Exercise 16.

- **Normal shock** (repetition)
  - Abrupt change in supersonic flow
  - If $k > 1$ (e.g. air) the flow from → super- to subsonic
  - The chock results in losses
    - ➢ Isentropic assumption not valid through chock
  - Need to use Mach number relations e.g.

$$\frac{p_2}{p_1} = 1 + \frac{2\gamma}{\gamma+1}\left[\mathrm{Ma}_1^2 - 1\right] \qquad \text{Eq. (9.55)}$$

$$\mathrm{M}_2^2 = \frac{(\gamma-1)\mathrm{Ma}_1^2+2}{2\gamma\,\mathrm{Ma}_1^2-(\gamma-1)} \qquad \text{Eq. (9.57)}$$

  - Can also use relations from Eq. (9.58)

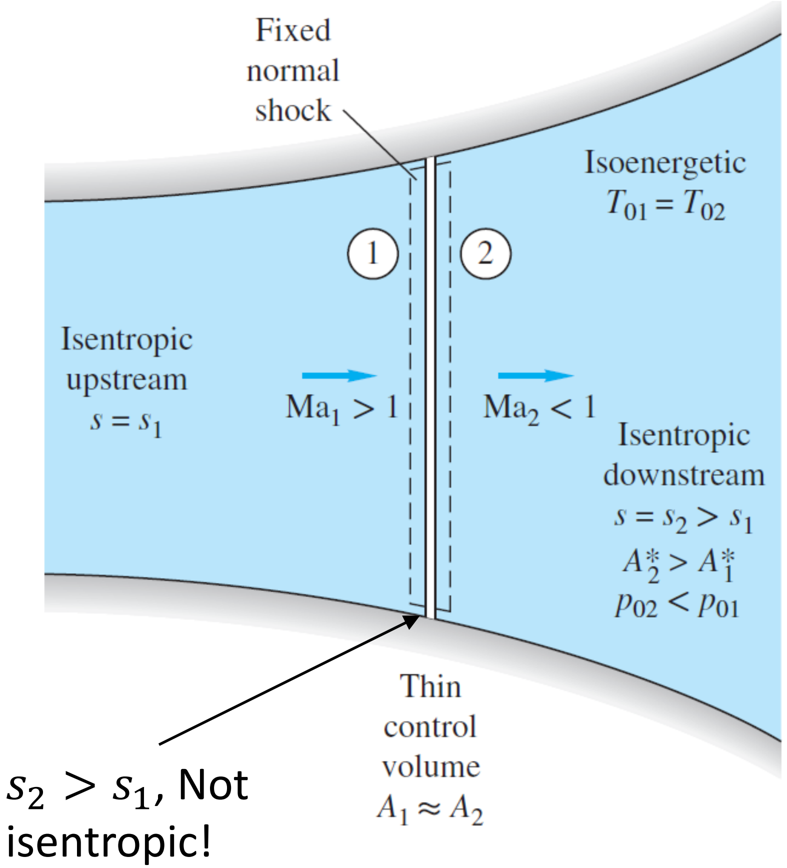
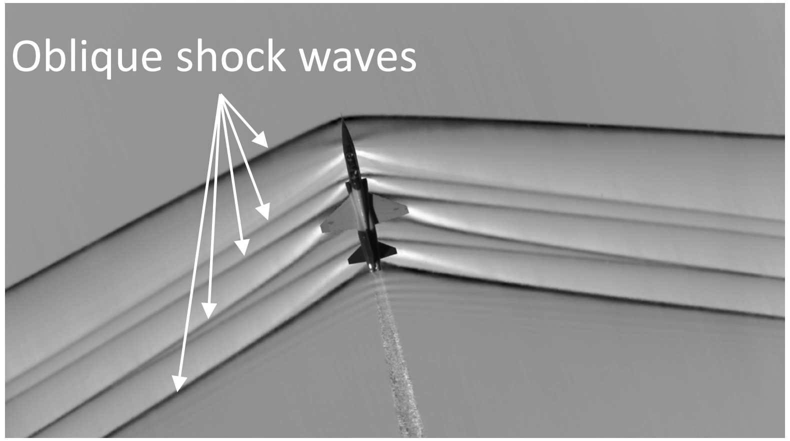


