ME 6135: Advanced Aerodynamics

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Lecture-12

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Normal Shock Waves and Related Topics

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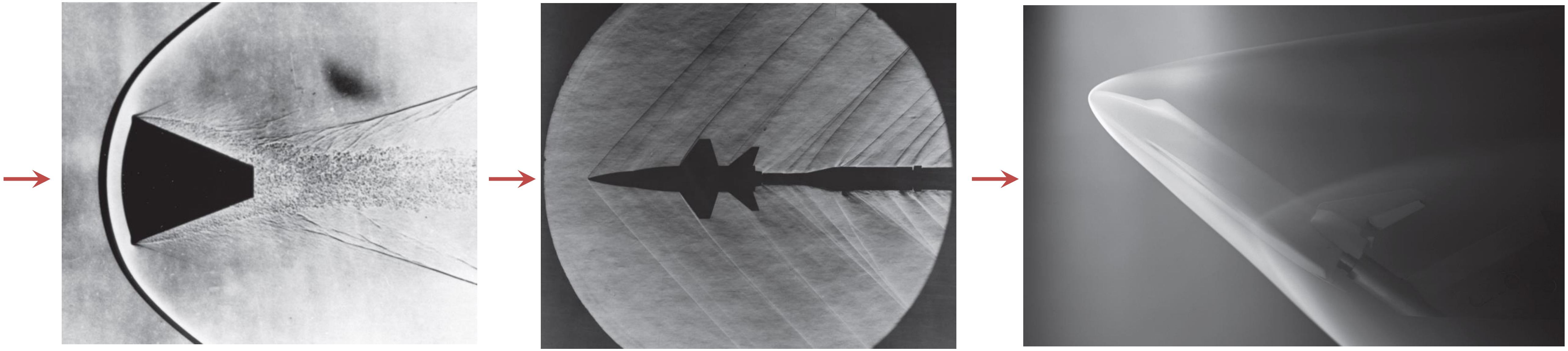
Shock Waves



(a) (b) (c)

Schlieren photographs illustrating shock waves on various bodies. (*a*) Mercury capsule wind-tunnel model at Mach 8. (*b*) X-15 wind tunnel model at Mach 7. (Both photos: *NASA*) (c) Space Shuttle Orbiter model at Mach 6.

Special optical systems, such as shadowgraphs, schlieren, and interferometers, take advantage of optical refraction arises from density gradient and allow the visual imaging of shock waves on a screen or a photographic negative.

Normal Shock Waves

Isentropic flow relations:

$$\boxed{\frac{T_0}{T} = 1 + \frac{\gamma - 1}{2} M^2} \tag{8.40}$$

$$\frac{p_0}{p} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\gamma/(\gamma-1)} \tag{8.42}$$

$$\frac{\rho_0}{\rho} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{1/(\gamma-1)} \tag{8.43}$$

Appendix-A can be used to get the data

$$\frac{T^*}{T_0} = \frac{2}{\gamma + 1} \tag{8.44}$$

$$\frac{p^*}{p_0} = \left(\frac{2}{\gamma + 1}\right)^{\gamma/(\gamma-1)} \tag{8.45}$$

$$\frac{\rho^*}{\rho_0} = \left(\frac{2}{\gamma + 1}\right)^{1/(\gamma-1)} \tag{8.46}$$

