Third Edition

Fluid Mechanics

Fundamentals and Applications

INSTRUCTOR'S SOLUTIONS MANUAL

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1-29

Solution The acceleration of an aircraft is given in g's. The net upward force acting on a man in the aircraft is to be determined.

Analysis From Newton's second law, the applied force is

$$F = ma = m(6\text{ g}) = (90\text{ kg})(6 \times 9.81\text{ m/s}^2)\left(\frac{1\text{ N}}{1\text{ kg}\cdot\text{m/s}^2}\right) = 5297\text{ N} \cong \mathbf{5300\ N}$$

where we have rounded off the final answer to three significant digits.

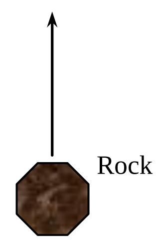
Discussion The man feels like he is six times heavier than normal. You get a similar feeling when riding an elevator to the top of a tall building, although to a much lesser extent.

1-30

Solution A rock is thrown upward with a specified force. The acceleration of the rock is to be determined.

Analysis The weight of the rock is

$$W = mg = (5\text{ kg})(9.79\text{ m/s}^2)\left(\frac{1\text{ N}}{1\text{ kg}\cdot\text{m/s}^2}\right) = 48.95\text{ N} \cong \mathbf{49.0\ N}$$



Then the net force that acts on the rock is

$$F_{net} = F_{up} - F_{down} = 150 - 48.95 = 101.05\text{ N}$$

From Newton's second law, the acceleration of the rock becomes

$$a = \frac{F}{m} = \frac{101.05\text{ N}}{5\text{ kg}}\left(\frac{1\text{ kg}\cdot\text{m/s}^2}{1\text{ N}}\right) = \mathbf{20.2\ m/s^2}$$

Discussion This acceleration is more than twice the acceleration at which it would fall (due to gravity) if dropped.

2-48

Solution The density of seawater at the free surface and the bulk modulus of elasticity are given. The density and pressure at a depth of 2500 m are to be determined.

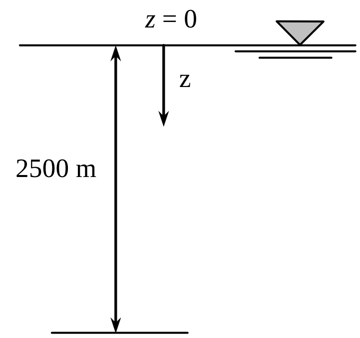
Assumptions **1** The temperature and the bulk modulus of elasticity of seawater is constant. **2** The gravitational acceleration remains constant.

Properties The density of seawater at free surface where the pressure is given to be 1030 kg/m^3, and the bulk modulus of elasticity of seawater is given to be 2.34×10^9 N/m^2.

Analysis The coefficient of compressibility or the bulk modulus of elasticity of fluids is expressed as

$$\kappa = \rho\left(\frac{\partial P}{\partial \rho}\right)_T \quad \text{or} \quad \kappa = \rho\frac{dP}{d\rho} \quad \text{(at constant } T\text{)}$$

The differential pressure change across a differential fluid height of dz is given as



$$dP = \rho g dz$$

Combining the two relations above and rearranging,

$$\kappa = \rho\frac{\rho g dz}{d\rho} = g\rho^2\frac{dz}{d\rho} \quad \rightarrow \quad \frac{d\rho}{\rho^2} = \frac{gdz}{\kappa}$$

Integrating from $z = 0$ where $\rho = \rho_0 = 1030$ kg/m^3 to $z = z$ where $\rho = \rho$ gives

$$\int_{\rho_0}^{\rho}\frac{d\rho}{\rho^2} = \frac{g}{\kappa}\int_0^z dz \quad \rightarrow \quad \frac{1}{\rho_0} - \frac{1}{\rho} = \frac{gz}{\kappa}$$

