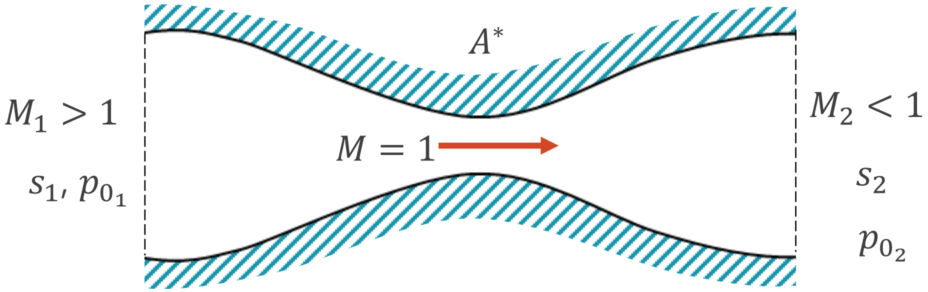
Diffusers and Wind Tunnels

Internal Compressible Flows – Lesson 5

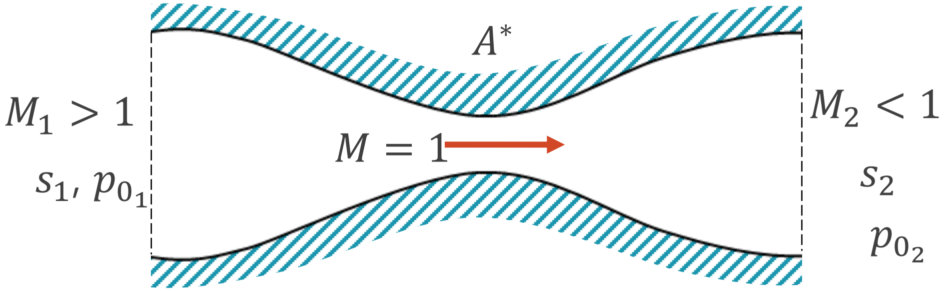
Intro

- Any duct designed to slow down an incoming gas flow to a lower velocity is called a *diffuser*.
- Incoming flow can be either subsonic or supersonic based on the application.
- A *diffuser* is designed such that the *loss in total pressure is minimal* during the slowing down of the flow.
- Diffusers are commonly used in propulsion systems such as air breathing engines, rocket engines etc.
- Diffusers are also integral components in many wind tunnel designs.



Ideal vs. Real Diffuser

- An *ideal diffuser* is one in which the incoming flow is slowed by an isentropic compression to lower velocities.
- The supersonic flow entering the diffuser at M_1 is isentropically compressed in a convergent duct to Mach 1 at the throat ($area = A^*$) and is then further isentropically compressed in a divergent duct to a low subsonic Mach number at the exit.
- However, in the converging portion of the diffuser, the flow will generate oblique shocks as the supersonic flow is turned into itself.
- Due to viscosity, there will be an entropy increase within the boundary layers on the walls of the diffuser.
- For this reason, an ideal diffuser can never be constructed for engineering applications.

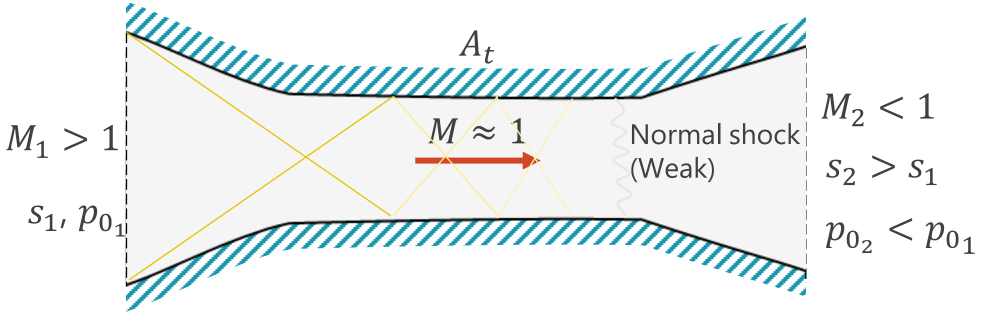


$$s_2 = s_1$$

$$p_{0,2} = p_{0,1}$$

Ideal vs. Real Diffuser (cont.)

