4.1 Introduction

- A shock wave represents an abrupt change in fluid properties.
- Finite variations in $T$, $p$, & density occur over a finite thickness comparable to the mean free path of the gas molecules.
- Recall, a subsonic flow can adjust to the presence of a body by gradual changes in fluid properties.
- A supersonic flow adjusts to the presence of a body through a shock wave.
- In this chapter normal shock waves will be examined, that is a planar shock wave normal to the flow direction.
- As mentioned earlier, a series of weak compression waves can coalesce and form a finite strength compression shock wave.
4.2 Formation of a Normal Shock Wave

- As shown in section 2.2, when a piston in a tube is given a steady push to the right with magnitude \( \text{d}V \), a sound wave is sent out ahead of the piston (fig 4.1).

- Now suppose the piston is given a second push, with an incremental velocity \( \text{d}V \), causing a second wave to move into the compressed gas behind the first wave.

- Location of the waves & pressure distribution in the tube, after a time \( t \), are shown. Each wave travels @ the speed of sound, with respect to the gas into which it is moving.

- Since the 2nd wave is moving into the gas which is:
  
  a) already moving to the right with velocity \( \text{d}V \),
  
  b) moving into a compressed gas having a slightly elevated temperature,
  
  so the second wave travels at a greater absolute velocity than the 1st wave and gradually overtakes it.
4.2 Formation of a Normal Shock Wave

- Let's examine this process:
  1. At time, \( t = t_1 \), the 1st compression wave passes through the fluid @ speed \( "a" \) raising the pressure to \( p + dp \) and the temperature to \( T + dT \), increasing the "a" for the next wave.
  2. At time, \( t = t_2 \), where \( t_2 > t_1 \), a 2nd wave travels through the compressed fluid with a larger value of "a" (fig 4.2a).

3. At time, \( t = t_3 \), where \( t_3 > t_2 > t_1 \), the 2nd wave is catching up to the 1st wave (fig 4.2b).

- Now suppose the piston is accelerated from rest to a finite velocity increment \( \Delta V \), to the right. The velocity increment can be thought to consist of a large # of infinitesimal \( dV \) increments.
4.2 Formation of a Normal Shock Wave

Fig 4.3 displays velocity of piston vs. time, with incremented dV superimposed.

As in fig 4.2, the waves next to the piston overtake those farther down in the tube, see fig 4.4.

As t passes, compression wave steepens.

The tendency of the higher $\rho$ parts of the wave to overtake the lower $\rho$ parts are finally counteracted by heat condition & viscous effects, taking place internal to the wave.

The resultant constant-shape compression shock wave produced by the addition of the weak compression waves then moves through the undisturbed gas ahead of the piston.
4.2 Formation of a Normal Shock Wave

- The slopes of temperature & pressure vs. distance in the wave itself are not infinite, and so the shock can be approximated by a discontinuity (fig 4.5).

\[ \delta = \text{shock thickness (} \approx 2.5 \times 10^{-5} \text{ cm)} = 0.25 \mu \text{m} \]

Note: 
- a) \(1\mu \text{m} = 4/100,000 \text{ inch} \)
- b) The typical human hair is from 20 to 80 \( \mu \text{m} \)

- If the piston in fig 4.1 is suddenly given an incremental velocity \(dV\) to the left, a weak expansion wave propagates to the right @ the velocity of sound.

- When a second incremental \(dV\) is given, a 2\(^{nd}\) expansion wave moves into the expanded gas behind the first wave, see fig 4.6.

- Each wave travels @ the speed of sound with respect to the gas into which it is moving.
4.2 Formation of a Normal Shock Wave

The expansion waves & gas are moving in opposite directions.

Also, the 2nd wave is traveling into a gas that has already been expanded & cooled, which lowers the value of “a”.

This reduces the absolute velocity, & cause the 2nd wave to fall farther & farther behind the 1st.

This increase in spacing continues to increase with each incremental dV to the left.

Hence, expansion waves spread out and therefore, are not able to reinforce one another.

Figure 4.7

4.3 Equations of Motions for a Normal Shock Wave

- As previously mentioned a shock wave involves rapid, but finite changes in $p$ & $T$.

- Processes taking place within a wave are complex and cannot be studied via equilibrium thermodynamics.

- In fact, temperature & velocity gradients internal to the shock reveal heat conduction & viscous dissipation, which render the shock process internally irreversible.

