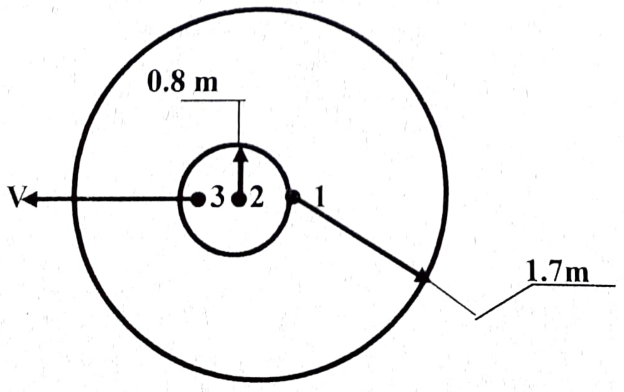
Sheet-1

1. Air flows through a long duct of constant area at o.15 kg/s. A short section of the duct is cooled by liquid nitrogen. The absolute pressure, temperature and velocity entering the cooled section are 188 kPa,440 K and 210 m/s, respectively. At the outlet, absolute pressure,temperature and flow Mach no. are 213 kPa , 351 K and 1.337, respectively. Compute the duct cross sectional area and the changes in enthalpy, internal energy, entropy, flow Mach no. at inlet and amount of heat loss for this system.
2. An airplane flies at a constant speed of **900** km/hr. at an altitude corresponding to **-50°C**. Pressure survey shows that air at the nose of air plane is brought to rest. Calculate the temperature at the nose of air plane.
3. Air is flowing at the following conditions: pressure= **1.6** * **10**^{5}N/m^2 ,temperature=**500°C**and velocity =**160** m/s. Find the (a) Stagnation temperature and (b) Stagnation pressure.
4. Air flows at the rate of 10 kg/s in an adiabatic channel. At one section where area is 50 cm^2, the pressure is **2** * **10**^{5}N/m^2 and the temperature is **650°C.** At downstream in other section M_2=**1.2**. Find A_2 if flow is isentropic.
5. Air enters a machine at 373K with a speed of 200m/s and leaves it at a temperature of 288K. Find the exit speed :
    (i) When the machine delivers work output of 100kJ of air
    (ii) When the machine is idling.
6. A flow channel is supplied with a steady stream of a perfect gas at a pressure of 7 * **10**^{5} N/m^2 and a temperature of**318K**. Density at the entry is 4.5 kg/m^3 and velocity is 120m/s. Assuming the flow to be reversible and adiabatic,
    (i) Determine the temperature and velocity of the gas at the nozzle exit where the pressure is **4** * **10**^{5}N/m^2
    (ii) If the mass flow rate is 1 kg/s determine the areas at entry and exit of the channel.
7. Air at rate of 10 kg/s is flowing in an adiabatic duct. At one section the pressure is 2 * **10**^{5}N/m^2, the temperature is **650°C** and area is 50 cm^2. At a .downstream section the Mach number is 1.2. (a) Sketch the general shape of the duct. (b) Find A_2 if the flow is isentropic (c) Find A_2 if there is an entropy change of **42**J/kg.K.
8. An aeroplane is flying with a Mach number of M=1.5 at an altitude of 2000 m in a day when temperature at that altitude is 25°c. What is speed of the plane and how long after passing directly above the ground observer , is the sound of the aeroplane heard by the ground observer?
9. A small source of sound moves with a velocity **V** to the left in a straight line from point 1, in air at temperature 293 K while generating sound waves as shown. The points 1, 2 and 3 are the positions of the source at various times. The circles represent the sound waves generated at the different times. Find the speed of the source, V.



Sheet-2

1. Air flows through an adiabatic system. $M_1 = 4.0$ and $p_{01} = 45$ psia. At a point downstream, $M_2 = 1.8$ and $p_2 = 7.0$ psia.
   (a) Are there losses in this system? If so, compute Δs.
   (b) Determine the ratio of A_2/A_1.

2. The following information is common to each of parts (a) and (b). Air flows through a diverging section with $A_1 = 1.5$ ft^2 and $A_2 = 4.5$ ft^2. You may assume steady, one-dimensional flow, $Q = Ws = 0$, negligible potential changes, and no losses.
   (a) If $M_1 = 0.7$ and $p_1 = 70$ psia, find M_2 and p_2.
   (b) If $M_1 = 1.7$ and $T_1 = 95°F$, find M_2 and T_2.

3. Air enters a converging section where $A_1 = 0.50$ m^2. At a downstream section $A_2 = 0.25$ m^2, $M_2 = 1.0$, and $\Delta s_{1-2} = 0$. It is known that $p_2 > p_1$. Find the initial Mach number (M_1) and the temperature ratio (T_2/T_1).