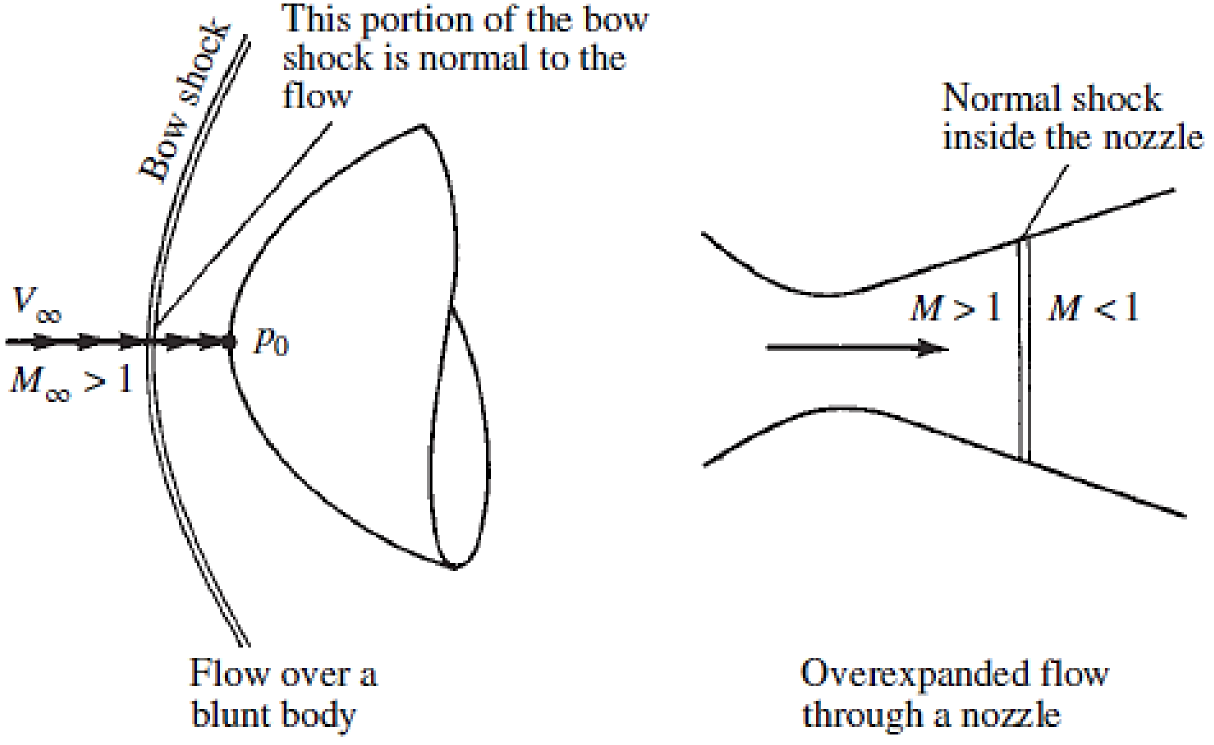


Figure 8.1 Two examples where normal shock waves are of interest.

For $\gamma = 1.4$, these ratios are

$$\frac{T^*}{T_0} = 0.833 \qquad \frac{p^*}{p_0} = 0.528 \qquad \frac{\rho^*}{\rho_0} = 0.634$$

Normal Shock Waves

The property relations across a normal shock wave are –

⇨ $$M_2^{\,2} = \frac{(\gamma-1)M_1^2 + 2}{2\gamma M_1^2 - (\gamma-1)}$$

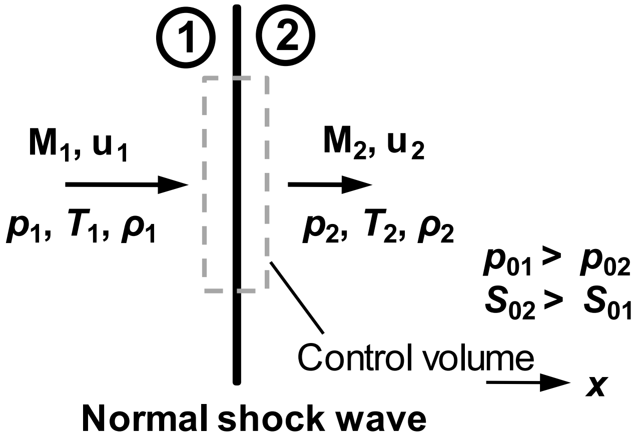
⇨ $$\frac{p_2}{p_1} = 1 + \frac{2\gamma}{\gamma+1}(M_1^2 - 1)$$

⇨ $$\frac{T_2}{T_1} = [1 + \frac{2\gamma}{\gamma+1}(M_1^2 - 1)][\frac{2+(\gamma-1)M_1^2}{(\gamma+1)M_1^2}]$$

⇨ $$\frac{\rho_2}{\rho_1} = \frac{(\gamma+1)M_1^{\,2}}{2+(\gamma-1)M_1^{\,2}}$$

$$\boxed{\frac{p_{0,2}}{p_{0,1}} = e^{-(s_2-s_1)/R}} \qquad (8.73)$$

The total pressure decreases across a shock wave.