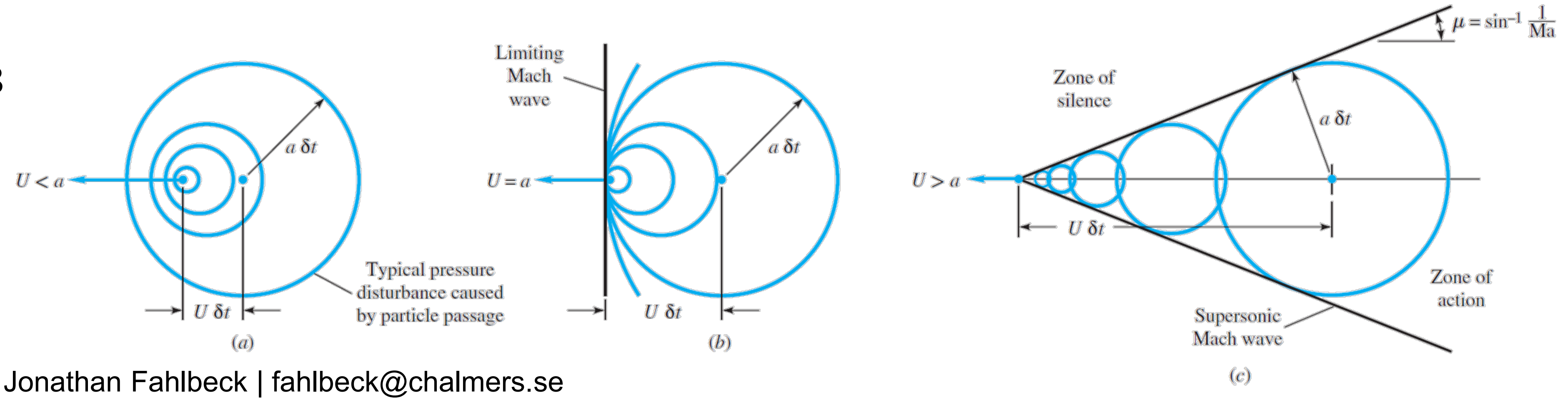
Fig. 9.8

Exercise 16.



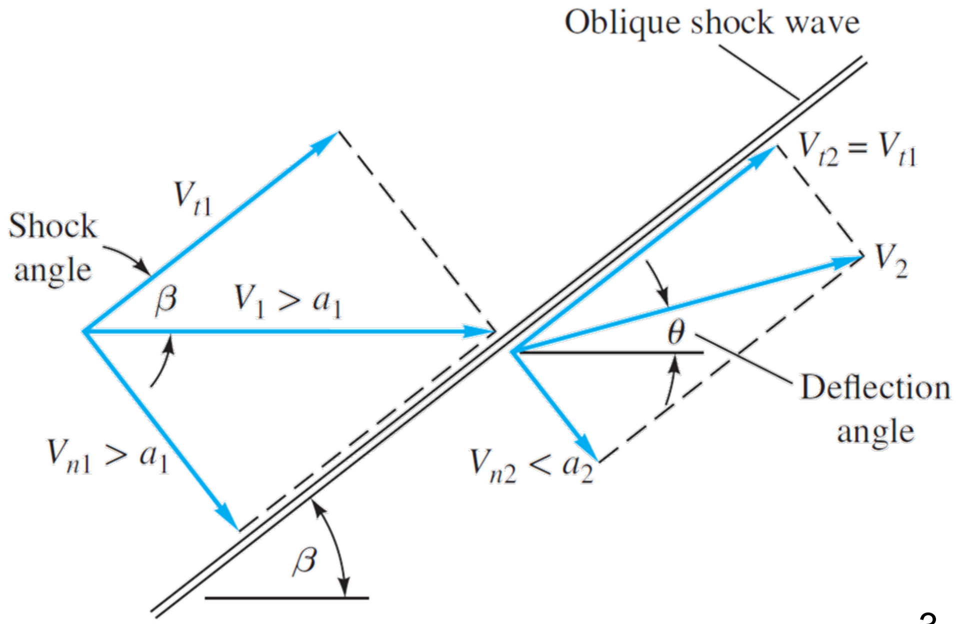
- **Oblique shock**
  - Pressure-waves move with the sound speed
  - a) Object move with $U < a \rightarrow$ pressure waves move faster
  - b) Object move with $U = a \rightarrow$ Mach wave by the object
  - c) Object move with, $U > a$
    - ➢ pressure waves are accumulated → Mach waves
    - ➢ Flow upstream the wave do no '*see/feel*' the wave until the object has passed
    - ➢ The flow is bent after the Mach wave has passed