4. Air flows with $T_1 = 250$ K, $p1 = 3$ bar abs., $p_{01} = 3.4$ bar abs., and the cross-sectional area $A_1 = 0.40$ m^2. The flow is isentropic to a point where $A_2 = 0.30$ m^2. Determine the temperature at section 2.

5. The following information is known about the steady flow of air through an adiabatic system:
   At section 1, $T_1 = 510$K, p_1,= 3 Mpa
   At section 2, $T_2 = 460$K, $Tt2 = 610$K, p_2,= 2 Mpa
   (a) Find M_2, V_2, and p_{02}.
   (b) Determine M_1, V_1, and p_{01}.
   (c) Compute the area ratio $A2/A1$.
   (d) Sketch a physical diagram of the system along with a $T-s$ diagram.

6. Air flows through an adiabatic system. $M1 = 4.0$ and $p_{01} = 45$ psia. At a point downstream, $M_2 = 1.8$ and $p_2 = 7.0$ psia.

   (a) Are there losses in this system? If so, compute Δs.

   (b) Determine the ratio of $A2/A1$.

7. Air flows in a constant-area, horizontal, insulated duct. Conditions at section 1 are $p_1 = 50$ MPa, $T_1 = 600$K, and $V_1 = 867$ m/s. At a downstream section the temperature is $T_2 = 1048$ K.
   (a) Determine M_1 and T_{01}.
   (b) Find V_2 and p_2.
   (c) What is the entropy change between the two sections?

8. Air enters a convergent–divergent nozzle at 20 bar abs. and 40°C. At the end of the nozzle the pressure is 2.0 bar abs. Assume a frictionless adiabatic process. The throat area is 20 cm^2.
   (a) What is the area at the nozzle exit?
   (b) What is the mass flow rate in kg/s?

9. A converging–diverging nozzle is designed to operate with an exit Mach number of M = 2.25. It is fed by a large chamber of air at 15.0 MPa and 600K and exhausts into the room at 14.7 MPa. Assuming the losses to be negligible, compute the velocity in the nozzle throat.

10. A converging–diverging nozzle discharges air into a receiver where the static pressure is 15 MPa. A 1.5 m^2 duct feeds the nozzle with air at 100 MPa, 800K, and a velocity such that the Mach number M_1 = 0.3. The exit area is such that the pressure at the nozzle exit exactly matches the receiver pressure. Assume steady, one-dimensional flow, perfect gas, and so on. The nozzle is adiabatic and there are no losses.

    (a) Calculate the flow rate.

    (b) Determine the throat area.

    (c) Calculate the exit

11. Two venturi meters as shown in Fig-1(a) are installed in a 30 cm diameter duct that is insulated. The conditions are such that sonic flow exists at each throat (i.e. M_1=M_4=1.0). Although, each venturi is isentropic, the connecting duct has friction and hence losses exist between sections 2 and 3. p_1= 3 bar (abs.), and p_4= 2.5 bar (abs.). If the diameter at section-1 is 15 cm and the fluid is air, find the following:

    (i) Compute the change in entropy, Δs_{23} for the connecting duct.

    (ii) Find the diameter at section 4.

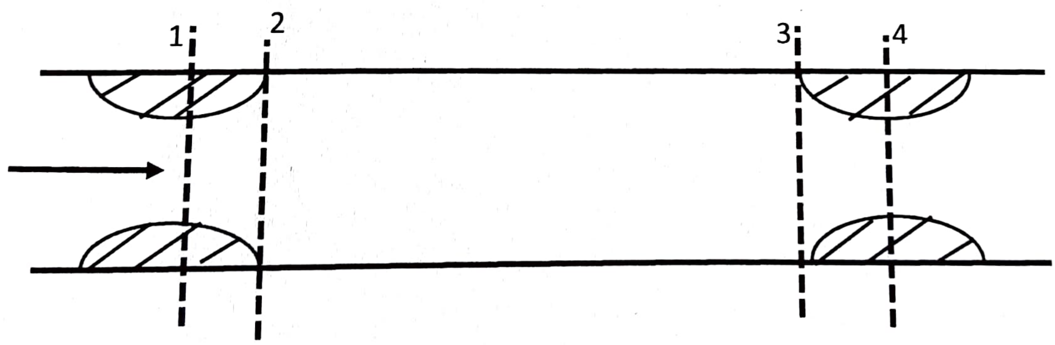


Fig-1(a)

12. Assuming the flow of a perfect gas in an adiabatic, no work system, show that sonic velocity corresponding to the stagnation condition (a_0) is related to sonic velocity (a^*) where the Mach number is unity by the following equation: $\frac{a^*}{a_0} = \sqrt{\frac{2}{\gamma+1}}$

Prob. Sheet-3

$$\frac{p_{t2}}{p_{t1}} = e^{-\Delta s/R} \qquad \text{for } Q = W = 0 \tag{4.28}$$

PROBLEMS

4.1. Compute and compare sonic velocity in air, hydrogen, water, and mercury. Assume normal room temperature and pressure.