- An *actual supersonic diffuser* slows down an incoming flow by a series of reflected oblique shocks in the convergent section and the throat (usually in the form of a constant area section).
- Interaction of shock waves with the viscous flows near the wall weakens and diffuses the reflected shock patterns, which ends up in the form of a weak normal shock wave at the end of the constant area throat.
- The subsonic flow downstream of the throat is subsequently slowed down via a diverging section.
- As the flow is no longer isentropic, the entropy at the exit is higher and the total pressure is lower.
- Design problem of a diffuser - *design the converging, constant area and the diverging section to obtain the desired exit Mach number with the least possible total pressure loss.* (In other words, trying to keep $p_{0,2}/p_{0,1}$ as close to unity as possible.)



$$s_2 > s_1$$

$$p_{0,2} < p_{0,1}$$

Note that due to entropy increase across shock waves and boundary layers, the real diffuser throat area, $A_t > A*$

Wind Tunnel Design and The Role of Diffusers

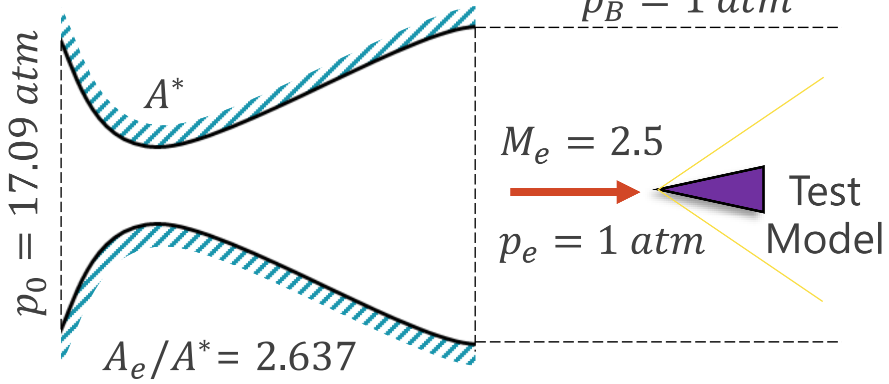
- Let's assume we want to create a uniform Mach 2.5 flow for an experiment. We need a converging-diverging nozzle with an area ratio $A_e/A^* = 2.637$ and we need to establish a pressure ratio of $p_0/p_e = 17.09$ across this nozzle for a shock-free expansion to $M_e = 2.5$ at the exit.

- If we exhaust the nozzle directly into the laboratory, the Mach 2.5 flow passes on to the test model as a free jet as shown.

- For the free jet to not have any shock or expansion waves, the nozzle exit pressure p_e must be equal to the back pressure p_B.

- As the back pressure is the atmospheric pressure in the lab, $p_B = p_e = 1$ atm, implying that at the inlet we would need a pressure of $p_0 = 17.09$ atm.

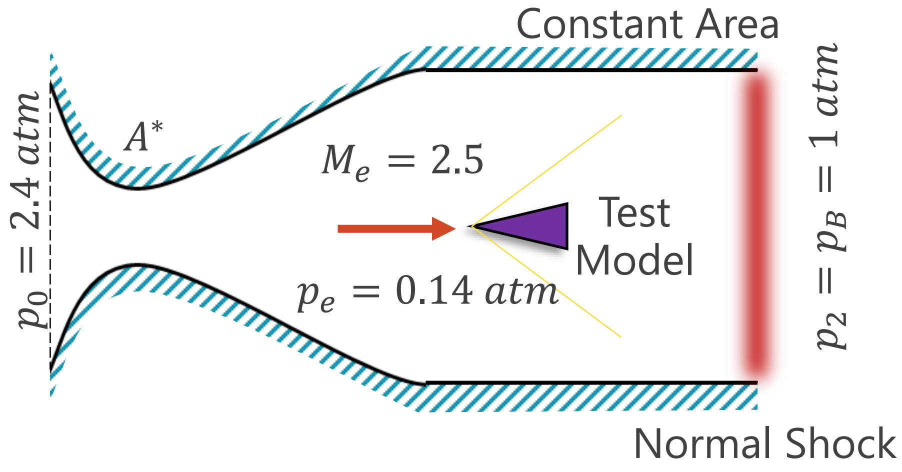
- This setup would be very expensive to build and operate due to the higher cost associated with such high-pressure devices and storage systems.



Nozzle exhausting directly into the atmosphere

Normal Shock Diffuser

- Let's change the setup so that the nozzle exits the flow into a constant area section instead of a free jet into the laboratory as shown here.
- The constant area section contains a normal shock wave standing at the end of the constant-area section.
- As a result, the pressure downstream of the normal shock wave is $p_2 = p_B = 1\ atm$. At $M = 2.5$, the static pressure ratio across the shock will be $p_2/p_e = 7.125$.
- Thus, $p_e = 0.14\ atm$ at the nozzle exit. In order to ensure proper isentropic flow through the nozzle, requiring a pressure ratio of $p_0/p_e = 17.09$, we would now need a reservoir with a pressure of only $2.4\ atm$!
- This is considerably less than 17.09 atm required in the previous design.
- The normal shock wave acts as a diffuser by slowing the air at $M = 2.5$ to the subsonic value of $M = 0.513$ behind the shock.



