Venturi Tube

A venturi tube, fabricated with a machined entrance cone according to ASME specifications, is inserted in a 4-in.-ID pipe and has a throat diameter of 3 in. If the flowing fluid is 60°F water, the pressure-sensing lines are filled with water, and the pressure transducer reads 4 psi, what is the water flow rate?

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TABLE B.2 Properties of Saturated Water, British Units

Temperature (°F)	Density, ρ (lbm/ft^3)	Viscosity, μ (lbm/hr-ft)	Specific Heat, c (Btu/lbm-°F)	Thermal Conductivity, k (Btu/hr-ft-°F)	Prandtl Number, Pr	Bulk Modulus, B $\times 10^{-3}$ (lbf/in^2)
32	62.42	4.33	1.009	0.327	13.37	293
40	62.42	3.75	1.005	0.332	11.36	294
60	62.34	2.71	1.000	0.344	7.88	311
80	62.17	2.08	0.998	0.355	5.85	322
100	61.99	1.65	0.997	0.364	4.52	327
120	61.73	1.36	0.997	0.372	3.65	333
140	61.39	1.14	0.998	0.378	3.01	330
160	61.01	0.97	1.000	0.384	2.53	326
180	60.57	0.84	1.002	0.389	2.16	313
200	60.13	0.74	1.004	0.392	1.90	308
210	59.88	0.69	1.005	0.393	1.76	301

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TABLE 10.1 Discharge Coefficients for Venturi Tubes

Rough-Cast Entrance Cone and Rough-Welded Sheet-Metal Cone	Machined Entrance Cone
$C = 0.984 \pm 1.0\%$	$C = 0.995 \pm 1.0\%$
$4 \text{ in.} \leq D \leq 48 \text{ in.}$	$2 \text{ in.} \leq D \leq 10 \text{ in.}$
$0.3 \leq \beta \leq 0.75$	$0.3 \leq \beta \leq 0.75$
$2 \times 10^5 \leq {}^*\text{Re} \leq 2 \times 10^6$	$2 \times 10^5 \leq \text{Re} \leq 2 \times 10^6$

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ρ = 62.34 lbm/ft^3, μ = 2.72 lbm/hr.ft, and C = 0.995

$$Q = \frac{CA_2}{\sqrt{1 - \left({A_2}/{A_1}\right)^2}} \sqrt{\frac{2\Delta P}{\rho}}$$

$$A_2/A_1 = \frac{\frac{\pi}{4} {D_2}^2}{\frac{\pi}{4} {D_1}^2} = \left({D_2}/{D_1}\right)^2$$

$$Q = \frac{CA_2}{\sqrt{1 - \left({A_2}/{A_1}\right)^2}} \sqrt{\frac{2\Delta P}{\rho}}$$

$$Q = \frac{(0.995)\left(\frac{\pi}{4} \times (3/12)^2\right)}{\sqrt{1 - \left({3}/{4}\right)^2}} \sqrt{\frac{2(4 \times 144)}{(62.34/32.17)}} = 1.44\ ft^3/sec$$

Flow Nozzle

A critical flow nozzle has been proposed for measuring airflow into a chamber designed to operate between 1 and 3 atm (absolute pressure). Compressed air at 690 kPa (gage) and ambient temperature (20 ^oC) are available for this application. The system needs approximately 0.1 kg/s of air. For air, γ = 1.4 and R = 287 J/kg.K

a. Is a critical flow nozzle appropriate for this application?
b. If applicable, calculate the throat area of the nozzle.
c. What measurements are necessary to accurately calculate the flow?
d. How will the flow vary with changes in chamber pressure?

Flow Nozzle

Solution:

(a) We have to check whether the flow across the nozzle will remain choked as the pressure varies from 1 to 3 atm. We have

atm = 101325 Pa

$$\text{Supply pressure} = \frac{690}{101.3} = 6.8 \text{ atm (gage)}$$

$$\text{Maximum chamber-to-line pressure ratio} = \frac{P_c}{P_s} = \frac{3}{6.8 + 1} = 0.38$$

→ 7.8

We must compare this value with the critical ratio obtained from Eq. (10.11). For air ($\gamma = 1.4$),

$$\frac{P_{\text{crit}}}{P_0} = \frac{1}{[(1.4 + 1)/2]^{1.4/(1.4-1)}} = 0.528$$

Because $P_c/P_s \leq P_{\text{crit}}/P_0$, the flow will be choked and a critical flow nozzle will be appropriate.