4.2. At what temperature and pressure would carbon monoxide, water vapor, and helium have the same speed of sound as standard air (288 K and 1 atm)?

* **4.3.** Start with the relation for stagnation pressure that is valid for a perfect gas:

$$p_t = p\left(1 + \frac{\gamma - 1}{2}M^2\right)^{\gamma/(\gamma-1)}$$

Expand the right side in a binomial series and evaluate the result for small (but not zero) Mach numbers. Show that your answer can be written as

$$p_t = p + \frac{\rho V^2}{2g_c} + \text{HOT}$$

Remember, the higher-order terms are negligible only for very small Mach numbers. (See Problem 4.4.)

4.4. Measurement of airflow shows the static and stagnation pressures to be 30 and 32 psig, respectively. (Note that these are gage pressures.) Assume that $p_{\text{amb}} = 14.7$ psia and the temperature is 120°F.

(a) Find the flow velocity using equation (4.21).

(b) Now assume that the air is incompressible and calculate the velocity using equation (3.39).

(c) Repeat parts (a) and (b) for static and stagnation pressures of 30 and 80 psig, respectively.

(d) Can you reach any conclusions concerning when a gas may be treated as a constant-density fluid?

4.5. If $\gamma = 1.2$ and the fluid is a perfect gas, what Mach number will give a temperature ratio of $T/T_t = 0.909$? What will the ratio of p/p_t be for this flow? $\gamma = ?$

4.6. Carbon dioxide with a temperature of 335 K and a pressure of 1.4×10^5 N/m² is flowing with a velocity of 200 m/s. $M = \frac{V}{a}$

(a) Determine the sonic velocity and Mach number. $a = \sqrt{\gamma R T}$

(b) Determine the stagnation density.

4.7. The temperature of argon is 100°F, the pressure 42 psia, and the velocity 2264 ft/sec. Calculate the Mach number and stagnation pressure.

4.8. Helium flows in a duct with a temperature of 50°C, a pressure of 2.0 bar abs., and a total pressure of 5.3 bar abs. Determine the velocity in the duct.

4.9. An airplane flies 600 mph at an altitude of 16,500 ft, where the temperature is 0°F and the pressure is 1124 psfa. What temperature and pressure might you expect on the nose of the airplane?

4.10. Air flows at $M = 1.35$ and has a stagnation enthalpy of 4.5×10^5 J/kg. The stagnation pressure is 3.8×10^5 N/m². Determine the static conditions (pressure, temperature, and velocity).

4.11. A large chamber contains a perfect gas under conditions p_1, T_1, h_1, and so on. The gas is allowed to flow from the chamber (with $q = w_s = 0$). Show that the velocity cannot be greater than

Prandtl Velo ellipse

$$V_{\max} = a_1 \left(\frac{2}{\gamma - 1} \right)^{1/2}$$

$\frac{a^2}{\gamma-1} + \frac{V^2}{2} = \frac{a_0^2}{\gamma-1} = h_0$

$V_{max} = \sqrt{2h_0} = \sqrt{\frac{2a_0^2}{\gamma-1}} = a_0\sqrt{\frac{2}{\gamma-1}}$

If the velocity is the maximum, what is the Mach number?

67.3 50

4.12. Air flows steadily in an adiabatic duct where no shaft work is involved. At one section, the total pressure is 50 psia, and at another section, it is 67.3 psia. In which direction is the fluid flowing, and what is the entropy change between these two sections?

$s_2 - s_1 = -R \ln \frac{p_{t2}}{p_{t1}} = V + W$

4.13. Methane gas flows in an adiabatic, no-work system with negligible change in potential. At one section $p_1 = 14$ bar abs., $T_1 = 500$ K, and $V_1 = 125$ m/s. At a downstream section $M_2 = 0.8$.

(a) Determine T_2 and V_2.

(b) Find p_2 assuming that there are no friction losses.

(c) What is the area ratio A_2/A_1?

4.14. Air flows through a constant-area, insulated passage. Entering conditions are $T_1 = 520°R$, $p_1 = 50$ psia, and $M_1 = 0.45$. At a point downstream, the Mach number is found to be unity.

(a) Solve for T_2 and p_2.

(b) What is the entropy change between these two sections?

(c) Determine the wall frictional force if the duct is 1 ft in diameter.

4.15. Carbon dioxide flows in a horizontal adiabatic, no-work system. Pressure and temperature at section 1 are 7 atm and 600 K. At a downstream section, $p_2 = 4$ atm., $T_2 = 550$ K, and the Mach number is $M_2 = 0.90$.

(a) Compute the velocity at the upstream location.

(b) What is the entropy change?