- Let’s examine the gross changes that take place across a shock wave, neglecting these internal complexities.
Recap:
1) shocks are irreversible,
2) shocks are adiabatic (there is a T gradient across a shock, but no Q within the CV boundaries),
3) a shock is extremely thin; hence no change in area across wave.

• Assume a 1-D steady flow with a fixed plane shock (fig 4.8)
• Apply the conservation of mass:
\[ \rho V_1 = \rho V_2 \quad (4.1) \]
• Neglect all external forces except pressure forces and apply the conservation of Momentum (Eq 1.14);

\[
\sum \vec{F} = \iint_S \vec{V} \left( \rho \vec{V} \cdot d\vec{A} \right)
- p(\hat{i} \cdot \hat{n})dA = \iint_S \vec{V}_x \left( \rho \vec{V} \cdot d\vec{A} \right)
\]

• Recall: \( A_1 = A_2 \) so,

\[ p_1 + \rho_1 V_1^2 = p_2 + \rho_2 V_2^2 \quad (4.2) \]
4.3 Equations of Motions for a Normal Shock Wave

• Apply the energy eq. Eq 1.19,

\[
\frac{\partial}{\partial t} \int_{C^f} e \rho d\gamma + \int_{S} \left( h + \frac{1}{2} V^2 + gZ \right) (\rho \vec{V} \cdot d\vec{A}) = \frac{d}{dt} (Q - W)
\]

• Eliminate term 1 for steady flow, neglect P.E., let Q = 0 (an adiabatic process) & W = 0, therefore,

\[
\int_{S} \left( h + \frac{1}{2} V^2 \right) (\rho \vec{V} \cdot d\vec{A}) = 0
\]

• Also, we know for an ideal gas,

\[
p = \rho RT \quad \& \quad \frac{dh}{dt} = c_p dT \quad \& \quad a^2 = \gamma RT
\]
• Recall for an ideal gas (constant specific heats) undergoing an adiabatic process, the total temperature is constant, hence Eq 4.3 represents the stagnation enthalpy ($h_t$)

$$h_t = h_1 + \frac{V_1^2}{2} = h_2 + \frac{V_2^2}{2}$$

4.3 Equations of Motions for a Normal Shock Wave

We can equating the previous 2 equations to obtain,

$$h_t - h_1 = c_p (T_t - T_1)$$

and since

$$c_p (T_t - T_1) = \frac{V_1^2}{2}$$

or

$$T_t = T_1 + \frac{V_1^2}{2c_p}$$

Also recall: $c_p = \frac{\gamma R}{\gamma - 1}$
4.3 Equations of Motions for a Normal Shock Wave

• Therefore,

\[ T_i = T_1 \left[ 1 + \frac{(\gamma - 1)V_i^2}{2\gamma R T_1} \right] \]

since; \[ a^2 = \gamma R T \]

\[ T_i = T_1 \left( 1 + \frac{(\gamma - 1)}{2} M_1^2 \right) = T_2 \left( 1 + \frac{(\gamma - 1)}{2} M_2^2 \right) \]  

(4.4)

For ideal gas the conservation of Momentum, Eq.4.2 becomes,

\[ p_1 + \rho_1 V_1^2 = p_1 \left( 1 + \frac{\rho}{\rho_1} V_1^2 \right) \]

Combining Eqs 4.4 & 4.5 with Eq 4.1, (cons of energy, momentum, & mass)

\[ p_1 \left( 1 + \gamma M_1^2 \right) = p_2 \left( 1 + \gamma M_2^2 \right) \]

(4.5)

Combining Eqs 4.4 & 4.5 with Eq 4.1, (cons of energy, momentum, & mass)

\[ \frac{p_1}{RT_1} M_1 \sqrt{\gamma R T_1} = \frac{p_2}{RT_2} M_2 \sqrt{\gamma R T_2} \]

(4.1)

yields,

\[ \frac{M_1}{1 + \gamma M_1^2} \sqrt{1 + \frac{\gamma - 1}{2} M_1^2} = \frac{M_2}{1 + \gamma M_2^2} \sqrt{1 + \frac{\gamma - 1}{2} M_2^2} \]