Fig. 9.18



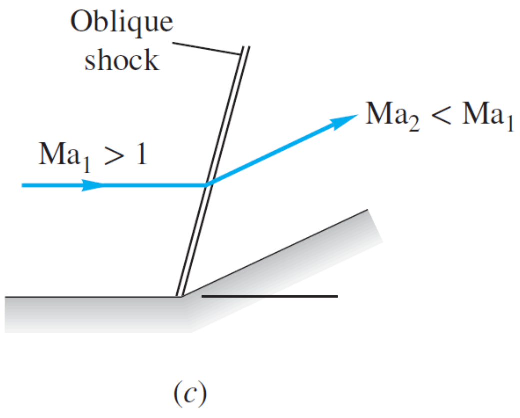
Exercise 16.

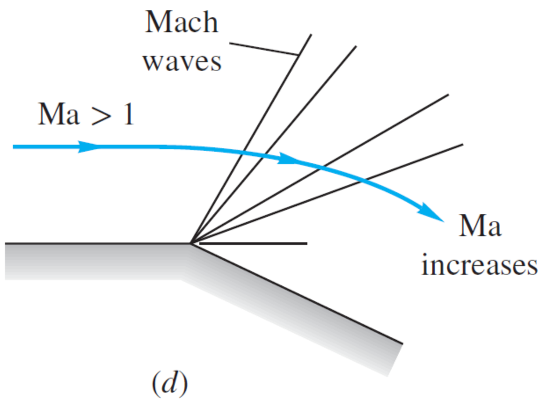
- **Oblique shock**
  - Sudden change in *supersonic* flow
  - Threated as a normal shock with respect to the normal direction, $\mathrm{Ma_n}$
    - Flow from **supersonic to subsonic** in the **normal** direction ($\mathrm{M_{n1}} > 1, \mathrm{M_{n2}} < 1$)
    - The **absolute flow *can*** be supersonic before and after ($\mathrm{M_1} > 1$, and $\mathrm{M_2} > 1$)
  - The shock results in losses
    - Can not use isentropic relations through the shock
  - Use the Eqns. (9.82 – 9.86)



Exercise 16.