(c) Determine the area ratio A_2/A_1.

4.16. Oxygen with $T_{t1} = 1000°R$, $p_{t1} = 100$ psia, and $M_1 = 0.2$ enters a device with a cross-sectional area $A_1 = 1$ ft² . There is no heat transfer, work transfer, or losses as the gas passes through the device and expands to 14.7 psia.

(a) Compute ρ_1, V_1, and $\dot{m}$.

(b) Compute M_2, T_2, V_2, ρ_2, and A_2.

(c) What force does the fluid exert on the device?

4.17. Consider steady, one-dimensional, constant-area, horizontal, isothermal flow of a perfect gas with no shaft work (Figure P4.17). The duct has a cross-sectional area A and perimeter P. Let τ_w be the shear stress at the wall.

5.1 The following information is common to each of parts (a) and (b). N_2 flows through a diverging section with $A_1 = 1.5\ ft^2$ and $A_2 = 4.5\ ft^2$. You may assume:–

steady, one-dimensional flow, $Q = W_s = 0$, negligible potential changes, and no losses.

(a) If $M_1 = 0.7$ and $p_1 = 70$ psia, find M_2 and p_2.

(b) If $M_1 = 1.7$ and $T_1 = 95°F$, find M_2 and T_2.

5.2. Air enters a converging section where $A_1 = 0.50\ m^2$. At a downstream section $A_2 = 0.25\ m^2$, $M_2 = 1.0$, and $\Delta s_{1-2} = 0$. It is known that $p_2 > p_1$. Find the initial Mach number (M_1) and the temperature ratio (T_2/T_1).

5.3. Oxygen flows into an insulated device with initial conditions as follows: $p_1 = 30$ psia, $T_1 = 750°R$, and $V_1 = 639$ ft/sec. The area changes from $A_1 = 6\ ft^2$ to $A_2 = 5\ ft^2$.

(a) Compute M_1, p_{t1}, and T_{t1}.

(b) Is this device a nozzle or diffuser?

(c) Determine M_2, p_2, and T_2 if there are no losses.

5.4. Air flows with $T_1 = 250$ K, $p_1 = 3$ bar abs., $p_{t1} = 3.4$ bar abs., and the cross-sectional area $A_1 = 0.40\ m^2$. The flow is isentropic to a point where $A_2 = 0.30\ m^2$. Determine the temperature at section 2.

5.5. The following information is known about the steady flow of air through an adiabatic system:

At section 1, $T_1 = 556°R$, $p_1 = 28.0$ psia

At section 2, $T_2 = 70°F$, $T_{t2} = 109°F$, $p_2 = 18$ psia

(a) Find M_2, V_2, and p_{t2}.

(b) Determine M_1, V_1, and p_{t1}.

(c) Compute the area ratio A_2/A_1.

(d) Sketch a physical diagram of the system along with a T–s diagram.

5.6. Assuming the flow of a perfect gas in an adiabatic, no-work system, show that sonic velocity corresponding to the stagnation conditions (a_t) is related to sonic velocity where the Mach number is unity (a^*) by the following equation:

$$\frac{a^*}{a_t} = \left(\frac{2}{\gamma + 1}\right)^{1/2}$$

$$\frac{a_1^2}{\gamma-1} + \frac{V_1^2}{2} = \frac{a_0^2}{\gamma-1}$$

when, $M_1 = 1$, $a_1 = a^*$

$V_1 = a_1 = a^*$.

$$a^{*2}\left(\frac{1}{\gamma-1} + \frac{1}{2}\right) = \frac{a_0^2}{\gamma-1}$$

$$\frac{a^{*2}}{a_0^2} = \frac{2}{\gamma+1}$$

$$\therefore \left(\frac{a^*}{a_0}\right) = \left(\frac{2}{\gamma+1}\right)^{1/2}$$

5.7. Carbon monoxide flows through an adiabatic system. $M_1 = 4.0$ and $p_{t1} = 45$ psia. At a point downstream, $M_2 = 1.8$ and $p_2 = 7.0$ psia.

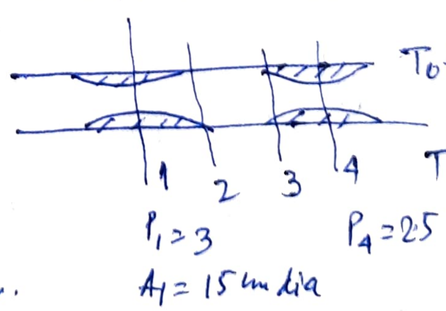
(a) Are there losses in this system? If so, compute Δs.

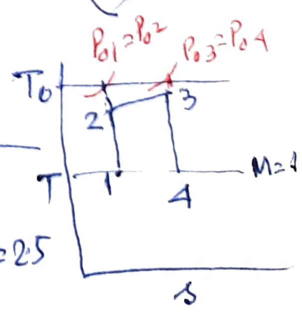
(b) Determine the ratio of A_2/A_1.

