University of Jordan
Chemical Engineering Department
Chemical Engineering Thermodynamics (1) – 905322

Lecture 6: Applications of the First Law

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Outline

- Balance equations.
- Mixing/splitting chambers.
- Heat exchangers.
- Throttling valves.
- Turbines, compressors, fans and pumps.
- Nozzles and diffusers.

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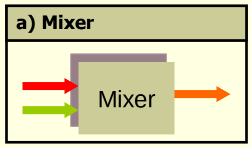
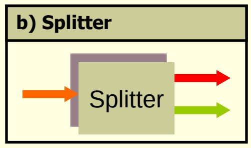
Mixers and Splitters

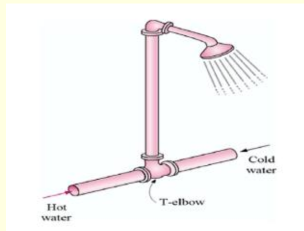
- The section where a mixing process occurs is called a mixer. The section at which a splitting process occurs is called a splitter.
- Characteristics
  - Negligible Q, W, PE, and KE.

$$\Delta H = 0$$

$$H_{\text{out}} = H_{\text{in}}$$







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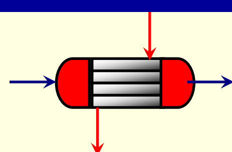
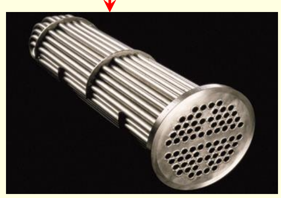
Heat Exchangers (HX)

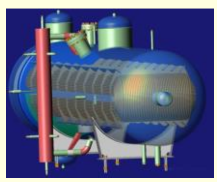
- Heat exchangers are devices where two moving fluid streams exchange heat without mixing.
- The heat exchanged may be sensible heat or phase change heat.
- Negligible W, PE, and KE.
- On one side,

$$\Delta H = H_{\text{out}} - H_{\text{in}} = \dot{Q}$$

An idealized HX is assumed to be isobaric on each side i.e., pressure drop is set to zero.



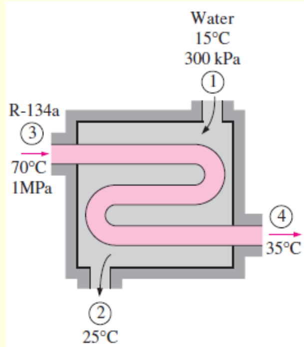




Refrigerant-134a is to be cooled by water in a condenser. The refrigerant enters the condenser with a mass flow rate of 6 kg/min at 1 MPa and 70°C and leaves at 35°C. The cooling water enters at 300 kPa and 15°C and leaves at 25°C. Neglecting any pressure drops, determine (*a*) the mass flow rate of the cooling water required and (*b*) the heat transfer rate from the refrigerant to water.

Mass balance: $\dot{m}_{in} = \dot{m}_{out}$

$\dot{m}_1 = \dot{m}_2 = \dot{m}_w$ $\dot{m}_3 = \dot{m}_4 = \dot{m}_R$



Energy balance:

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{dE_{system}/dt}_{\text{Rate of change in internal, kinetic, potential, etc., energies}} \overset{0 \text{ (steady)}}{=} 0$$

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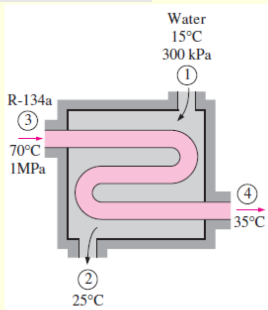
$\dot{E}_{in} = \dot{E}_{out}$

$\dot{m}_1 h_1 + \dot{m}_3 h_3 = \dot{m}_2 h_2 + \dot{m}_4 h_4$ (since $\dot{Q} \cong 0$, $\dot{W} = 0$, ke $\cong$ pe $\cong 0$)