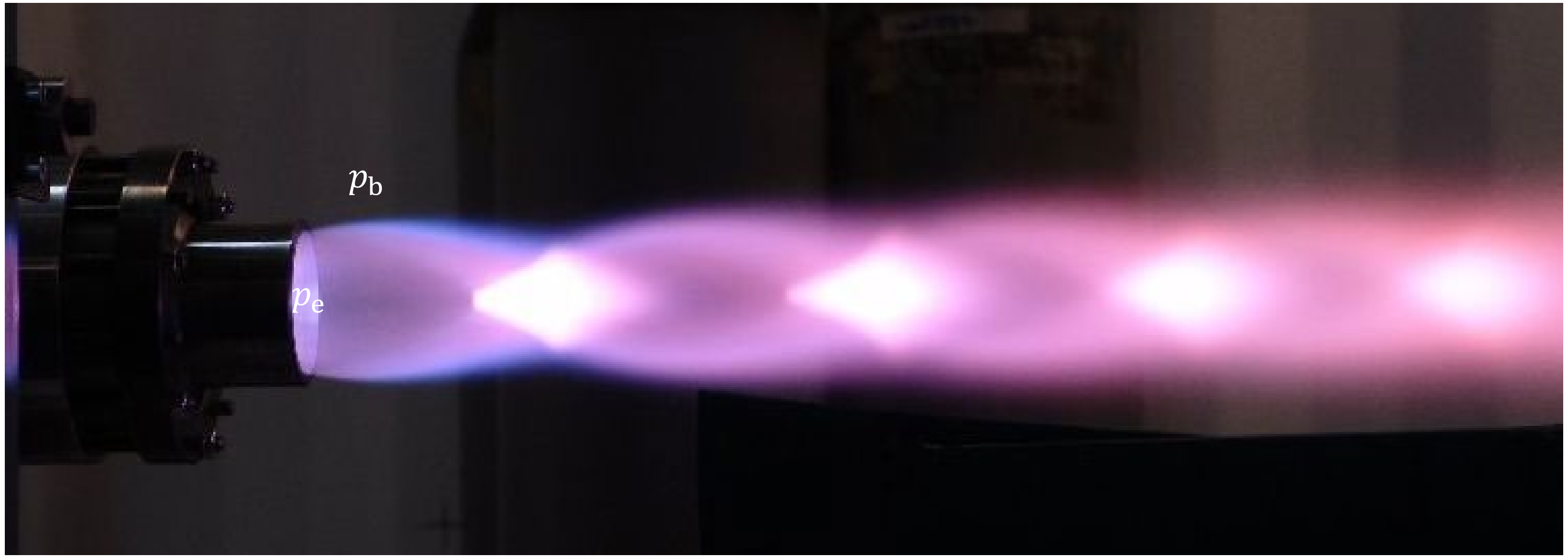
- **Expansion waves** (Prandtl Meyer)
  - – Opposite of a shock
    - ➢ Pressure decrees (expanding)
    - ➢ Mach number increase
  - – Isentropic expansion (assumption)
  - – Use isentropic relations and Eq. (9.99) or table B.5

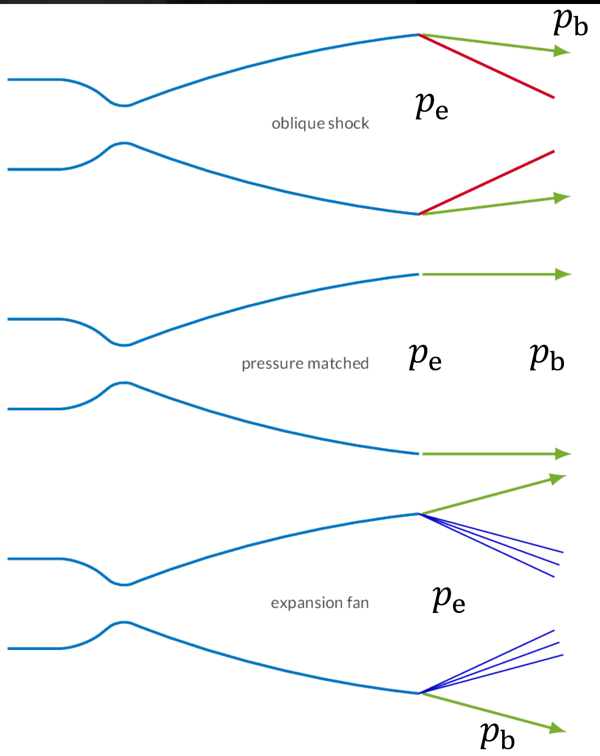




$\omega(\mathrm{Ma}) = K^{1/2}\tan^{-1}\left(\frac{\mathrm{M}^2-1}{K}\right)^{1/2} - \tan^{-1}(\mathrm{M}^2-1)^{1/2}$ Eq. (9.99), or use table B.5

where $K = \frac{\gamma+1}{\gamma-1}$





Overexpanded nozzle:

$p_e < p_b$

Pressure matched nozzle

$p_e = p_b$

Underexpanded nozzle

$p_e > p_b$