ME 200 –Thermodynamics I
Spring 2016

Lecture 17-18: Illustrations_1: Nozzles, Diffusers, Turbines, Compressors

Yong Li
Shanghai Jiao Tong University
Institute of Refrigeration and Cryogenics
800 Dong Chuan Road Shanghai, 200240, P. R. China
Email : liyo@sjtu.edu.cn
Phone: 86-21-34206056; Fax: 86-21-34206056

Lecture Contents

- Last lecture---Open system (Control Volume system)

Mass balance

Energy balance

»

$$\boxed{\frac{dm_{cv}}{dt} = \sum_i \dot{m}_i - \sum_e \dot{m}_e}$$

$$\boxed{\frac{dE_{cv}}{dt} = \dot{Q}_{cv} - \dot{W}_{cv} + \sum_i \dot{m}_i\left(h_i + \frac{V_i^2}{2} + gz_i\right) - \sum_e \dot{m}_e\left(h_e + \frac{V_e^2}{2} + gz_e\right)}$$

» Steady state

$$\dot{m}_1 = \dot{m}_2$$

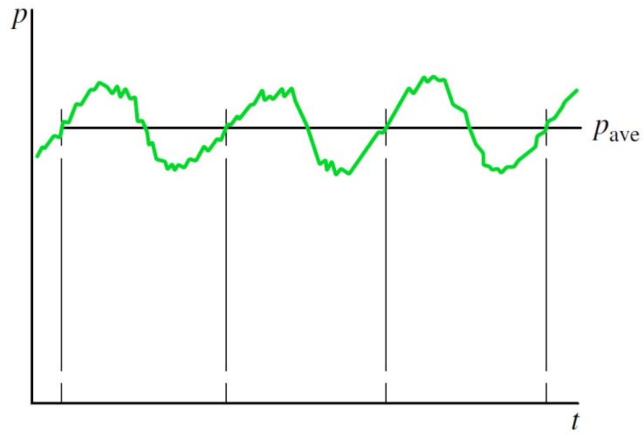
$$\boxed{0 = \dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}\left[(h_1 - h_2) + \frac{(V_1^2 - V_2^2)}{2} + g(z_1 - z_2)\right]}$$

- This lecture---Illustrations
  - » Modeling Control Volumes at Steady State
  - » Nozzles, diffusers, turbines
  - » Compressors, pumps

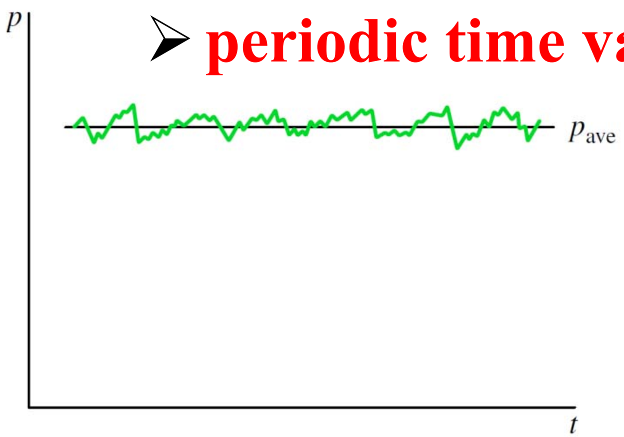
Modeling Control Volumes at Steady State

$$\boxed{\cancelto{0}{\frac{dE_{cv}}{dt}} = \dot{Q}_{cv} - \dot{W}_{cv} + \sum_i \dot{m}_i\left(h_i + \frac{V_i^2}{2} + gz_i\right) - \sum_e \dot{m}_e\left(h_e + \frac{V_e^2}{2} + gz_e\right)}$$

- The CV is **modeled** by **making assumptions**.
- The step of **listing assumptions** is necessary in every **engineering analysis**.
- **Steady-state** assumption apply when
  - properties **fluctuate slightly** about their averages
  - **periodic time variations**



(b)



(a)

- There is no net change in the total energy and the total mass within the control volume.
- The time-averaged mass flow rates, heat transfer rates, work rates, and properties of the substances crossing the control surface all remain constant.