5.8. Two venturi meters are installed in a 30-cm-diameter duct that is insulated (Figure P5.8). The conditions are such that sonic flow exists at each throat (i.e., $M_1 = M_4 = 1.0$). Although each venturi is isentropic, the connecting duct has friction and hence losses exist between sections 2 and 3. $p_1 = 3$ bar abs. and $p_4 = 2.5$ bar abs. If the diameter at section 1 is 15 cm and the fluid is air:

(a) Compute Δs for the connecting duct.

(b) Find the diameter at section 4.





At sec-1, $M = 1$, $\frac{P_1}{P_{01}} = 0.5284$

$P_{01} = P_{02} = ✓$

At sec-4, $M = 1$, $\frac{P_4}{P_{04}} = 0.5284$ $\therefore P_{03} = P_{04} = ✓$.

$\frac{P_{03}}{P_{02}} = e^{-\Delta S/R}$ $\therefore \Delta S = ✓$

$\frac{A_3^*}{A_2^*} = e^{+\Delta S/R}$

or, $\frac{A_4}{A_1} = e^{\Delta S/R}$ $\Rightarrow A_4 = ✓$.

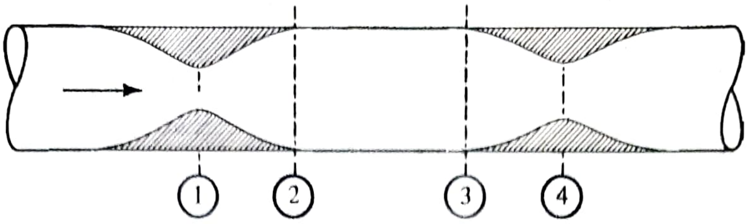


Figure P5.8

5.9. Starting with the flow rate as from equation (2.30), derive the following relation:

$$\frac{\dot{m}}{A} = M\left(1 + [(\gamma - 1)/2]M^2\right)^{-(\gamma+1)/2(\gamma-1)} \left(\frac{\gamma g_c}{R}\right)^{1/2} \frac{p_t}{\sqrt{T_t}}$$

5.10. A smooth 3-in.-diameter hole is punched into the side of a large chamber where oxygen is stored at 500°R and 150 psia. Assume frictionless flow.

(a) Compute the initial mass flow rate from the chamber if the surrounding pressure is 15.0 psia.

(b) What is the flow rate if the pressure of the surroundings is lowered to zero?

(c) What is the flow rate if the chamber pressure is raised to 300 psia?

5.11. Nitrogen is stored in a large chamber under conditions of 450 K and 1.5×10^5 N/m^2. The gas leaves the chamber through a convergent-only nozzle whose outlet area is 30 cm^2. The ambient room pressure is 1×10^5 N/m^2 and there are no losses.

(a) What is the velocity of the nitrogen at the nozzle exit?

(b) What is the mass flow rate?

(c) What is the maximum flow rate that could be obtained by lowering the ambient pressure?

F = R - 460

5.12. A converging-only nozzle has an efficiency of 96%. Air enters with negligible velocity at a pressure of 150 psia and a temperature of 750°R. The receiver pressure is 100 psia. What are the actual outlet temperature, Mach number, and velocity?

27 N/m² → 333 K

5.13. A large chamber contains air at 80 psia and 600°R. The air enters a converging–diverging nozzle which has an area ratio (exit to throat) of 3.0.

(a) What pressure must exist in the receiver for the nozzle to operate at its first critical point?

(b) What should the receiver pressure be for third critical (design point) operation?

(c) If operating at its third critical point, what are the density and velocity of the air at the nozzle exit plane?

F = 600 - 460 = 140

C = 5*(140-32)/9 = 60°C

5.14. Air enters a convergent–divergent nozzle at 20 bar abs. and 40°C. At the end of the nozzle the pressure is 2.0 bar abs. Assume a frictionless adiabatic process. The throat area is 20 cm^2.

(a) What is the area at the nozzle exit?

(b) What is the mass flow rate in kg/s?

K = 333

K = 5/9 R

1 PSI = 7.8×10³ N/m²

1" = 2.54 cm.
12" = 2.54×12
1 ft = 30.44 cm.
1 ft² = 930 cm²

5.15. A converging–diverging nozzle is designed to operate with an exit Mach number of $M = 2.25$. It is fed by a large chamber of oxygen at 15.0 psia and 600°R and exhausts into the room at 14.7 psia. Assuming the losses to be negligible, compute the velocity in the nozzle throat.