Normal shock wave

① **Conditions just upstream of the shock**

② **Conditions just downstream of the shock**

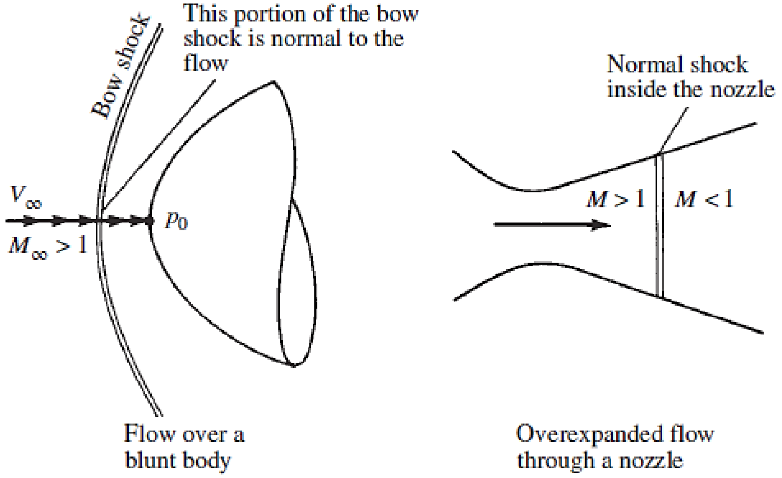
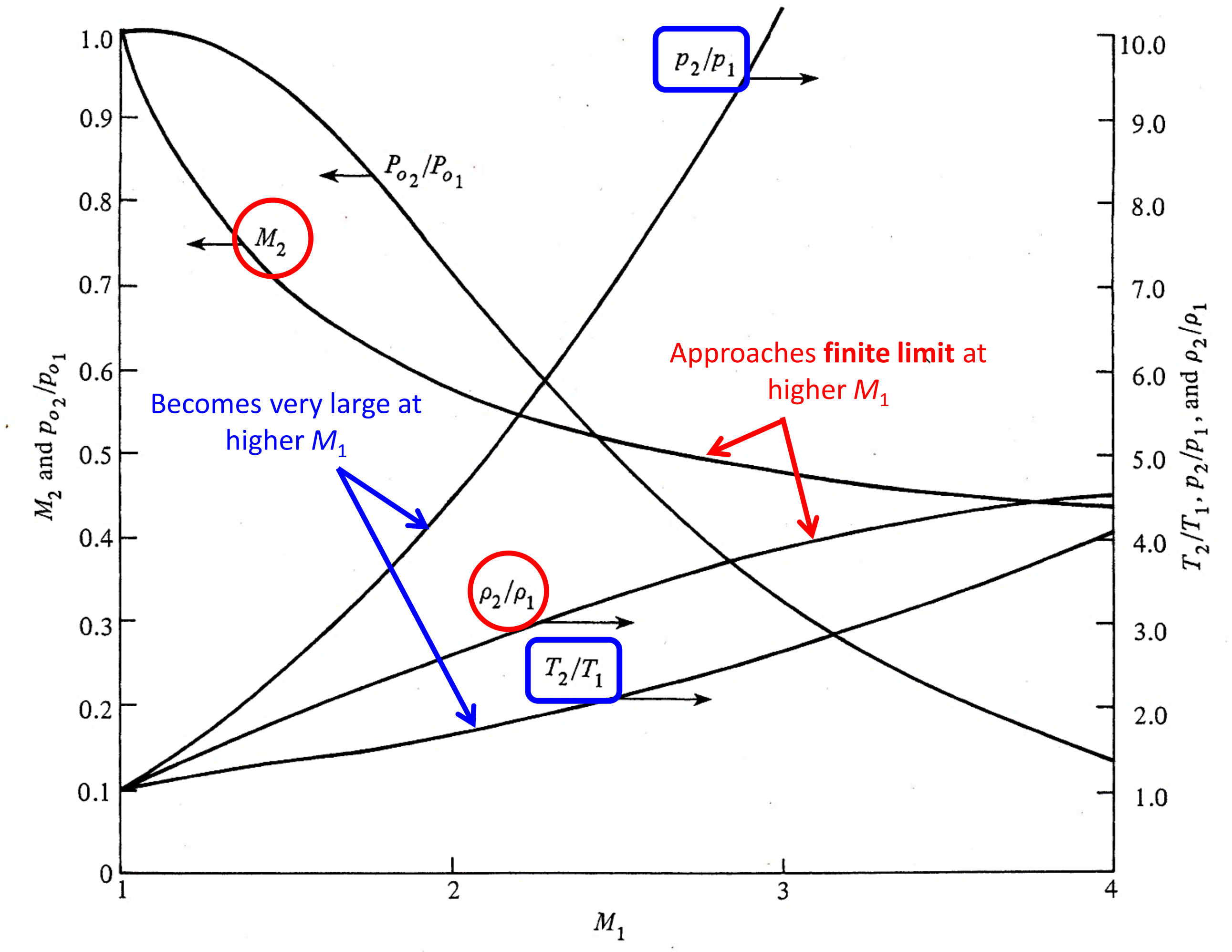