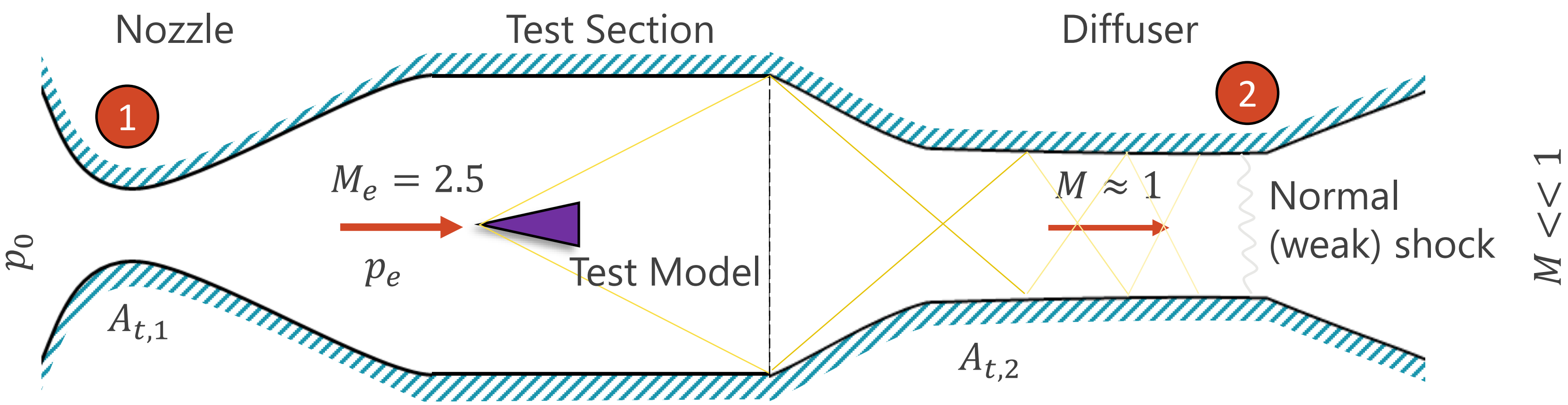
Nozzle exhausting into a constant area duct with a normal shock at the exit

Normal Shock Diffuser (cont.)

- The addition of the diffuser allows us to produce the required $M = 2.5$ flow more efficiently. However, this approach has some problems:
  - A normal shock is the strongest possible shock and creates the largest pressure loss. Replacing it with weaker shocks can help reduce the total pressure loss and the required reservoir pressure p_0.
  - Flow unsteadiness and instabilities cause the normal shock to move and fluctuate constantly. This would give rise to uncertainty about the quality of the flow in the constant-area duct.
  - The introduction of the test model in the test section would cause oblique waves from the model to propagate downstream, making the flow three-dimensional and causing the normal shock to vanish.

Oblique Shock Diffuser

- Replacing the normal shock diffuser with an oblique shock diffuser as shown, we have a converging-diverging diffuser which slows the flow down to a low subsonic speed.



- This arrangement is referred to as a *supersonic wind tunnel*. The main source of pressure loss in a supersonic wind tunnel is the diffuser.

- Reducing the velocity of a supersonic flow progressively via consecutive oblique shocks to a low supersonic value and further reducing it to subsonic speeds across a normal shock results in a smaller total pressure loss compared to a single strong normal shock.

- An oblique shock diffuser is usually more efficient than a normal shock diffuser. However, the presence of shock wave–boundary layer interactions and the skin friction exerted on the surface adds to inefficiencies.

Two Throats of a Supersonic Wind Tunnel

- As seen from the schematic, the supersonic wind tunnel has two throats:
  - Nozzle throat with area $A_{t,1}$ called the first throat
  - Diffuser throat with area $A_{t,2}$ called the second throat

- For steady flow through the wind tunnel:

$$\dot{m} = \rho_1^* V_1^* A_{t,1} = \rho_2 V_2 A_{t,2}$$

- Since the thermodynamic state of the gas is irreversibly changed when going through shock waves, the properties at the two locations will differ and thus the two throats must have different areas.

- Assuming sonic flow at both stations 1 and 2, we can get the following relation using the isentropic equations:

$$\frac{A_{t,2*}}{A_{t,1}} = \frac{p_{0,1}}{p_{0,2}}$$

- As the total pressure always decreases across shock waves, $p_{0,2} < p_{0,1}$, the second throat must always be larger than the first throat, $A_{t,2*} > A_{t,1}$.