* **5.16.** A converging–diverging nozzle (Figure P5.16) discharges air into a receiver where the static pressure is 15 psia. A 1-ft² duct feeds the nozzle with air at 100 psia, 800°R, and a velocity such that the Mach number $M_1 = 0.3$. The exit area is such that the pressure at the nozzle exit exactly matches the receiver pressure. Assume steady, one-dimensional flow, perfect gas, and so on. The nozzle is adiabatic and there are no losses.

(a) Calculate the flow rate.

(b) Determine the throat area.

(c) Calculate the exit area.

15 lb/in² = 15 kg/(2.2 (2.54)²) cm² = 15/(2.2(2.54)²) kg/cm² = 15×0.078 kg/cm² = 1.17 kg/cm² = 1.17 kg/cm² ×10⁵ = 0.117 MPa

15 lb/in² = 1.17×10⁵ N/m²

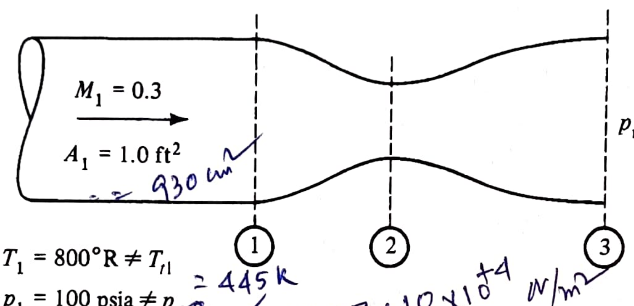


Figure P5.16

T₁ = 800−460 = 340°F
C/5 = (F−32)/9
C = 5×(340−32)/9
°K = 445 K

1 lb/in² = 1.17/15 ×10⁵ N/m² = 7.8×10³ N/m²

* **5.17.** Ten kilograms per second of air is flowing in an adiabatic system. At one section the pressure is 2.0×10^5 N/m², the temperature is 650°C, and the area is 50 cm². At a downstream section $M_2 = 1.2$.

(a) Sketch the general shape of the system.

(b) Find A_2 if the flow is frictionless.

(c) Find A_2 if there is an entropy change between these two sections of 42 J/kg-K.

5.18. Carbon monoxide is expanded adiabatically from 100 psia, 540°F and negligible velocity through a converging–diverging nozzle to a pressure of 20 psia.

(a) What is the ideal exit Mach number?

(b) If the actual exit Mach number is found to be $M = 1.6$, what is the nozzle efficiency?

(c) What is the entropy change for the flow?

(d) Draw a T–s diagram showing the ideal and actual processes. Indicate pertinent temperatures, pressures, etc.

5.19. Air enters a converging–diverging nozzle with $T_1 = 22°C$, $p_1 = 10$ bar abs., and $V_1 \approx 0$. The exit Mach number is 2.0, the exit area is 0.25 m², and the nozzle efficiency is 0.95.

(a) What are the actual exit values of T, p, and p_t?

Sheet 4

PROBLEMS

Unless otherwise indicated, you may assume that there is no friction in any of the following flow systems; thus the only losses are those generated by shocks.

6.1. A standing normal shock occurs in air that is flowing at a Mach number of 1.8.

(a) What are the pressure, temperature, and density ratios across the shock?

(b) Compute the entropy change for the air as it passes through the shock.

(c) Repeat part (b) for flows at $M = 2.8$ and 3.8.

6.2. The difference between the total and static pressure before a shock is 75 psi. What is the maximum static pressure that can exist at this point ahead of the shock? The gas is oxygen. (*Hint:* Start by finding the static and total pressures ahead of the shock for the limiting case of $M = 1.0$.)

6.3. In an arbitrary perfect gas, the Mach number before a shock is infinite.

(a) Determine a general expression for the Mach number after the shock. What is the value of this expression for $\gamma = 1.4$?

(b) Determine general expressions for the ratios p_2/p_1, T_2/T_1, ρ_2/ρ_1, and p_{t2}/p_{t1}. Do these agree with the values shown in Appendix H for $\gamma = 1.4$?

6.4. It is known that sonic velocity exists in each throat of the system shown in Figure P6.4. The entropy change for the air is 0.062 Btu/lbm-°R. Negligible friction exists in the duct. Determine the area ratios A_3/A_1 and A_2/A_1.

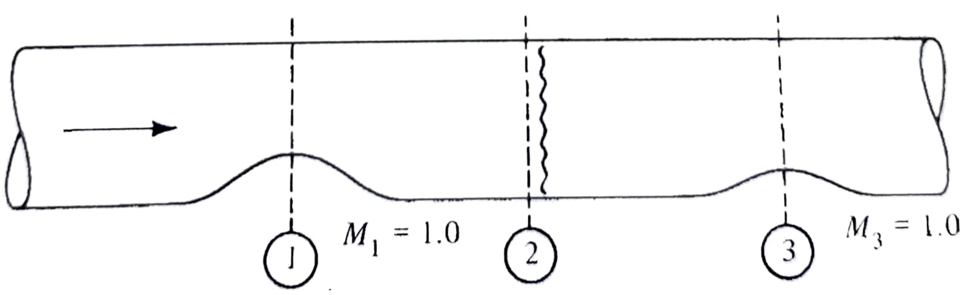


Figure P6.4

6.5. Air flows in the system shown in Figure P6.5. It is known that the Mach number after the shock is $M_3 = 0.52$. Considering p_1 and p_2, it is also known that one of these pressures is twice the other.