Figure 8.1 Two examples where normal shock waves are of interest.

Appendix-B can be used to get the data



Becomes very large at higher M_1

Approaches **finite limit** at higher M_1

Figure 3.10 | Properties behind a normal shock wave as a function of upstream Mach number.

$$\lim_{M_1\to\infty} M_2 = \sqrt{\frac{\gamma-1}{2\gamma}} = 0.378$$

$$\lim_{M_1\to\infty} \frac{\rho_2}{\rho_1} = \frac{\gamma+1}{\gamma-1} = 6$$

$$\lim_{M_1\to\infty} \frac{p_2}{p_1} = \infty$$

$$\lim_{M_1\to\infty} \frac{T_2}{T_1} = \infty$$

EXAMPLE 8.18

The velocity and temperature of the flow ahead of a normal shock wave are 1215 m/s and 300 K, respectively. Calculate the velocity of the flow behind the shock.

Example 8.13

A ramjet engine is an air-breathing propulsion device with essentially no rotating machinery (no rotating compressor blades, turbine, etc.). The basic generic parts of a conventional ramjet are sketched in Figure 8.9. The flow, moving from left to right, enters the inlet, where it is compressed and slowed down. The compressed air then enters the combustor at very low subsonic speed, where it is mixed and burned with a fuel. The hot gas then expands through a nozzle. The net result is the production of thrust toward the left in Figure 8.9. In this figure the ramjet is shown in a supersonic freestream with a detached shock wave ahead of the inlet. The portion of the shock just to the left of point 1 is a normal shock. (A detached normal shock wave in front of the inlet of a ramjet in a supersonic flow is not the ideal operating condition; rather, it is desirable that the flow pass through one or more *oblique* shock waves before entering the inlet. Oblique shock waves are discussed in Chapter 9.) After passing through the shock wave, the flow from point 1 to point 2, located at the entrance to the combustor, is isentropic. The ramjet is flying at Mach 2 at a standard altitude of 10 km, where the air pressure and temperature are 2.65 × 10^4 N/m2 and 223.3 K, respectively. Calculate the air temperature and pressure at point 2 when the Mach number at that point is 0.2.