Solving for ρ gives the variation of density with depth as

$$\rho = \frac{1}{(1/\rho_0) - (gz/\kappa)}$$

Substituting into the pressure change relation $dP = \rho g dz$ and integrating from $z = 0$ where $P = P_0 = 98$ kPa to $z = z$ where $P = P$ gives

$$\int_{P_0}^{P} dP = \int_0^z \frac{gdz}{(1/\rho_0) - (gz/\kappa)} \quad \rightarrow \quad P = P_0 + \kappa\ln\left(\frac{1}{1 - (\rho_0 gz/\kappa)}\right)$$

which is the desired relation for the variation of pressure in seawater with depth. At $z = 2500$ m, the values of density and pressure are determined by substitution to be

$$\rho = \frac{1}{1/(1030\ \text{kg/m}^3) - (9.81\ \text{m/s}^2)(2500\ \text{m})/(2.34\times10^9\ \text{N/m}^2)} = \mathbf{1041\ kg/m^3}$$

$$P = (98{,}000\ \text{Pa}) + (2.34\times10^9\ \text{N/m}^2)\ln\left(\frac{1}{1 - (1030\ \text{kg/m}^3)(9.81\ \text{m/s}^2)(2500\ \text{m})/(2.34\times10^9\ \text{N/m}^2)}\right)$$

$$= 2.550\times10^7\ \text{Pa}$$

$$= \mathbf{25.50\ MPa}$$

since 1 Pa = 1 N/m^2 = 1 kg/m·s^2 and 1 kPa = 1000 Pa.

Discussion Note that if we assumed $\rho = \rho_o$ = constant at 1030 kg/m^3, the pressure at 2500 m would be $P = P_0 + \rho gz$ = 0.098 + 25.26 = 25.36 MPa. Then the density at 2500 m is estimated to be

$$\Delta\rho = \rho\alpha\Delta P = (1030)(2340\ \text{MPa})^{-1}(25.26\ \text{MPa}) = 11.1\ \text{kg/m}^3 \text{ and thus } \rho = 1041\ \text{kg/m}^3$$

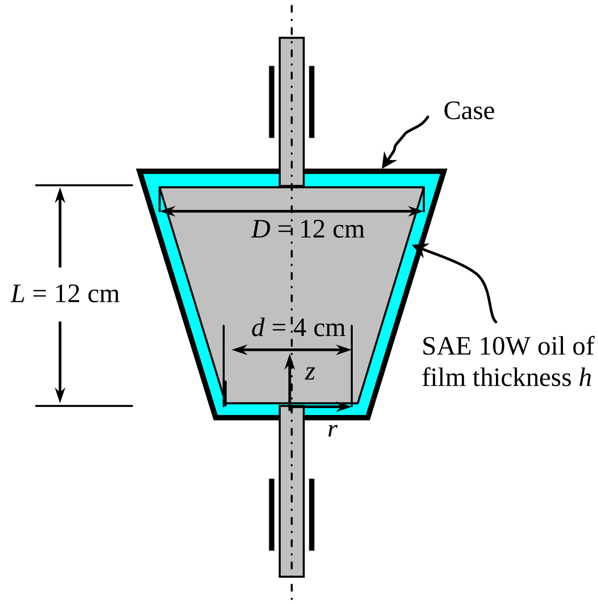
2-90

Solution A frustum shaped body is rotating at a constant angular speed in an oil container. The power required to maintain this motion and the reduction in the required power input when the oil temperature rises are to be determined.

Assumptions The thickness of the oil layer remains constant.

Properties The absolute viscosity of oil is given to be μ = 0.1 Pa·s = 0.1 N·s/m^2 at 20°C and 0.0078 Pa·s at 80°C.

Analysis The velocity gradient anywhere in the oil of film thickness h is V/h where $V = \omega r$ is the tangential velocity. Then the wall shear stress anywhere on the surface of the frustum at a distance r from the axis of rotation is



$$\tau_w = \mu \frac{du}{dr} = \mu \frac{V}{h} = \mu \frac{\omega r}{h}$$

The shear force acting on differential area dA on the surface, the torque it generates, and the shaft power associated with it are expressed as

$$dF = \tau_w dA = \mu \frac{\omega r}{h} dA \qquad d\mathrm{T} = r dF = \mu \frac{\omega r^2}{h} dA$$

$$\mathrm{T} = \frac{\mu\omega}{h} \int_A r^2 dA \qquad \dot{W}_{\text{sh}} = \omega \mathrm{T} = \frac{\mu\omega^2}{h} \int_A r^2 dA$$

__Top surface__: For the top surface, $dA = 2\pi r dr$. Substituting and integrating,

$$\dot{W}_{\text{sh, top}} = \frac{\mu\omega^2}{h} \int_{r=0}^{D/2} r^2 (2\pi r) dr = \frac{2\pi\mu\omega^2}{h} \int_{r=0}^{D/2} r^3 dr = \frac{2\pi\mu\omega^2}{h} \frac{r^4}{4}\Bigg|_{r=0}^{D/2} = \frac{\pi\mu\omega^2 D^4}{32h}$$

__Bottom surface__: A relation for the bottom surface is obtained by replacing D by d, $\dot{W}_{\text{sh, bottom}} = \dfrac{\pi\mu\omega^2 d^4}{32h}$

__Side surface__: The differential area for the side surface can be expressed as $dA = 2\pi r dz$. From geometric considerations, the variation of radius with axial distance is expressed as $r = \dfrac{d}{2} + \dfrac{D-d}{2L} z$.

