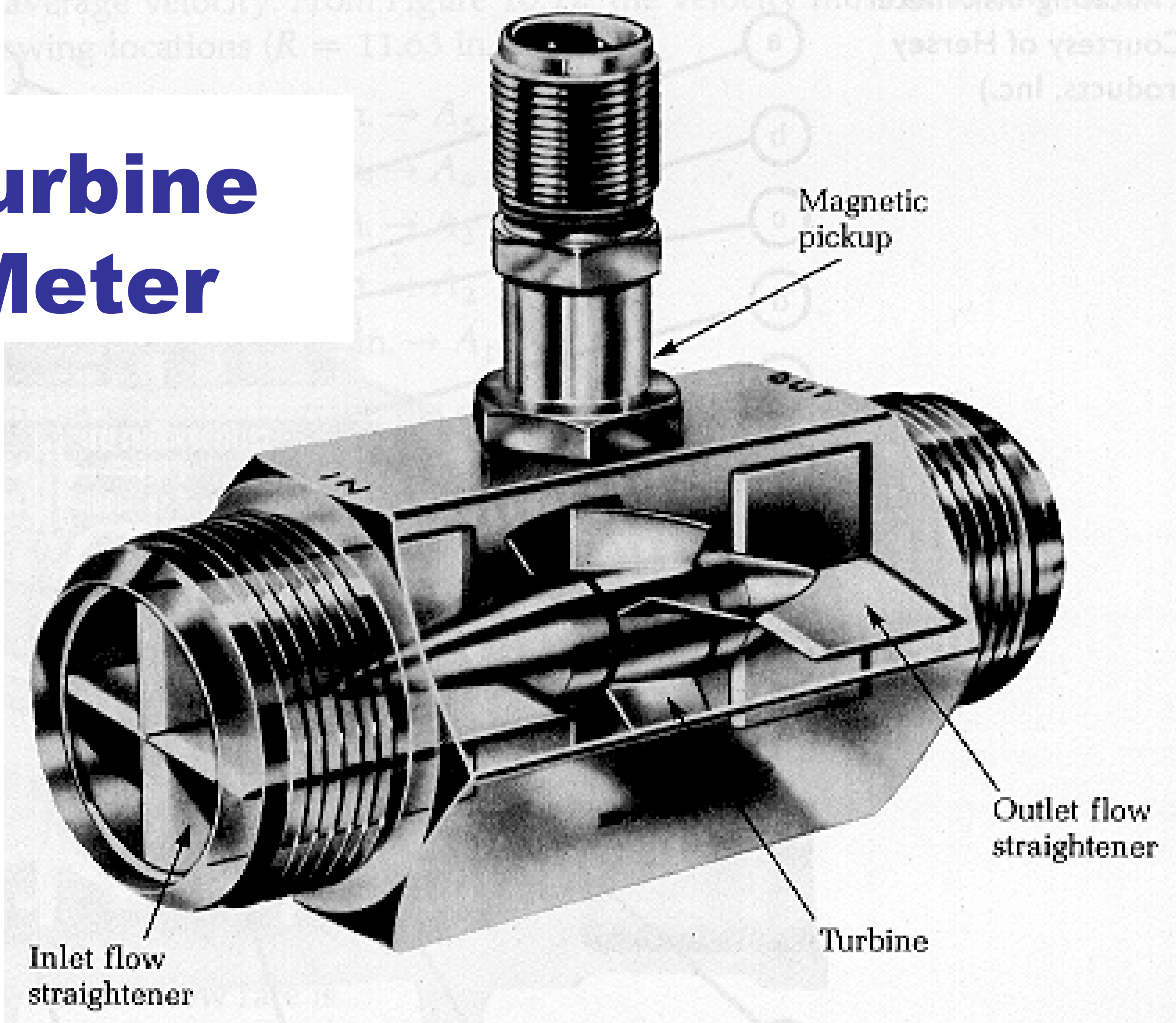


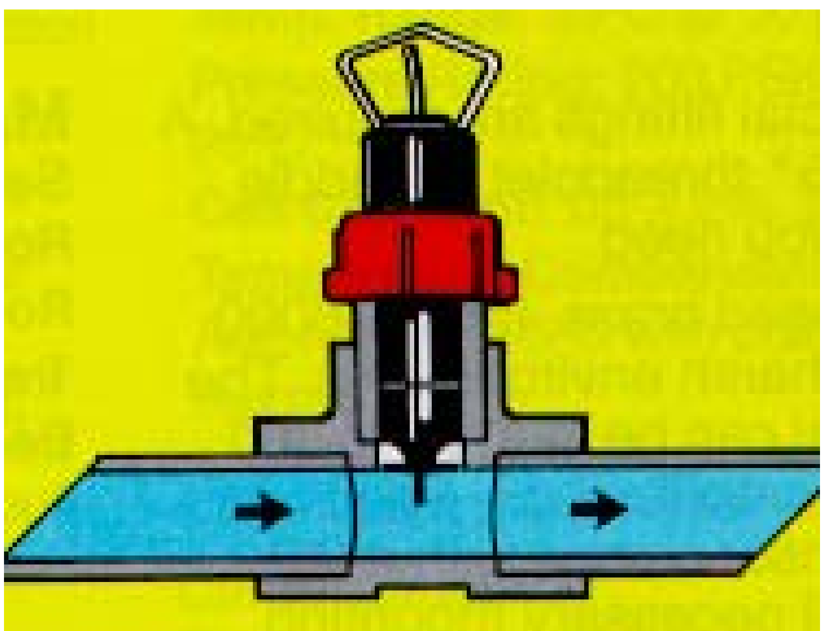
Figure 7.4 Turbine meter unit (Figure courtesy of Kent Instruments)