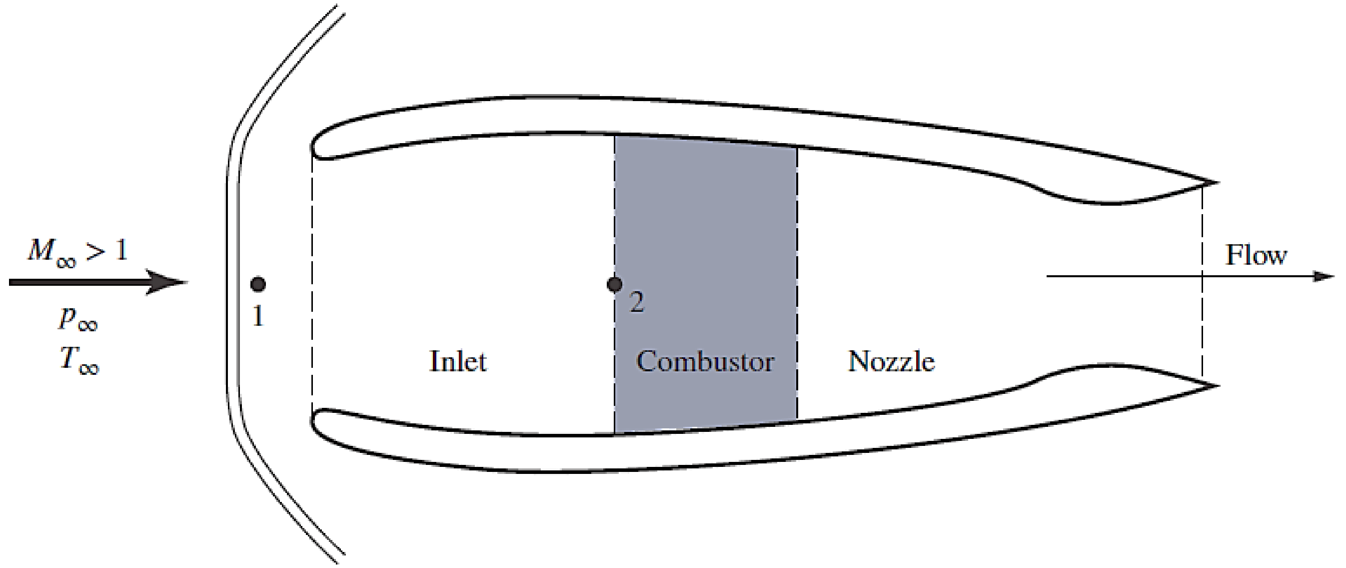


Figure 8.9 Schematic of a conventional subsonic-combustion ramjet engine.

Example 8.14

Repeat Example 8.13, except for a freestream Mach number $M_\infty = 10$. Assume that the ramjet has been redesigned so that the Mach number at point 2 remains equal to 0.2.

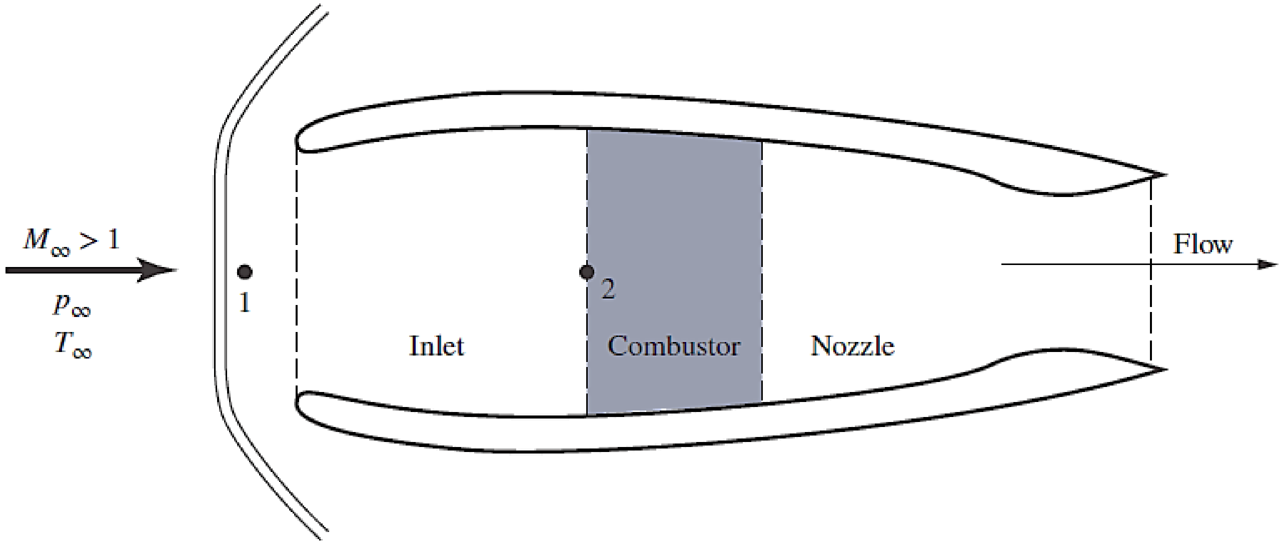


Figure 8.9 Schematic of a conventional subsonic-combustion ramjet engine.