Differentiating gives $dr = \dfrac{D-d}{2L} dz$ or $dz = \dfrac{2L}{D-d} dr$. Therefore, $dA = 2\pi dz = \dfrac{4\pi L}{D-d} r dr$. Substituting and integrating,

$$\dot{W}_{\text{sh, top}} = \frac{\mu\omega^2}{h} \int_{r=0}^{D/2} r^2 \frac{4\pi L}{D-d} r dr = \frac{4\pi\mu\omega^2 L}{h(D-d)} \int_{r=d/2}^{D/2} r^3 dr = \frac{4\pi\mu\omega^2 L}{h(D-d)} \frac{r^4}{4}\Bigg|_{r=d/2}^{D/2} = \frac{\pi\mu\omega^2 L(D^2 - d^2)}{16h(D-d)}$$

Then the total power required becomes

$$\dot{W}_{\text{sh, total}} = \dot{W}_{\text{sh, top}} + \dot{W}_{\text{sh, bottom}} + \dot{W}_{\text{sh, side}} = \frac{\pi\mu\omega^2 D^4}{32h}\left[1 + (d/D)^4 + \frac{2L[1-(d/D)^4)]}{D-d}\right],$$

where d/D = 4/12 = 1/3. Substituting,

$$\dot{W}_{\text{sh, total}} = \frac{\pi(0.1\,\text{N}\cdot\text{s/m}^2)(200\,\text{/s})^2(0.12\,\text{m})^4}{32(0.0012\,\text{m})}\left[1 + (1/3)^4 + \frac{2(0.12\,\text{m})[1-(1/3)^4)]}{(0.12-0.04)\,\text{m}}\right]\left(\frac{1\,\text{W}}{1\,\text{Nm/s}}\right) = \mathbf{270\,W}$$

Noting that power is proportional to viscosity, the power required at 80°C is

$$\dot{W}_{\text{sh, total,80°C}} = \frac{\mu_{80°C}}{\mu_{20°C}} \dot{W}_{\text{sh, total,20°C}} = \frac{0.0078\,\text{N}\cdot\text{s/m}^2}{0.1\,\text{N}\cdot\text{s/m}^2}(270\,\text{W}) = 21.1\,\text{W}$$

Therefore, the reduction in the requires power input at 80°C is $\text{Reduction} = \dot{W}_{\text{sh, total, 20°C}} - \dot{W}_{\text{sh, total, 80°C}} = 270 - 21.1 = \mathbf{249\,W}$, which is about 92%.

Discussion Note that the power required to overcome shear forces in a viscous fluid greatly depends on temperature.

2-136

In a water distribution system, the pressure of water can be as low as 1.4 psia. The maximum temperature of water allowed in the piping to avoid cavitation is