Modeling Control Volumes at Steady State

$$\frac{dE_{cv}}{dt} = \underbrace{\cancel{\dot{Q}_{cv}}}_{0} - \dot{W}_{cv} + \sum_i \dot{m}_i \left(h_i + \frac{V_i^2}{2} + gz_i \right) - \sum_e \dot{m}_e \left(h_e + \frac{V_e^2}{2} + gz_e \right)$$

- $\boxed{\dot{Q}_{cv} = 0}$ in the energy rate balance **because it is small** relative to other energy transfers across the boundary. **Valid when**:
  - The outer surface of the CV is **well insulated**.
  - The **outer surface area** is too **small** for there to be effective heat transfer.
  - The ***ΔT*** between the CV and its surroundings is so **small** that the heat transfer can be ignored.
  - The gas or liquid **passes through** the CV so **quickly** that there is not enough time for significant heat transfer to occur.

Modeling Control Volumes at Steady State

$$\boxed{0 = \cancel{\dot{Q}_{cv}} - \dot{W}_{cv} + \dot{m}\left[(h_1 - h_2) + \cancel{\frac{(V_1^2 - V_2^2)}{2}} + \cancel{g(z_1 - z_2)}\right]}$$

0 0 0

- $\boxed{W_{CV} = 0}$ when there are no **rotating shafts**, **displacements of the boundary, electrical effects, or other work mechanisms** associated with the CV being considered.
- The **KE and PE** of the matter entering and exiting the control volume are neglected when they are small relative to other energy transfers.