(4.6)
4.3 Equations of Motions for a Normal Shock Wave

• One solution is when \( M_1 = M_2 \) corresponds to the isentropic flow case (the trivial solution). So let’s solve Eq 4.6 for \( M_2 \) in terms of \( M_1 \),

\[
\frac{M_1^2}{(1 + \gamma M_1^2)^4} \left( 1 + \frac{\gamma - 1}{2} M_1^2 \right) = \frac{M_2^2}{(1 + \gamma M_2^2)^4} \left( 1 + \frac{\gamma - 1}{2} M_2^2 \right)
\]

\[
L \left( 1 + \gamma M_2^2 \right)^2 = M_2^2 \left( 1 + \frac{\gamma - 1}{2} M_2^2 \right)
\]

\[
M_2^4 \left( 1 - \frac{1}{2} \gamma^2 L \right) + M_2^2 \left( 1 - 2 \gamma L \right) - L = 0
\]

• The solution is:

\[
M_2^2 = \frac{M_1^2 + \frac{2}{\gamma - 1}}{\frac{2\gamma}{\gamma - 1} \frac{M_1^2}{\gamma - 1} - 1}
\]  

(4.8)
4.3 Equations of Motions for a Normal Shock Wave

- Eq. 4.8 is plotted for $\gamma = 1.4$ in Fig 4.10
- Note when:
  a) $M_1 > 1$ then $M_2 < 1$; applying Eq 4.5:
  $$p_1 \left(1 + \gamma M_1^2\right) = p_2 \left(1 + \gamma M_2^2\right)$$
  (one obtains $p_2 >> p_1$ indicating a compression shock)
  b) $M_2 > 1$ then $M_1 < 1$

- Combine Eqs 4.4 and 4.8 to yield $T_2/T_1 = f(M_1, \gamma)$ and likewise Eqs 4.5 and 4.8 can be combined to yield
  $$p_2/p_1 = g(M_1, \gamma)$$
- For a ideal gas (constant $c_p$) the entropy can be determined from Eq 1.30,
  $$s_2 - s_1 = c_p \ln \frac{T_2}{T_1} - R \ln \frac{p_2}{p_1}$$
- Therefore substituting $p_2/p_1$ and $T_2/T_1$ one obtains for an Ideal gas
4.3 Equations of Motions for a Normal Shock Wave

- Recall the shock process is assumed to be adiabatic and irreversible.
- And from the 2nd law of thermodynamics for an irreversible process,
  \[ ds > \frac{\delta Q}{T} \] (1.21)
  Therefore, for a shock process \( ds > 0 \).

- From the normal shock equations for an ideal gas (constant \( c_p \)), Eq 4.4 was derived.

\[
\frac{T_2}{T_1} = \frac{1 + \frac{\gamma - 1}{2} M_1^2}{1 + \frac{\gamma - 1}{2} M_2^2}
\]

Now combine eq 4.5 with eq 4.8 to yield,

\[
\frac{p_2}{p_1} = \frac{2\gamma M_1^2}{\gamma + 1} - \frac{\gamma - 1}{\gamma + 1}
\] (4.11)
4.3 Equations of Motions for a Normal Shock Wave

Finally applying eq 4.1:

\[ \rho_1 V_1 = \rho_2 V_2 \]

or

Substituting from eqs 4.8 & 4.10 we obtain,

\[ \frac{\rho_2}{\rho_1} = \frac{M_1}{M_2} \sqrt{\frac{T_1}{T_2}} \]

\[ \frac{\rho_2}{\rho_1} = \frac{M_1}{M_2} \left( \frac{2\gamma}{\gamma - 1} + \frac{\gamma - 1}{2} \right) \]

\[ \frac{2\gamma}{\gamma - 1} \left( \frac{2\gamma}{\gamma - 1} M_1^2 - 1 \right) \]

\[ \frac{M_1}{M_2} \left( \frac{2\gamma}{\gamma - 1} + \frac{\gamma - 1}{2} \right) \]

\[ \frac{1}{\gamma - 1} \frac{2\gamma}{\gamma - 1} M_1^2 - 1 \]

Numerical values of \( M_1, p_2/p_1, T_2/T_1 \), and \( \rho_2/\rho_1 \) are presented in Normal Shock tables for \( \gamma = 1.4, 1.3, \) and 5/3.

For steady flow of a ideal gas (const cp) there is no change in the stagnation temperature for the adiabatic process.