(*a*) 50°F (*b*) 77°F (*c*) 100°F (*d*) 113°F (*e*) 140°F

Answer (*d*) 113°F

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
P=1.4 [psia]
T_max=temperature(steam, P=P, x=1)
```

2-137

The thermal energy of a system refers to

(*a*) Sensible energy (*b*) Latent energy (*c*) Sensible + latent energies
(*d*) Enthalpy (*e*) Internal energy

Answer (*c*) Sensible + latent energies

2-138

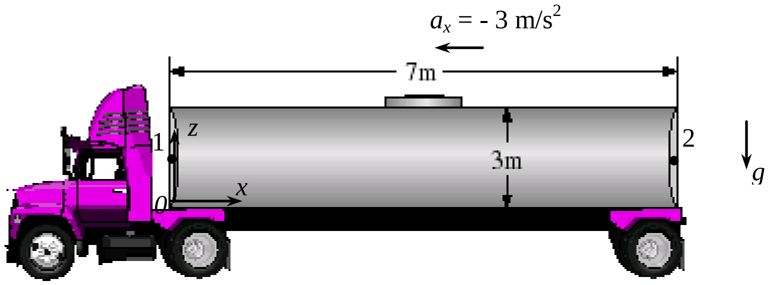
The difference between the energies of a flowing and stationary fluid per unit mass of the fluid is equal to

(*a*) Enthalpy (*b*) Flow energy (*c*) Sensible energy (*d*) Kinetic energy
(*e*) Internal energy

Answer (*b*) Flow energy

3-130

Solution Water is transported in a completely filled horizontal cylindrical tanker accelerating at a specified rate. The pressure difference between the front and back ends of the tank along a horizontal line when the truck accelerates and decelerates at specified rates.



Assumptions **1** The acceleration remains constant. **2** Water is an incompressible substance.

Properties We take the density of the water to be 1000 kg/m^3.

Analysis (*a*) We take the *x*- and *z*- axes as shown. The horizontal acceleration is in the negative *x* direction, and thus a_x is negative. Also, there is no acceleration in the vertical direction, and thus a_z = 0. The pressure difference between two points 1 and 2 in an incompressible fluid in linear rigid body motion is given by

$$P_2 - P_1 = -\rho a_x (x_2 - x_1) - \rho (g + a_z)(z_2 - z_1) \quad \rightarrow \quad P_2 - P_1 = -\rho a_x (x_2 - x_1)$$

since z_2 - z_1 = 0 along a horizontal line. Therefore, the pressure difference between the front and back of the tank is due to acceleration in the horizontal direction and the resulting compression effect towards the back of the tank. Then the pressure difference along a horizontal line becomes

$$\Delta P = P_2 - P_1 = -\rho a_x (x_2 - x_1) = -(1000 \text{ kg/m}^3)(-3 \text{ m/s}^2)(7 \text{ m})\left(\frac{1 \text{ kN}}{1000 \text{ kg}\cdot\text{m/s}^2}\right) = 21 \text{ kN/m}^2 = \mathbf{21\ kPa}$$

since x_1 = 0 and x_2 = 7 m.

(*b*) The pressure difference during deceleration is determined the way, but a_x = 4 m/s^2 in this case,

$$\Delta P = P_2 - P_1 = -\rho a_x (x_2 - x_1) = -(1000 \text{ kg/m}^3)(4 \text{ m/s}^2)(7 \text{ m})\left(\frac{1 \text{ kN}}{1000 \text{ kg}\cdot\text{m/s}^2}\right) = -28 \text{ kN/m}^2 = \mathbf{-28\ kPa}$$

Discussion Note that the pressure is higher at the back end of the tank during acceleration, but at the front end during deceleration (during breaking, for example) as expected.

6-79

Solution An ice skater is holding a flexible hose (essentially weightless) which directs a stream of water horizontally at a specified velocity. The velocity and the distance traveled in 5 seconds, and the time it takes to move 5 m and the velocity at that moment are to be determined.