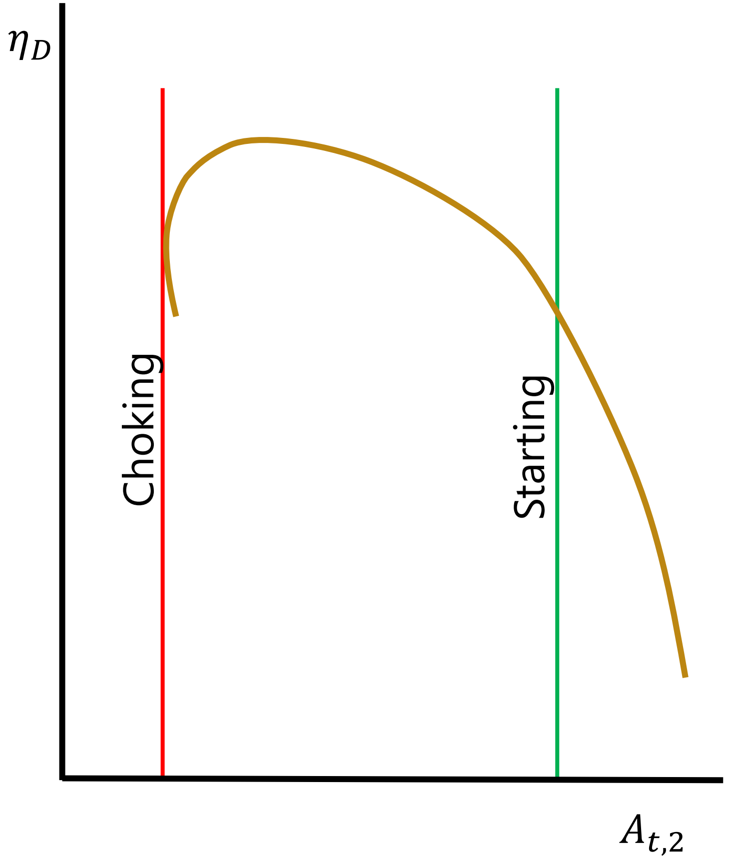
Efficiency of Diffusers

- The efficiency of a diffuser can be evaluated based on several figures of merit.

- The most commonly used definition (related to wind tunnel work) is based on the comparison of the actual total pressure ratio across the diffuser p_{d_0}/p_0, with the total pressure ratio across a hypothetical normal shock wave at the test section Mach number p_{0_2}/p_{0_1}:

$$\eta_D = \frac{\left(p_{d_0}/p_0\right)_{actual}}{\left(p_{0_2}/p_{0_1}\right)_{normal\ shock\ at\ M_e}}$$

- For typical supersonic diffusers, the efficiency η_D is very sensitive to the second throat area $A_{t,2}$ as shown in the plot.
  - As $A_{t,2}$ decreases from a large value, η_D first increases up to a peak value and then rapidly decreases.
  - The peak efficiency is obtained by a value of $A_{t,2}$ slightly larger than the value obtained from the equation on previous slide ($A_{t,2*}$).
  - Below $A_{t,2*}$ the flow is choked, and the efficiency drops significantly.



The Starting Problem

- When the flow through a wind tunnel is first started, a complicated transient flow pattern is established, which, after some time, settles to a steady flow as we have discussed in this lesson.

- In most cases, the starting process is usually accompanied by a normal shock wave traversing the entire duct – from the nozzle entrance to the diffuser exit.

- When this starting shock wave is at the inlet to the diffuser, the second throat area must be large enough to allow the passage of the mass flow behind a normal shock. This value is given by $A_{t,2*}$ corresponding to the total pressure ratio across a normal shock at the test section Mach number, $p_{0,2}/p_{0,1}$.
  - This starting value of throat area is always larger than that corresponding to the peak efficiency.
  - If $A_{t,2}$ is less than this starting value, the normal shock will remain upstream of the diffuser, and the wind tunnel will not start properly.
  - If $A_{t,2}$ is equal to or more than this value then the normal shock will proceed through the diffuser section and the wind tunnel will start properly.

- This is the reason why many advanced wind tunnels use variable-geometry diffusers.

Summary

- In this lesson we analyzed flows through diffusers and wind tunnels where diffusers play a vital role.
- We looked at the differences between an idealized and a real diffuser.
- We also looked at the two throats of a supersonic wind tunnel and how they give rise to the starting problem and the means with which it can be addressed.

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