Physically, the increase in static temperature, \( T \) following a shock wave is compensated for by a decrease in the kinetic energy of the gas. Hence no change in \( T_{total} \).

\[ s_2 - s_1 = c_p \ln \frac{T_2}{T_1} - R \ln \frac{p_2}{p_1} \]
4.3 Equations of Motions for a Normal Shock Wave

• Expressing $\Delta s$ in terms of the stagnation properties,

$$
\frac{T_s}{T} = \left(1 + \frac{\gamma - 1}{2} M^2 \right)^{\frac{\gamma}{\gamma - 1}}
$$

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

• therefore, eq 4.9 becomes,

$$
\frac{s_2 - s_1}{R} = \frac{c_p}{R} \ln \left[ \frac{\left(1 + \frac{\gamma - 1}{2} M_1^2 \right)}{\left(1 + \frac{\gamma - 1}{2} M_2^2 \right)} \right] \frac{T_{t_2}}{T_{t_1}} - \ln \left[ \frac{\left(1 + \frac{\gamma - 1}{2} M_1^2 \right)}{\left(1 + \frac{\gamma - 1}{2} M_2^2 \right)} \right] \frac{p_{t_2}}{p_{t_1}}
$$

\[\frac{A}{B} = \frac{p_{t_2}}{p_{t_1}}\] (4.13)

• Subtract the two RH terms,

$$
\frac{s_2 - s_1}{R} = - \ln \frac{p_{t_2}}{p_{t_1}}
$$

• From the 2nd Law of Thermodynamics with and for a fixed normal shock,

$$
\frac{p_{t_2}}{p_{t_1}} = \frac{p_{t_2} p_1}{p_2 p_{t_1}}
$$
4.3 Equations of Motions for a Normal Shock Wave

• Which can be rewritten as,

\[
\frac{p_{t_2}}{p_{t_1}} = \left(1 + \frac{\gamma - 1}{2} M_2^2\right)^{\frac{\gamma}{\gamma - 1}} \left(\frac{2\gamma M_1^2}{\gamma + 1} - \frac{\gamma - 1}{\gamma + 1}\right) \frac{1}{\left(1 + \frac{\gamma - 1}{2} M_1^2\right)^{\frac{\gamma}{\gamma - 1}}}
\]

• Substituting for M2 from eq (4.8)

\[
M_2^2 = \frac{M_1^2 + \frac{2}{\gamma - 1}}{\gamma - 1} - \frac{2\gamma}{\gamma - 1} M_1^2 - 1
\]

therefore,

\[
\frac{p_{t_2}}{p_{t_1}} = \left[\frac{\gamma + 1}{2} M_1^2 \right]^{\frac{\gamma}{\gamma - 1}} \left[\frac{1}{\gamma + 1} \frac{2\gamma}{\gamma + 1} M_1^2 - \frac{\gamma - 1}{\gamma + 1}\right]^\frac{1}{(\gamma - 1)}
\]

(4.14)
4.3 Equations of Motions for a Normal Shock Wave

- For an adiabatic process, the stagnation pressure represents a measure of the available flow energy.
- A decrease in $p_{total}$ or an increase entropy denotes the dissipation of energy (loss of available energy).
- This eq has also been tabulated in the normal shock tables for $\gamma = 1.4$

### Example 4.1

An air stream with a velocity of 500 m/s, a static pressure of 50 kPa, and static temperature of 250 K, undergoes a normal shock. Determine the air velocity, static and stagnation conditions after the wave.
4.3 Equations of Motions for a Normal Shock Wave
4.3 Equations of Motions for a Normal Shock Wave

- Recall for an isentropic flow, the area at which $M = 1$ was defined as $A^*$. Since a normal shock is not isentropic; if a shock occurs in a channel (fig 4.12), the flow areas downstream of the shock (2 to e) cannot be referred to with the same $A^*$ value as the flow from i to 1. In other words.
4.3 Equations of Motions for a Normal Shock Wave

Applying the conservation of mass between we get

\[ \dot{m}_{A_i^*} = \dot{m}_{A_e^*} \]  

(Eq 3.9)

Therefore,

\[ \frac{p_{t1} A_{i1}^*}{\sqrt{T_{t1}}} f(\gamma, M) = \frac{p_{t2} A_{e2}^*}{\sqrt{T_{t2}}} f(\gamma, M) \]

Recall \( M = 1 @ A_{i1}^* \) and @ \( A_{e2}^* \)

So since the shock is assumed to be adiabatic, \( T_{t1} = T_{t2} \), thus;

\[ p_{t1} A_{i1}^* = p_{t2} A_{e2}^* \]  

(4.15)

Example 4.2:

An air stream @ \( M_i = 2.0 \), pressure of 100 kPa & temperature of 270K enters a diverging channel, \( A_e / A_i = 3 \).

\[ A_1 = 2 A_i \]
\[ A_e = 3 A_i \]

Determine the back pressure necessary to produce a normal shock in the diverging part of the channel @ \( A_1 \).