$\dot{m}_w (h_1 - h_2) = \dot{m}_R (h_4 - h_3)$



For Water

$h_1 \cong h_{f\,@\,15°C} = 62.982$ kJ/kg
$h_2 \cong h_{f\,@\,25°C} = 104.83$ kJ/kg (Table A–4)

Compressed liquid

The refrigerant

$\left.\begin{array}{l} P_3 = 1 \text{ MPa} \\ T_3 = 70°C \end{array}\right\}$ $h_3 = 303.85$ kJ/kg (Table A–13)

$\left.\begin{array}{l} P_4 = 1 \text{ MPa} \\ T_4 = 35°C \end{array}\right\}$ $h_4 \cong h_{f\,@\,35°C} = 100.87$ kJ/kg (Table A–11)

Compressed liquid

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$$\dot{m}_w(62.982 - 104.83)\ \text{kJ/kg} = (6\ \text{kg/min})[(100.87 - 303.85)\ \text{kJ/kg}]$$

$$\dot{m}_w = \mathbf{29.1\ kg/min}$$

(*b*)

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\substack{\text{Rate of net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{dE_{system}/dt}_{\substack{\text{Rate of change in internal, kinetic,}\\ \text{potential, etc., energies}}}\overset{\nearrow 0\ \text{(steady)}}{} = 0$$

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{Q}_{w,\,in} + \dot{m}_w h_1 = \dot{m}_w h_2$$

$$\dot{Q}_{w,\,in} = \dot{m}_w(h_2 - h_1) = (29.1\ \text{kg/min})[(104.83 - 62.982)\ \text{kJ/kg}]$$

$$= \mathbf{1218\ kJ/min}$$

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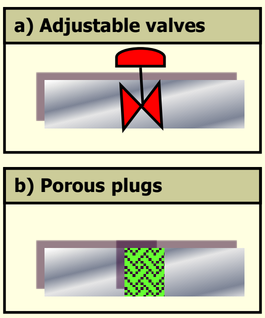
Throttling Processes

- Throttling valves are any kind of flow-restricting devices that causes appreciable pressure drop in the fluid stream.
  - Pressure drop (expansion) is usually accompanied by drop in the temperature.
    - **Ideal gas is an exception since its temperature will remain the same.**
  - If a saturated liquid is throttled to a lower pressure, some of the liquid vaporizes or flashes, producing a mixture of saturated liquid and saturated vapor at the lower pressure.
  - Throttling of “wet” steam to sufficiently low pressure may cause the liquid to evaporate, or the vapor to become superheated.



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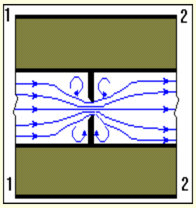
Analysis of Throttling Processes

- Negligible Q.
- Negligible W.
- Negligible PE.
- Negligible KE.
- Expansion occurs at constant enthalpy (**isenthalpic**).

$$\Delta H = 0$$
$$H_{out} = H_{in}$$



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Refrigerant-134a enters the capillary tube of a refrigerator as saturated liquid at 0.8 MPa and is throttled to a pressure of 0.12 MPa. Determine the quality of the refrigerant at the final state and the temperature drop during this process.

At inlet: $P_1 = 0.8\text{ MPa}$, sat. liquid $\quad T_1 = T_{sat\,@\,0.8\text{ MPa}} = 31.31°C$, $h_1 = h_{f\,@\,0.8\text{ MPa}} = 95.47\text{ kJ/kg}$ (Table A–12)

At exit: $P_2 = 0.12\text{ MPa}$ $(h_2 = h_1)$ $\longrightarrow$ $h_f = 22.49\text{ kJ/kg}$, $h_g = 236.97\text{ kJ/kg}$, $T_{sat} = -22.32°C$