Turbine Meter



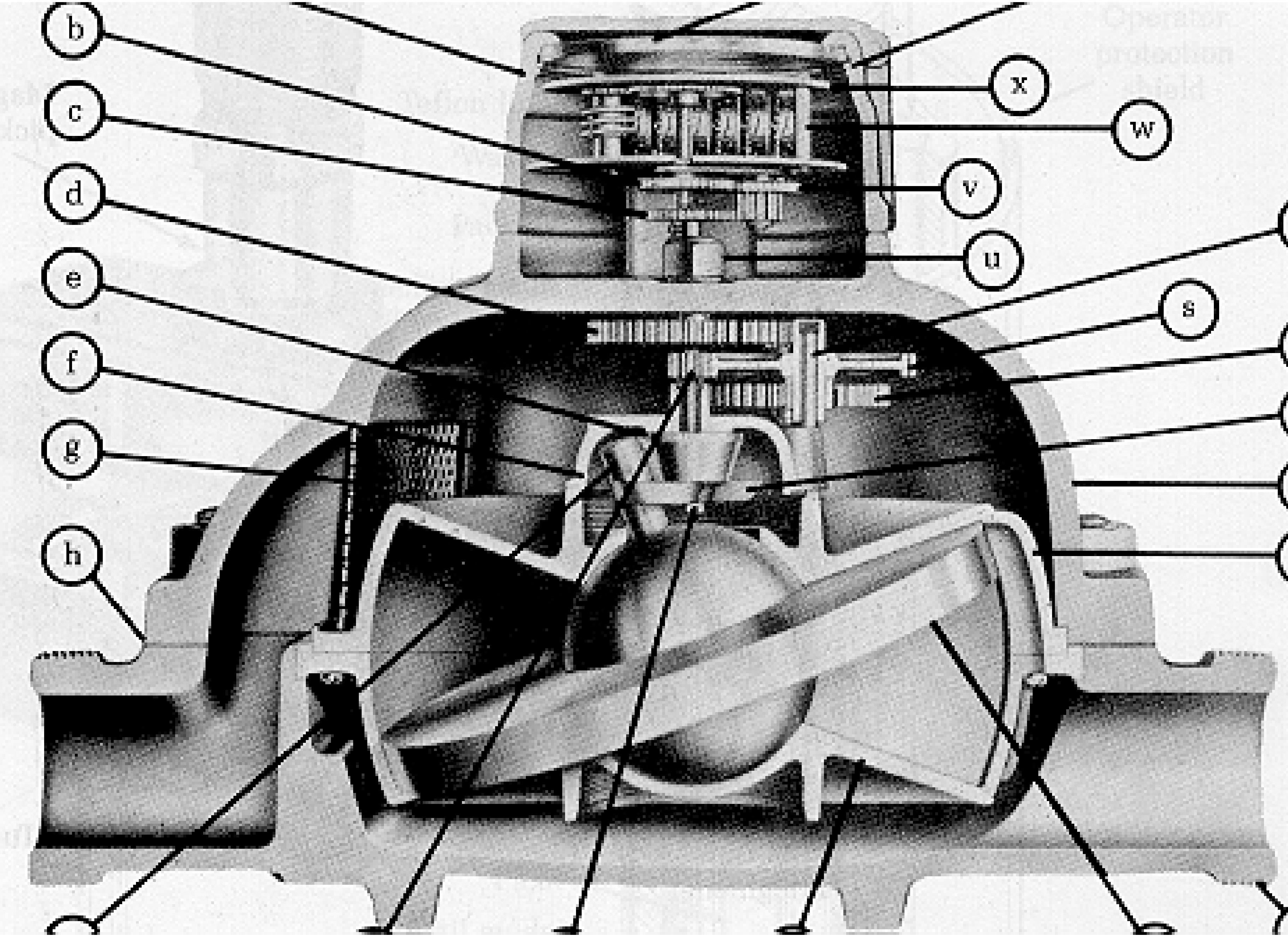
Paddlewheel Meter

- "Poor man's" turbine meter- cheaper but less accurate.
- Partial insertion in flow.



Water Meter

- Some rate flow meters can integrate volumetric flow over time to get total volume (a “totalizing” meter).
- a water meter gives a positive displacement measurement of total volume of liquid passed through (rather than flow rate).
- Similar meters are used for measuring water usage, gasoline pumped, etc.
- Following is a nutating vane water meter.


b
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s

Mass Flow Meter/Controller

- A mass flow meter is a gas flow instrument that is relatively insensitive to gas P, ρ and T.
- Based on relation: $q = \dot{m} \cdot c_p \cdot \Delta T$
- The value of c_p is known and relatively constant over a fairly broad T range.
- The value of q is measured as $q = I^2R$.
- The value of ΔT is measured also, so the only unknown is $\dot{m}$

Mass Flow Meter

- The mass flow meter can be used as feedback to control a modulating valve, thus providing a “mass flow controller.”
- Mass flow meter works only on a single gas.
- Mass flow meters provide about ±1% accuracy at rated conditions and cost $1200 to $2000.
- The “controller” option adds ~$600 to cost.

Mass flow meter schematic