Assume 1-D, steady flow of an ideal gas undergoing isentropic flow, except at the shock.

Let, \( \gamma = 1.4 \)
4.3 Equations of Motions for a Normal Shock Wave
4.3 Equations of Motions for a Normal Shock Wave

--- The End ---
4.3 Equations of Motions for a Normal Shock Wave

Example 4.3: A rocket nozzle has an ratio of exit to throat areas of 4.0. Exhaust gases are generated in the combustion chamber with $p_i = 3$ MPa and $T_i = 1500$K.

Assume the exhaust-gas mixture to behave as a perfect gas having a molecular mass of 20. Determine the rocket exhaust velocity for isentropic nozzle flow & for the case where a normal shock is located just inside the nozzle exit plane.

Solution:

\[\text{Figure 4.14a}\]
4.3 Equations of Motions for a Normal Shock Wave

--- The End ---

4.4 Moving Normal Shock Wave

Moving shocks arise in situations such as when:

a) a blunt body reenters the atmosphere, a bow wave is set up and travels a short distance ahead of the body,

b) an explosion, which transmits a shock from the point of the detonation, or

c) ignition of a spark plug in a internal combustion engine.

266. Sphere at $M=1.53$. A shadowgraph catches a $\frac{1}{2}$-inch sphere in free flight through air. The flow is subsonic behind the part of the bow wave that is ahead of the sphere, and over its surface back to $45^\circ$. At about $90^\circ$ the laminar boundary layer separates through an oblique shock wave, and quickly becomes turbulent. The fluctuating wake generates a system of weak disturbances that merge into the second shock wave. Photograph by A. C. Charters
4.4 Moving Normal Shock Wave

- Consider a fixed observer, and a normal shock moving at constant velocity into air at rest. The observer sees an unsteady flow.

\[ V_s \]  
\[ V_g \]

**Figure 4.15a**

- where \( V_s \) and \( V_g \) are the velocities measured w.r.t. the observer.
\[ V_s = \text{absolute shock velocity} \]
\[ V_g = \text{velocity of gases behind shock} \]

Note: the flow is not steady

4.4 Moving Normal Shock Wave

- Now consider the observer moving @ the shock velocity, (i.e., the observer is sitting on the shock wave) so the shock is now fixed w.r.t. the observer.

\[ V_s - V_g \]

**Figure 4.15b**

- To apply the equations of motion for a stationary shock to a moving shock, one must consider the effect of observer velocity on the static & stagnation properties.

- Static properties - those properties measured by an instrument moving at the absolute flow velocity.
4.4 Moving Normal Shock Wave

- That is the relative velocity between a measurement transducer and the local fluid is zero. Thus static properties are independent of the observer velocity.

Hence the static properties can be equated as follows:

\[ \frac{p_2}{p_1} = \frac{p_b}{p_a} \quad \text{and} \quad \frac{T_2}{T_1} = \frac{T_b}{T_a} \]

- If \( T_1 = T_a \) and \( p_1 = p_a \), it is evident from the isentropic flow equations that;

\[ T_{t_1} > T_{t_a} \quad \text{and} \quad p_{t_1} > p_{t_a} \]

- Since the gas in condition "1" has a velocity \( V_s \) and the gas in condition "a" has zero velocity.

- That is the relative velocity between a measurement transducer and the local fluid is zero. Thus static properties are independent of the observer velocity.

4.4 Moving Normal Shock Wave

- Stagnation properties - are dependent on the observer velocity.

- Therefore to calculate the variation in stagnation properties across a moving shock wave, both static conditions and velocities must be known.
4.4 Moving Normal Shock Wave

Example 4.4:
A shock moves @ a constant velocity \( V_s = 500 \text{ m/s} \) into still air, \( p_a = 100 \text{ kPa} \) and \( T_a = 0\text{EC} = 273 \text{ K} \).