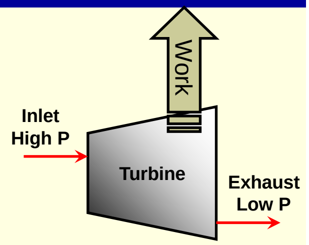
$$h_f < h_2 < h_g;$$

$$x_2 = \frac{h_2 - h_f}{h_{fg}} = \frac{95.47 - 22.49}{236.97 - 22.49} = \mathbf{0.340}$$

$$\Delta T = T_2 - T_1 = (-22.32 - 31.31)°C = \mathbf{-53.63°C}$$

Turbines

- A turbine is a device to **produce work** (drives the electric generator) by reducing the pressure of the working fluid.
  - The turbine is most commonly found in gas, steam and hydroelectric power plants.
  - **Inlet stream** is called **driving fluid**,
  - **Outlet stream** is called the **exhaust**.



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Analysis of Turbines

- Negligible Q & PE.
- KE has an influence, but usually negligible compared to enthalpy changes.
- Work is negative W<0 (extracted from the system).
- Energy balance

$$\dot{W}_s = \Delta H = H_{out} - H_{in}$$

- Isentropic processes means that they are reversible adiabatic ($S_{out}=S_{in}$).

An idealized turbine is assumed to be isentropic i.e., entropy at the inlet is the same as that at the outlet

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Analysis of Turbines (2)

- The **isentropic** shaft work ($\dot{W}_s$) is the **maximum** that can be obtained from an **adiabatic** turbine.

$$\dot{W}_s\,(\text{isentropic}) = (\Delta H)_S$$

- Actual work produced by the turbine ($\dot{W}$) is less than the isentropic ($\dot{W}_s$) work.
- Turbine efficiency (range 0.7 – 0.8)

$$\eta = \frac{\dot{W}}{\dot{W}_s\,(\text{isentropic})} = \frac{\Delta H}{(\Delta H)_S}$$

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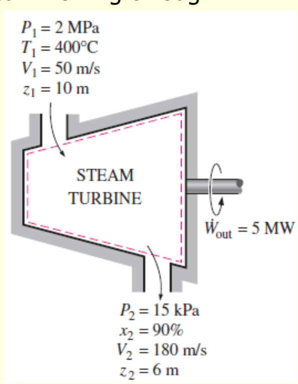
The power output of an adiabatic steam turbine is 5 MW, and the inlet and the exit conditions of the steam are as shown

a. Compare the magnitudes of Δh, Δ ke, and Δ pe.
b. Determine the work done per unit mass of the steam flowing through the turbine.
c. Calculate the mass flow rate of the steam.



Steady-flow process

$$\Delta m_{CV} = 0 \text{ and } \Delta E_{CV} = 0.$$

1. At the inlet,

$$\left.\begin{aligned} P_1 &= 2\text{ MPa} \\ T_1 &= 400°\text{C} \end{aligned}\right\}$$

Steam is in a superheated vapor state,

$$h_1 = 3248.4 \text{ kJ/kg} \qquad \text{(Table A–6)}$$

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2. At the turbine exit

Saturated liquid–vapor mixture at 15-kPa pressure.

$$h_2 = h_f + x_2 h_{fg} = [225.94 + (0.9)(2372.3)]\ \text{kJ/kg} = 2361.01\ \text{kJ/kg}$$

$$\Delta h = h_2 - h_1 = (2361.01 - 3248.4)\ \text{kJ/kg} = \mathbf{-887.39\ kJ/kg}$$

$$\Delta \text{ke} = \frac{V_2^2 - V_1^2}{2} = \frac{(180\ \text{m/s})^2 - (50\ \text{m/s})^2}{2}\left(\frac{1\ \text{kJ/kg}}{1000\ \text{m}^2/\text{s}^2}\right) = \mathbf{14.95\ kJ/kg}$$

$$\Delta \text{pe} = g(z_2 - z_1) = (9.81\ \text{m/s}^2)[(6 - 10)\ \text{m}]\left(\frac{1\ \text{kJ/kg}}{1000\ \text{m}^2/\text{s}^2}\right) = \mathbf{-0.04\ kJ/kg}$$