Assumptions **1** Friction between the skates and ice is negligible. **2** The flow of water is steady and one-dimensional (but the motion of skater is unsteady). **3** The ice skating arena is level, and the water jet is discharged horizontally. **4** The mass of the hose and the water in it is negligible. **5** The skater is standing still initially at $t = 0$. **6** Jet flow is nearly uniform and thus the momentum-flux correction factor can be taken to be unity, $\beta \cong 1$.

Properties We take the density of water to be 1000 kg/m^3.

Analysis (*a*) The mass flow rate of water through the hose is

$$\dot{m} = \rho A V = \rho \frac{\pi D^2}{4} V = (1000 \text{ kg/m}^3) \frac{\pi (0.02 \text{ m})^2}{4} (10 \text{ m/s}) = 3.14 \text{ kg/s}$$

The thrust exerted on the skater by the water stream is simply the momentum flux of the water stream, and it acts in the reverse direction,

$$F = \text{Thrust} = \dot{m}V = (3.14 \text{ kg/s})(10 \text{ m/s})\left(\frac{1\text{ N}}{1 \text{ kg}\cdot\text{m/s}^2}\right) = 31.4 \text{ N (constant)}$$

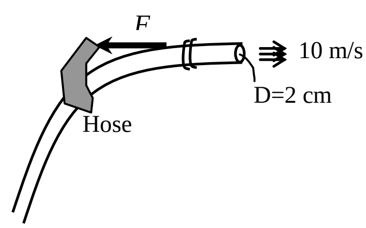
The acceleration of the skater is determined from Newton's 2nd law of motion $F = ma$ where m is the mass of the skater,

$$a = \frac{F}{m} = \frac{31.4 \text{ N}}{60 \text{ kg}}\left(\frac{1 \text{ kg}\cdot\text{m/s}^2}{1 \text{ N}}\right) = 0.523 \text{ m/s}^2$$

Note that thrust and thus the acceleration of the skater is constant. The velocity of the skater and the distance traveled in 5 s are

$$V_{\text{skater}} = at = (0.523 \text{ m/s}^2)(5 \text{ s}) = \mathbf{2.62 \text{ m/s}}$$

$$x = \tfrac{1}{2} at^2 = \tfrac{1}{2}(0.523 \text{ m/s}^2)(5 \text{ s})^2 = \mathbf{6.54 \text{ m}}$$



(*b*) The time it will take to move 5 m and the velocity at that moment are

$$x = \tfrac{1}{2} at^2 \quad \rightarrow \quad t = \sqrt{\frac{2x}{a}} = \sqrt{\frac{2(5 \text{ m})}{0.523 \text{ m/s}^2}} = \mathbf{4.4 \text{ s}}$$

$$V_{\text{skater}} = at = (0.523 \text{ m/s}^2)(4.4 \text{ s}) = \mathbf{2.3 \text{ m/s}}$$

Discussion In reality, the velocity of the skater will be lower because of friction on ice and the resistance of the hose to follow the skater. Also, in the $\beta \dot{m} V$ expressions, V is the fluid stream speed relative to a fixed point. Therefore, the correct expression for thrust is $F = \dot{m}(V_{jet} - V_{skater})$, and the analysis above is valid only when the skater speed is low relative to the jet speed. An exact analysis would result in a differential equation.

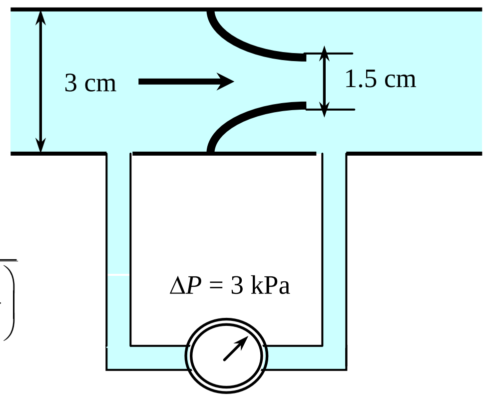
8-116

Solution The flow rate of water is to be measured with flow nozzle equipped with a differential pressure gage. For a given pressure drop, the flow rate, the average flow velocity, and head loss are to be determined.

Assumptions **1** The flow is steady and incompressible. **2** The discharge coefficient of the nozzle meter is C_d = 0.96.

Properties The density and dynamic viscosity of water are given to be ρ = 999.7 kg/m^3 and μ = 1.307×10^{-3} kg/m·s, respectively.

Analysis The diameter ratio and the throat area of the meter are



$$\beta = d/D = 1.5/3 = 0.50$$

$$A_0 = \pi d^2/4 = \pi(0.015\text{ m})^2/4 = 1.767\times10^{-4}\text{ m}^2$$

Noting that ΔP = 4 kPa = 4000 N/m^2, the flow rate becomes

$$\dot{V} = A_o C_d \sqrt{\frac{2(P_1-P_2)}{\rho(1-\beta^4)}}$$