(b) To calculate the throat area of the nozzle, we will use Eq. (10.12):

$$\dot{m} = \frac{A_2 P_0}{T_0^{1/2}}\left[\frac{\gamma}{R}\frac{2}{(\gamma + 1)^{(\gamma+1)/(\gamma-1)}}\right]^{1/2}$$

°C → K

$$0.1 = \left(A_2 \times 7.8 \times \frac{101{,}325}{293^{1/2}}\right)\left[\left(\frac{1.4}{287}\right)\frac{2}{(1.4 + 1)^{(1.4+1)/(1.4-1)}}\right]^{1/2}$$

$$A_2 = 5.36 \times 10^{-5}\ \text{m}^2 = 0.536\ \text{cm}^2 \quad \text{diameter} = 8.3\ \text{mm}$$

(c) To measure the flow accurately, the nozzle should be calibrated. For subsequent measurements, upstream temperature and pressure should be measured. To make sure that the flow is choked, downstream pressure should also be measured for each operational condition.

(d) As long as the flow is choked in the nozzle, it will not depend on the chamber pressure. To change the flow rate, upstream pressure (and possibly temperature) should be changed. If upstream pressure is changed, one should make sure that the flow remains critical.

Orifice Meter

A sharp-edge orifice with corner taps is to be used to measure water flow rate in a horizontal 2-in. pipe (2.067 in. ID). The maximum flow is expected to be about 7 cfm (cubic feet per minute). Determine the diameter of the orifice if a maximum pressure difference of about 2 psi is acceptable.

Solution: We will use Eqs. (10.6) and (10.13) for this purpose. First we have to determine the Reynolds number in the pipe. Using Table B.2, we find that $\rho = 62.34\ \text{lbm/ft}^3$ and that $\mu = 2.71$ lbm/hr-ft. The pipe area is $A_1 = \pi \times 2.067^2/(4 \times 144) = 0.0233\ \text{ft}^2$. The fluid velocity in the pipe is

$$V = \frac{Q}{A} = \frac{7/60}{0.0233} = 5.00\ \text{ft/sec}$$

Orifice Meter

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According to Eq. (10.7),

$$\mathrm{Re} = \frac{\rho V D}{\mu}$$

$$= \frac{(62.34/32.17) \times 5.00 \times (2/12)}{2.71/(32.17 \times 3600)}$$

$$= 69{,}000$$

The diameter of the orifice (d) must be determined by using Eq. (10.6) in a trial-and-error process because the discharge coefficient, C, is a function of $\beta = d/D$, which is initially unknown. We will assume that $C = 0.60$ and find d. We have

$$Q = \frac{CA_2}{\sqrt{1 - \left(\frac{A_2}{A_1}\right)^2}} \sqrt{\frac{2[(P_1 + g\rho z_1) - (P_2 + g\rho z_2)]}{\rho}}$$

Orifice Meter

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Since the pipe is horizontal, $z_1 = z_2$, and we obtain

$$7/60 = \frac{0.6 \times A_2}{\sqrt{1 + \left(\frac{A_2}{0.0233}\right)^2}} \sqrt{\frac{2(2 \times 144)}{(62.34/32.17)}}$$

$$A_2 = 0.01 \text{ ft}^2 \qquad d = 1.35 \text{ in.}$$

This gives $\beta = 1.35/2.067 = 0.653$. Substituting into Eq. (10.13), $C = 0.615$. Using Eq. (10.6) again, the final orifice diameter is 1.35 in.

Differential-Pressure Devices

- A differential-pressure device is used to determine the level of water in a pressure vessel (Figure 10.27). The water in the tank has a density of 60.47 lbm/ft^3. The pressure transducer is attached very close to the vessel. The upper sensing line rises a vertical distance of 15 ft and is filled with cooler water with a density of 61.8 lbm/ft^3 . The pressure transducer reads 2.73 psi with the upper sensing line side showing the higher pressure. Determine the height of the water surface above the transducer.

Differential-Pressure Devices

- The pressure difference that the transducer sees is the difference of the upper and lower sensing line pressures
- The upper sensing line pressure is

$$P_1 = P_V + \rho_1 g h_1 = P_V + (61.8 / 32.17) \times (32.17) \times (15)$$

$$P_1 = P_V + 927.0 \text{ lbf/ft}^2$$

- where P_V is the pressure of the vapor on top of the liquid in the tank
- The lower sensing line pressure is

$$P_2 = P_V + \rho_2 g h_2 = P_V + (60.47 / 32.17) \times (32.17) \times (h_2)$$

- The pressure transducer reads the difference between these two pressures:

$$\Delta P = g(\rho_2 h_2 - \rho_1 h_1) = 2.73 \times 144 = P_V + 927.0 - P_V - 60.47 \times h_2$$

- Solving for h_2,

$$h_2 = 8.83 \text{ ft}$$