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$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{dE_{system}/dt}_{\substack{\text{Rate of change in internal, kinetic,} \\ \text{potential, etc., energies}}} \nearrow^{0\ \text{(steady)}} = 0$$

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{m}\left(h_1 + \frac{V_1^2}{2} + gz_1\right) = \dot{W}_{out} + \dot{m}\left(h_2 + \frac{V_2^2}{2} + gz_2\right) \qquad (\text{since } \dot{Q} = 0)$$

Dividing by the mass flow rate $\dot{m}$

$$w_{out} = -\left[(h_2 - h_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)\right] = -(\Delta h + \Delta \text{ke} + \Delta \text{pe})$$

$$= -[-887.39 + 14.95 - 0.04]\ \text{kJ/kg} = \mathbf{872.48\ kJ/kg}$$

The required mass flow rate

$$\dot{m} = \frac{\dot{W}_{out}}{w_{out}} = \frac{5000\ \text{kJ/s}}{872.48\ \text{kJ/kg}} = \mathbf{5.73\ kg/s}$$

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Compressors

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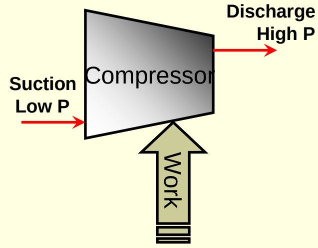
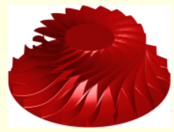
- The compressor is a device to increase the pressure of a gas stream.
  - The **inlet stream is called the suction**, while the **outlet stream is called the discharge**.
  - The ratio between the pressures on the discharge and suction is called the **compression ratio**.
  - To achieve high compression ratios, compressors are operated in a multistage operation with inter-cooling.
  - Typical compression ratios are in the order of 3 for a single stage.





Analysis of Compressors

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- Negligible Q, PE, and KE.
- Work is positive $W>0$ (imparted upon the system).
- Energy balance

$$\dot{W}_s = \Delta H = H_{\text{out}} - H_{\text{in}}$$

- The **isentropic** shaft work (W_s) is the **minimum** that can be supplied to an **adiabatic** compressor.

$$\dot{W}_s\,(\text{isentropic}) = (\Delta H)_S$$

An idealized compressor is assumed to be isentropic
i.e., entropy at the inlet is the same as that at the outlet

Analysis of Compressors (2)

- Actual compressors require work (W) greater than isentropic (W_s).
- Compressor efficiency (range 0.7 – 0.8)

$$\eta = \frac{\dot{W}_s\,(\text{isentropic})}{\dot{W}} = \frac{(\Delta H)_S}{\Delta H}$$

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A natural gas stream available at 1 bar and 180 K is to be used to produce liquefied methane. The compressed stream will be leaving the cooler at 180 K. The flash drum is adiabatic and operates at 1 bar, and each compressor stage can be assumed to operate reversibly and adiabatically. The compression ratio is the same in each compression stage and is equal to 5. Between each stage the gas is to be isobarically cooled to 180 K. (**Use the provided chart for methane**)

1) How many stages of compression are required for an outlet pressure from the cooler of 125 bars?
2) Calculate the amount of work required for each kilogram of methane that passes through the compressor in the simple liquefaction process.
3) Calculate the fractions of vapor and liquid leaving the flash drum in the simple liquefaction process and the amount of compressor work required for each kilogram of LNG produced.
4) What is the maximum permissible operating temperature out from the cooler?
5) Assuming that the recycled methane leaving the heat exchanger in the Linde process is at 1 bar and 180 K, calculate the amount of compressor work required per kilogram of LNG produced.

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Assumptions

1. Isentropic compression.
2. Equal compression ratio within compression stages.
3. Isobaric cooling and heat exchange.
4. Isenthalpic throttling valve.
5. Adiabatic flash drum.
6. No heat transfer or pressure drop through the pipes of the process.
7. Methane properties are described by the provided chart.