Determine the static and stagnation conditions present in the air after passage of the wave, as well as the gas velocity behind the wave.

Solution:

\[ V_g \]

\[ 500 \text{ m/s} \]

Fig 4.16 a
4.4 Moving Normal Shock Wave
4.4 Moving Normal Shock Wave

- From eq 4.12, for a fixed shock,

\[ \frac{V_1}{V_2} = \frac{(\gamma+1)M_i^2}{(\gamma-1)M_i^2 + 2} \]

where

\[ V_1 = V_s \quad \text{&} \quad V_2 = (V_s - V_g) \]

- Substituting yields

\[ \frac{V_s}{V_s - V_g} = \frac{(\gamma+1)\frac{V_s^2}{a_s^2}}{(\gamma-1)\frac{V_g^2}{a_s^2} + 2} \]

Now consider the case in which the gas velocity behind the wave is given & the shock velocity is to be determined for a shock moving into a gas at rest (fig 4.17).
4.4 Moving Normal Shock Wave

Cross multiplying gives
\[
\frac{(V_s - V_g)(\gamma + 1)V_s}{a_1^2} = \frac{\gamma - 1}{\gamma} \frac{V_g^2}{a_1^2} + 2
\]

Expanding terms,
\[
\frac{(\gamma + 1)V_s^2}{a_1^2} - \frac{(\gamma + 1)V_g V_s}{a_1^2} = \frac{\gamma - 1}{\gamma} \frac{V_g^2}{a_1^2} + 2
\]
\[
\frac{2V_s^2}{a_1^2} - \frac{(\gamma + 1)V_g V_s}{a_1^2} - 2 = 0
\]

Solve the quadratic equation for :
\[
V_s = \frac{\gamma + 1}{4a_1^2} \pm \sqrt{\frac{(\gamma + 1)^2 V_g^2}{a_1^4} + \frac{16}{a_1^2}}
\]

Example 4.5: A piston in a tube is suddenly accelerated to a velocity of 50 m/s, which causes normal shock to move into the air at rest within the tube. Several seconds later, the piston is suddenly accelerated to from 50 to 100 m/s, which causes a 2nd shock to move down the tube.

Find the velocities of the two shock waves for an initial $T_{\text{air}}=300$K.

Solution:

\[
V_s = \frac{\gamma + 1}{4} \pm \sqrt{\frac{(\gamma + 1)^2 V_g^2}{4} + \frac{a_1^2}{16}}
\]

(4.16)

Figure 4.18
4.4 Moving Normal Shock Wave
4.4 Moving Normal Shock Wave

--- The End ---

4.5 Reflected Normal Shock Waves

- When a shock wave impinges on the end of a tube (or hits a wall), fig 4.20a or enters the atmosphere, a reflected wave is generated, fig 20b.

<table>
<thead>
<tr>
<th>Incident shock</th>
<th>Incident shock</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_g$</td>
<td>$V_{fl}$</td>
</tr>
<tr>
<td>$V_g$</td>
<td>$V_{wr}$</td>
</tr>
<tr>
<td>Case (a) Closed tube</td>
<td>Case (b) Tube open to the atmosphere</td>
</tr>
</tbody>
</table>

figure 4.20
4.4 Moving Normal Shock Wave

- Let's examine both cases and determine whether the reflected wave is a compressive shock or a series of weak expansion waves.

- **Case I:** The gas next to the fixed end of the tube is at rest and the gas behind the incident shock is moving to the right with velocity \( V_g \).

- For an observer moving with the reflected wave (in Fig. 4.21), a velocity decrease across the reflected wave is indicated.

- Therefore, a normal shock reflects from the closed tube as a normal shock.

4.4 Moving Normal Shock Wave

- **Case II:** The boundary condition imposed on the system is the static pressure at the end of the tube.

- From Fig. 20b we see a decrease in pressure across the reflected wave. A normal shock reflects from an open end of a tube as a series of expansion waves.
4.4 Moving Normal Shock Wave

Example 4.6: A normal shock with a pressure ratio of 4.5 impinges on a plane wall (fig 4.22). In front of the incident wave the air $T = 20°C = 293K$.

Determine the static pressure ratio of the reflected normal shock.

---

4.4 Moving Normal Shock Wave
4.4 Moving Normal Shock Wave

--- The End ---