(a) Compute the Mach number at section 1.

(b) What is the area ratio A_1/A_2?

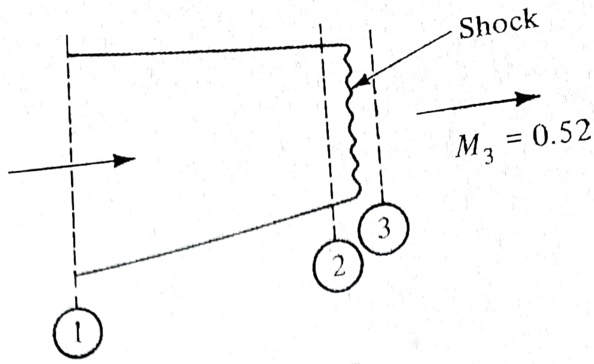


Figure P6.5

6.6. A shock stands at the inlet to the system shown in Figure P6.6. The free-stream Mach number is $M_1 = 2.90$, the fluid is nitrogen, $A_2 = 0.25\ \text{m}^2$, and $A_3 = 0.20\ \text{m}^2$. Find the outlet Mach number and the temperature ratio T_3/T_1.

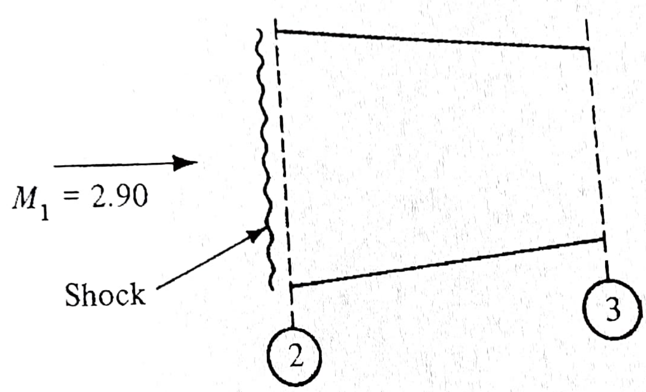


Figure P6.6

6.7. A converging–diverging nozzle is designed to produce a Mach number of 2.5 with air.

(a) What operating pressure ratio (p_{rec}/p_t inlet) will cause this nozzle to operate at the first, second, and third critical points?

(b) If the inlet stagnation pressure is 150 psia, what receiver pressures represent operation at these critical points?

(c) Suppose that the receiver pressure were fixed at 15 psia. What inlet pressures are necessary to cause operation at the critical points?

6.8. Air enters a convergent–divergent nozzle at $20 \times 10^5\ \text{N/m}^2$ and 40°C. The receiver pressure is $2 \times 10^5\ \text{N/m}^2$ and the nozzle throat area is $10\ \text{cm}^2$.

(a) What should the exit area be for the design conditions above (i.e., to operate at third critical?)

(b) With the nozzle area fixed at the value determined in part (a) and the inlet pressure held at $20 \times 10^5\ \text{N/m}^2$, what receiver pressure would cause a shock to stand at the exit?

(c) What receiver pressure would place the shock at the throat?

6.9. In Figure P6.9, $M_1 = 3.0$ and $A_1 = 2.0 \text{ ft}^2$. If the fluid is carbon monoxide and the shock occurs at an area of 1.8 ft^2, what is the minimum area possible for section 4?

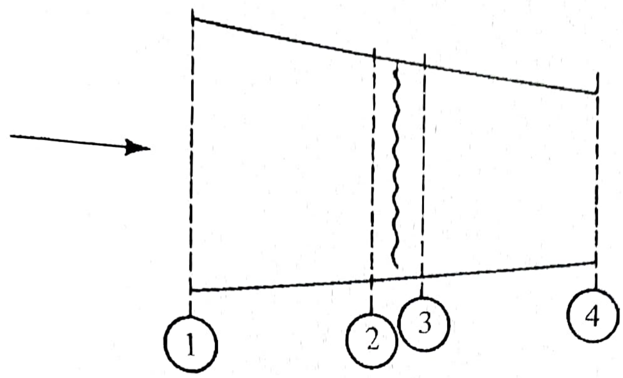


Figure P6.9

6.10. A converging–diverging nozzle has an area ratio of 7.8 but is not being operated at its design pressure ratio. Consequently, a normal shock is found in the diverging section at an area twice that of the throat. The fluid is oxygen.