Solution

1. Since the outlet pressure is 125 bar and the compression ratio is the same and equal 5 then the number of stages is

$$(r)^n = (5)^n = 125 = 5^3 \Rightarrow n = 3$$

2. The amount of work is calculated by stepping in the chart isentropically for the compression stages and isobarically for the cooling stages.

$$W = W_1 + W_2 + W_3$$
$$= (900-730) + (880-720) + (800-650)$$
$$= 480 \text{ kJ/kg feed natural gas.}$$

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3. The liquid fraction is about 0.5 using the isenthalpic expansion for the valve and flash drum section i.e., 50% of the feed is liquefied. Therefore the amount of work is 1040 kJ/kg LNG produced.
4. The maximum permissible temperature out of the cooler is the maximum temperature that will let the expansion process produce a stream in the two phase region i.e., saturated vapor at 1 bar and the same enthalpy coming out of the cooler. Using the chart again yields that the temperature is about 235 K.
5. The Linde process calculations are done around two sections (using the notation in the flowsheet in the lecture)

$$H_3 = x_L H_6 - (1-x_L) H_{5'}$$
$$320 = x_L(90) + (1-x_L)(720) \Rightarrow x_L = 0.635.$$

The work per kilogram feed is the same as that in the simple process. However, the feed in the Linde process is the same as the product. Consequently, the work per kilogram LNG is given as

$$W_{\text{Linde}} = \frac{480}{0.635} = 756 \text{ kJ/kg LNG.}$$

Notice that the Linde process increased the liquid fraction by about 27% while reducing the compressor work duty by about 25%.

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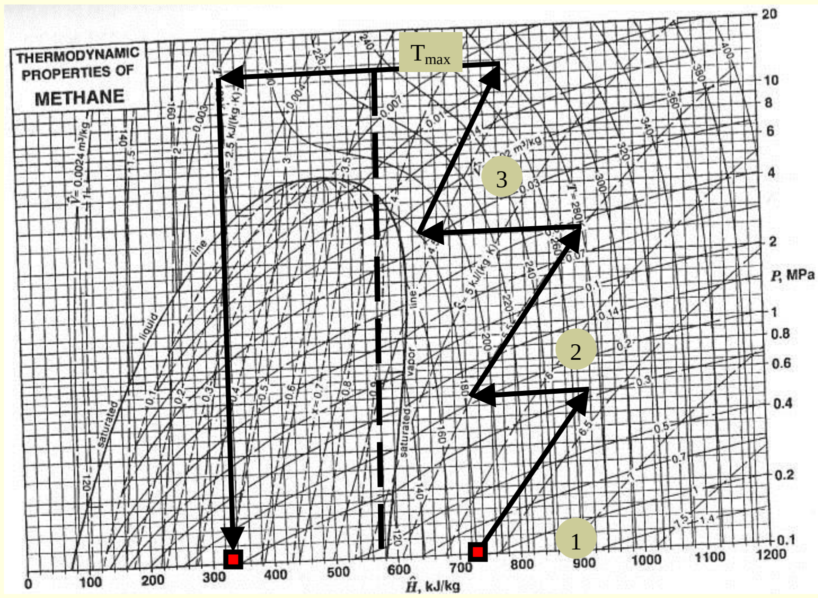

Obtain the power of the compressor required to compress a methane gas stream from 1 bar to 10 bar. The feed stream is at 200K.

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Compression of Ideal Gases

- Assume that the gas to be compressed is an ideal gas with constant heat capacity

$$T_2^{'} = T_1 \left(\frac{P_2}{P_1}\right)^{R/C_P}$$

$$\dot{W}_s\,(\text{isentropic}) = C_P\left(T_2^{'} - T_1\right) = C_P T_1\left[\left(\frac{P_2}{P_1}\right)^{R/C_P} - 1\right]$$

- For a nonisentropic case

$$T_2 = T_1 + \frac{T_2^{'} - T_1}{\eta}$$

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- Use the methane chart to obtain the power of the compressor required to compress a methane gas stream from 1 bar to 100 bar. The feed stream is at 300K.