$$= (1.767\times10^{-4}\text{ m}^2)(0.96)\sqrt{\frac{2\times3000\text{ N/m}^2}{(999.7\text{ kg/m}^3)((1-0.50^4)}\left(\frac{1\text{ kg}\cdot\text{m/s}^2}{1\text{ N}}\right)}$$

$$= 0.429\times10^{-3}\text{ m}^3/\text{s}$$

which is equivalent to 0.429 L/s. The average flow velocity in the pipe is determined by dividing the flow rate by the cross-sectional area of the pipe,

$$V = \frac{\dot{V}}{A_c} = \frac{\dot{V}}{\pi D^2/4} = \frac{0.429\times10^{-3}\text{ m}^3/\text{s}}{\pi(0.03\text{ m})^2/4} = 0.607\text{ m/s}$$

The Reynolds number of flow through the pipe is

$$\text{Re} = \frac{\rho VD}{\mu} = \frac{(999.7\text{ kg/m}^3)(0.607\text{ m/s})(0.03\text{ m})}{1.307\times10^{-3}\text{ kg/m}\cdot\text{s}} = 1.39\times10^4$$

Substituting the β and Re values into the orifice discharge coefficient relation gives

$$C_d = 0.9975 - \frac{6.53\beta^{0.5}}{\text{Re}^{0.5}} = 0.9975 - \frac{6.53(0.50)^{0.5}}{(1.39\times10^4)^{0.5}} = 0.958$$

which is close to the assumed value of 0.96. We do some iteration to obtain a more precise answer: Using this revised value of C_d we obtain $\dot{V} = 0.4284\times10^{-3}$ m^3/s, leading to a revised V and Re of 0.60602 m/s and 13906 respectively. This value of Re yields C_d = 0.9583. Another iteration yields $\dot{V} = 0.4285\times10^{-3}$ m^3/s, V = 0.60624 m/s, Re = 13911, and C_d = 0.95835. You can see that the convergence is rapid. After one final iteration to make sure we have converged enough, we give the final results: $\dot{V} = 0.42853\times10^{-3}$ m^3/s, V = 0.60625 m/s, Re = 13911, and C_d = 0.95835. Thus we have converged to 5 significant digits – way more than we need. The final answers to 3 significant digits are $\dot{V}$ = **0.429×10^{-3} m^3/s**, ***V*** **= 0.606 m/s**, Re = 139001, and C_d = 0.958.

Discussion The water column height corresponding to a pressure drop of 3 kPa is

$$h_w = \frac{\Delta P}{\rho_w g} = \frac{3000\text{ kg}\cdot\text{m/s}^2}{(999.7\text{ kg/m}^3)(9.81\text{ m/s}^2)} = 0.306\text{ m}$$

The head loss between the two measurement sections is determined from the energy equation, which for $z_1 = z_2$ simplifies to

$$h_L = \frac{P_1-P_2}{\rho_f g} - \frac{V_2^2-V_1^2}{2g} = h_w - \frac{[(D/d)^4-1]V_1^2}{2g} = 0.306\text{ m} - \frac{[(3/1.5)^4-1](0.607\text{ m/s})^2}{2(9.81\text{ m/s}^2)} = 0.024\text{ m H2O}$$

Note, however, that this is not the same as the total irreversible head loss through the entire flow nozzle (which can be thought of as a type of minor loss in the piping system). The total irreversible head loss would be much higher than that calculated here because losses downstream of the nozzle exit plane, where there is turbulent mixing and flow separation.

10-135

Air flows at 25°C with a velocity of 6 m/s over a flat plate whose length is 40 cm. The momentum thickness at the center of the plate is (The kinematic viscosity of air is 1.562×10^{-5} m^2/s.)

(*a*) 0.479 mm (*b*) 0.678 mm (*c*) 0.832 mm (*d*) 1.08 mm (*e*) 1.34 mm

Answer (*a*) 0.479 mm

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
T=25 [C]
V=6 [m/s]
x=0.2 [m]
nu=1.562E-5 [m^2/s]
Re_x=V*x/nu
theta=0.664*x/sqrt(Re_x)
```