(a) Find the Mach number at the exit and the operating pressure ratio.

(b) What is the entropy change through the nozzle if there is negligible friction?

6.11. The diverging section of a supersonic nozzle is formed from the frustrum of a cone. When operating at its third critical point with nitrogen, the exit Mach number is 2.6. Compute the operating pressure ratio that will locate a normal shock as shown in Figure P6.11.

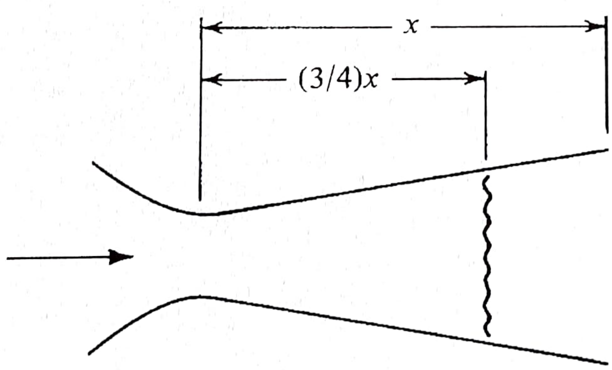


Figure P6.11

6.12. A converging–diverging nozzle receives air from a tank at 100 psia and 600°R. The pressure is 28.0 psia immediately preceding a plane shock that is located in the diverging section. The Mach number at the exit is 0.5 and the flow rate is 10 lbm/sec. Determine:

(a) The throat area.

(b) The area at which the shock is located.

(c) The outlet pressure required to operate the nozzle in the manner described above.

(d) The outlet area.

(e) The design Mach number.

6.13. Air enters a device with a Mach number of $M_1 = 2.0$ and leaves with $M_2 = 0.25$. The ratio of exit to inlet area is $A_2/A_1 = 3.0$.

(a) Find the static pressure ratio p_2/p_1.

(b) Determine the stagnation pressure ratio p_{t2}/p_{t1}.

6.14. Oxygen, with $p_t = 95.5$ psia, enters a diverging section of area 3.0 ft^2. At the outlet the area is 4.5 ft^2, the Mach number is 0.43, and the static pressure is 75.3 psia. Determine the possible values of Mach number that could exist at the inlet.

6.15. A converging–diverging nozzle has an area ratio of 3.0. The stagnation pressure at the inlet is 8.0 bar and the receiver pressure is 3.5 bar. Assume that $\gamma = 1.4$.

(a) Compute the critical operating pressure ratios for the nozzle and show that a shock is located within the diverging section.

(b) Compute the Mach number at the outlet.

(c) Compute the shock location (area) and the Mach number before the shock.

6.16. Nitrogen flows through a converging–diverging nozzle designed to operate at a Mach number of 3.0. If it is subjected to an operating pressure ratio of 0.5:

(a) Determine the Mach number at the exit.

(b) What is the entropy change in the nozzle?

(c) Compute the area ratio at the shock location.

(d) What value of the operating pressure ratio would be required to move the shock to the exit?

6.17. Consider a converging–diverging nozzle feeding air from a reservoir at p_1 and T_1. The exit area is $A_e = 4A_2$, where A_2 is the area at the throat. The back pressure p_{rec} is steadily reduced from an initial $p_{\text{rec}} = p_1$.

(a) Determine the receiver pressures (in terms of p_1) that would cause this nozzle to operate at first, second, and third critical points.

(b) Explain how the nozzle would be operating at the following back pressures: **(i)** $p_{\text{rec}} = p_1$; **(ii)** $p_{\text{rec}} = 0.990p_1$; **(iii)** $p_{\text{rec}} = 0.53p_1$; **(iv)** $p_{\text{rec}} = 0.03p_1$.

6.18. Draw a detailed T–s diagram corresponding to the *supersonic tunnel startup* condition (Figure 6.7). Identify the various stations (i.e., 1, 2, 3, etc.) in your diagram. You may assume no heat transfer and no frictional losses in the system.

6.19. Consider the wind tunnel shown in Figures 6.7 and 6.8. Atmospheric air enters the system with a pressure and temperature of 14.7 psia and 80°F, respectively, and has negligible velocity at section 1. The test section has a cross-sectional area of 1 ft^2 and operates at a Mach number of 2.5. You may assume that the diffuser reduces the velocity to approximately zero and that final exhaust is to the atmosphere with negligible velocity. The system is fully insulated and there are negligible friction losses. Find:

(a) The throat area of the nozzle.

(b) The mass flow rate.

(c) The minimum possible throat area of the diffuser.

(d) The total pressure entering the exhauster at startup (Figure 6.7).

(e) The total pressure entering the exhauster when running (Figure 6.8).

(f) The hp value required for the exhauster (based on an isentropic compression).