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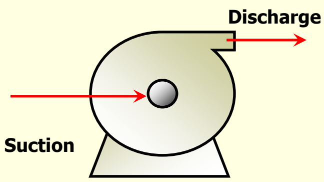
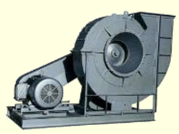
Fans or Blowers

- The fan or a blower are devices used to **slightly** increase the pressure of a gas stream, and mainly to mobilize it.
  - The **inlet stream is called the suction**, while the **outlet stream is called the discharge**.
  - Work is positive $W>0$ (imparted upon the system).
- Characteristics
  - Same as compressors, with lower compression ratios.





Pumps

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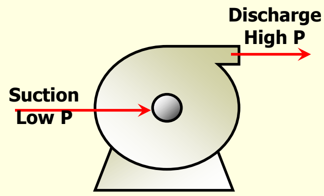
- The pump is device used to increase the pressure of a liquid stream.
  - The pump is the counterpart of a compressor for liquids.
  - The **inlet stream is called the suction**, while the **outlet stream is called the discharge**.
  - Work is positive $W>0$ (imparted upon the system).

An idealized pump is assumed to be isentropic i.e., entropy at the inlet is the same as that at the outlet



Analysis of Pumps

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- Negligible Q, PE, and KE.
- Energy balance (**isentropic**)

$$\dot{w}_S\,(\text{isentropic}) = (\Delta h)_S = v(P_2 - P_1)$$

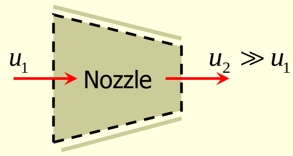
- To a good approximation

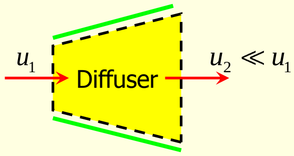
$$\Delta h = c_P \Delta T + v\Delta P(1-\beta T)$$

$$\Delta s = c_P \ln\frac{T_2}{T_1} - \beta v \Delta P$$

Nozzles and Diffusers

- A nozzle is a device which increases the velocity of a fluid at the expense of pressure.
- A diffuser is a device that increases the pressure of a fluid by decreasing its velocity.
- Characteristics
  - No shaft work is done.
  - Negligible heat transfer.
  - Negligible potential energy change
  - Kinetic energy is present.
  - Isentropic flow.





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Mach Number and Sub/Supersonic Flow

- The **Mach** number (**M**)is defined as the ratio between the speed of the fluid in the duct to speed of sound in the fluid = u/c.
- The flow is defined to be
  - Subsonic if ($\mathbf{M}<1$).
  - Sonic if ($\mathbf{M}=1$).
  - Supersonic if ($\mathbf{M}>1$).

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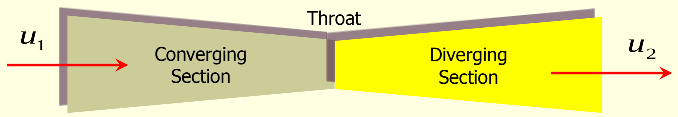
Analysis of Converging/Diverging Nozzles

- Energy balance $\Delta H + \frac{1}{2}\Delta V^2 = 0$
- Continuity equation $\frac{V_1 A_1}{v_1} = \frac{V_2 A_2}{v_2} = \text{constant} \Rightarrow \mathrm{d}\left(\frac{VA}{v}\right) = 0$
- Assuming isentropic nozzle with ideal gas law applied

$$V_2^2 - V_1^2 = \frac{2\gamma P_1 v_1}{\gamma - 1}\left[1 - \left(P_2 / P_1\right)^{\frac{\gamma-1}{\gamma}}\right]$$

- Pressure ratio at which the velocity becomes sonic

$$\frac{P_2}{P_1} = \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma-1}{\gamma}}$$



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