10-136

Water flows at 20°C with a velocity of 1.1 m/s over a flat plate whose length is 15 cm. The boundary layer thickness at the end of the plate is (The density and viscosity of water are 998 kg/m^3 and 1.002×10^{-3} kg/m·s, respectively.)

(*a*) 1.14 mm (*b*) 1.35 mm (*c*) 1.56 mm (*d*) 1.82 mm (*e*) 2.09 mm

Answer (*d*) 1.82 mm

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
T=20 [C]
V=1.1[m/s]
x=0.15 [m]
rho=998 [kg/m^3]
mu=1.002E-3 [kg/m-s]
nu=mu/rho
Re_x=V*x/nu
delta=4.91*x/sqrt(Re_x)
```

12-150

Solution Using EES (or other) software, the shape of a converging-diverging nozzle is to be determined for specified flow rate and stagnation conditions. The nozzle and the Mach number are to be plotted.

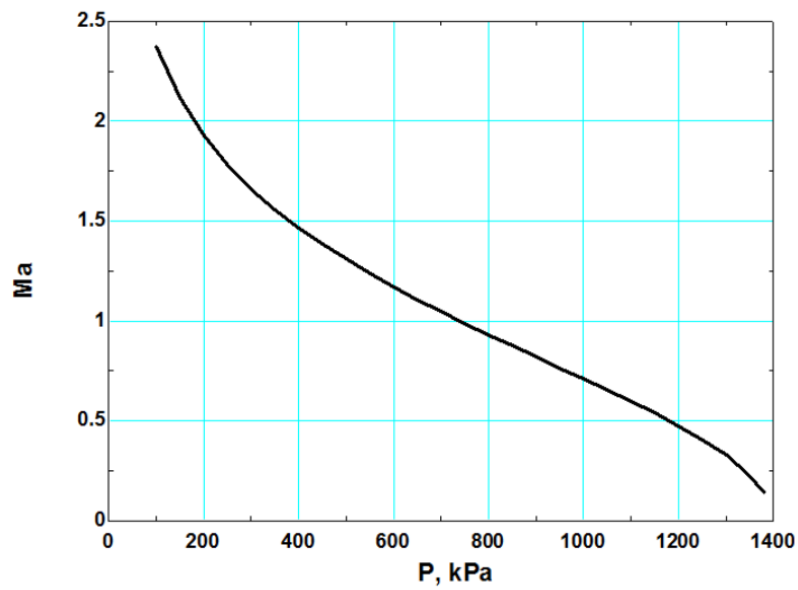
Assumptions **1** Air is an ideal gas with constant specific heats. **2** Flow through the nozzle is steady, one-dimensional, and isentropic. **3** The nozzle is adiabatic.

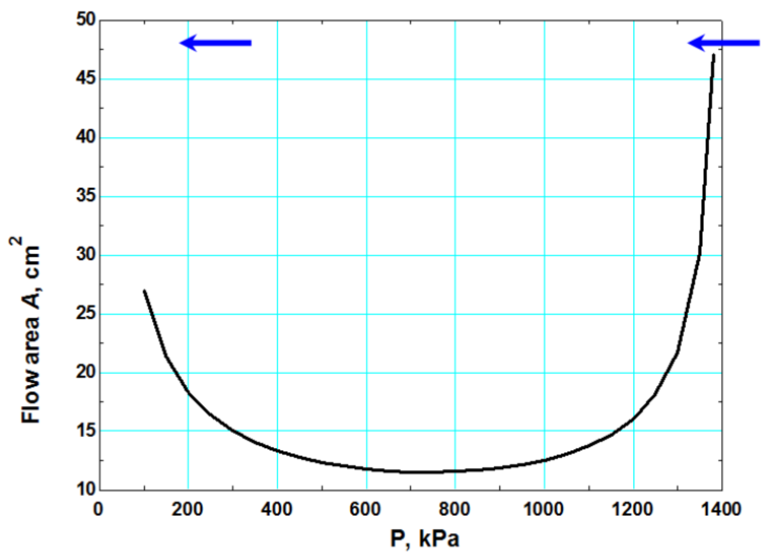
Properties The specific heat ratio of air at room temperature is 1.4.

Analysis The problem is solved using EES, and the results are tabulated and plotted below.

```
k=1.4
Cp=1.005 "kJ/kg.K"
R=0.287 "kJ/kg.K"
P0=1400 "kPa"
T0=200+273 "K"
m=3 "kg/s"
rho_0=P0/(R*T0)
rho=P/(R*T)
T=T0*(P/P0)^((k-1)/k)
V=SQRT(2*Cp*(T0-T)*1000)
A=m/(rho*V)*10000 "cm2"
C=SQRT(k*R*T*1000)
Ma=V/C
```

Pressure *P*, kPa	Flow area *A*, cm^2	Mach number Ma
1400	∞	0
1350	30.1	0.229
1300	21.7	0.327
1250	18.1	0.406
1200	16.0	0.475
1150	14.7	0.538
1100	13.7	0.597
1050	13.0	0.655
1000	12.5	0.710
950	12.2	0.766
900	11.9	0.820
850	11.7	0.876
800	11.6	0.931
750	11.5	0.988
700	11.5	1.047
650	11.6	1.107
600	11.8	1.171
550	12.0	1.237
500	12.3	1.308
450	12.8	1.384
400	13.3	1.467
350	14.0	1.559
300	15.0	1.663
250	16.4	1.784
200	18.3	1.929
150	21.4	2.114
100	27.0	2.373





Discussion The shape is not actually to scale since the horizontal axis is pressure rather than distance. If the pressure decreases linearly with distance, then the shape *would* be to scale.