$\dot{Q} = const$

Steady State
Steady flow SSSF

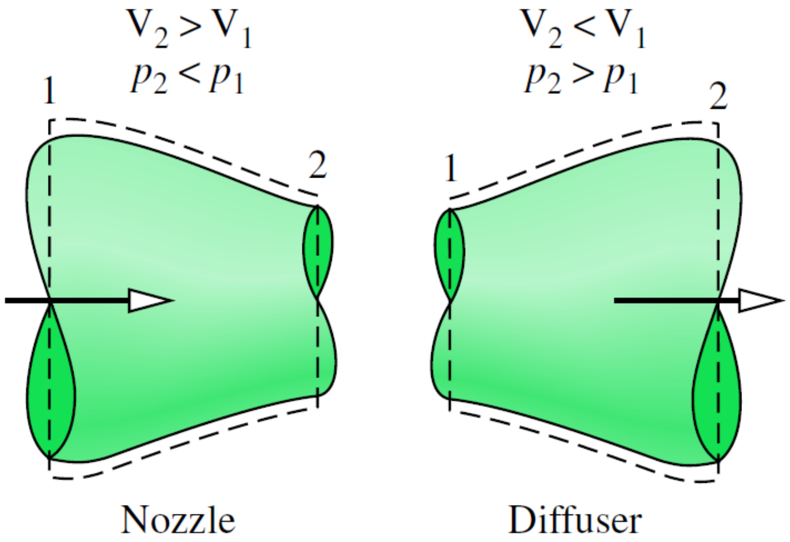
$$\dot{m} = const$$

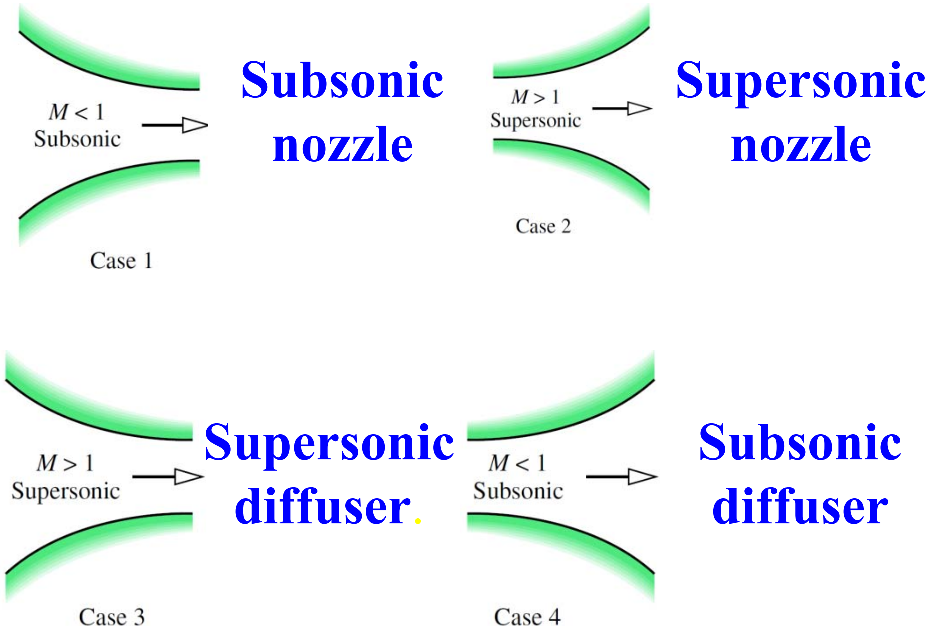
Steady State

$$\dot{Q}_{cv} = const \quad \dot{W} = const \quad \dot{m} = const$$

Nozzle & Diffuser

- **Nozzle :::** a **gas or liquid flow passage** of varying cross-sectional area in which the **V** ↑ in the direction of flow.
- **Diffuser :::** a **gas or liquid flow passage** of varying cross-sectional area in which the **V** ↓ in the direction of flow.



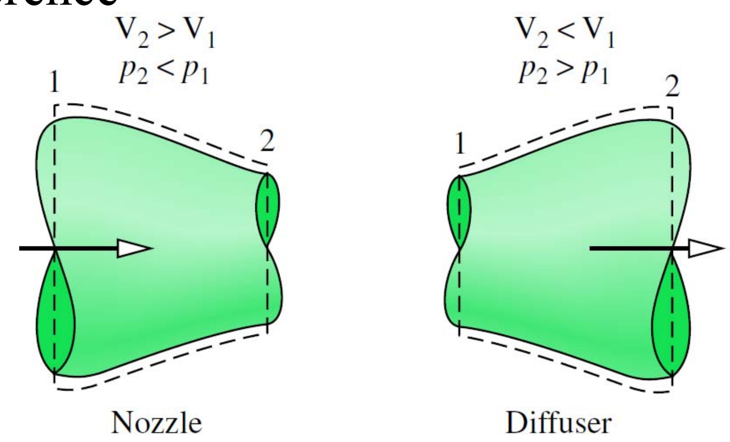


Features of Nozzle & Diffuser

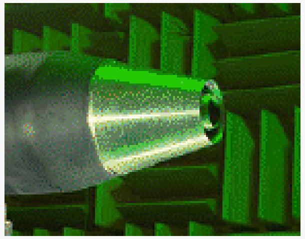
- In a **nozzle**, **V** ↑ while ***p*** ↓ decreases from inlet to exit (***v*** ↑)
- In a **diffuser**, **V**↓ while ***p***↑ from inlet to exit (***v***↓)
- **For nozzles and diffusers**
  - » The only work is flow work at locations where mass enters and exits the control volume
  - » Heat transfer always negligible

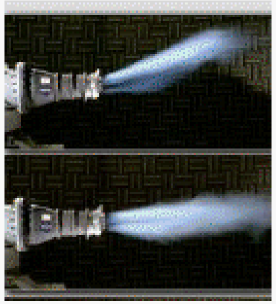
    Small area; less time available for heat transfer due to

    Large velocities; small temperature difference
  - » PE changes usually negligible



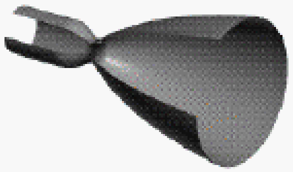
Applications

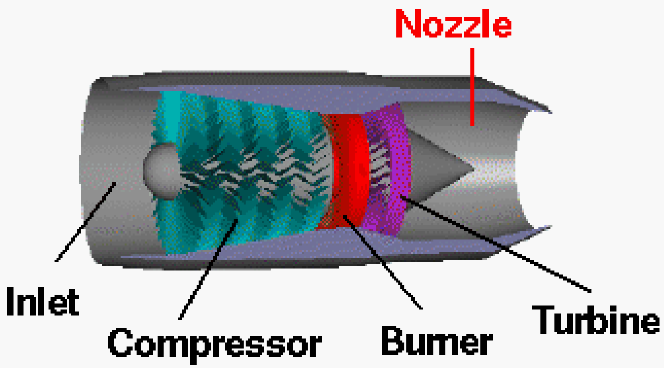

Co–annular

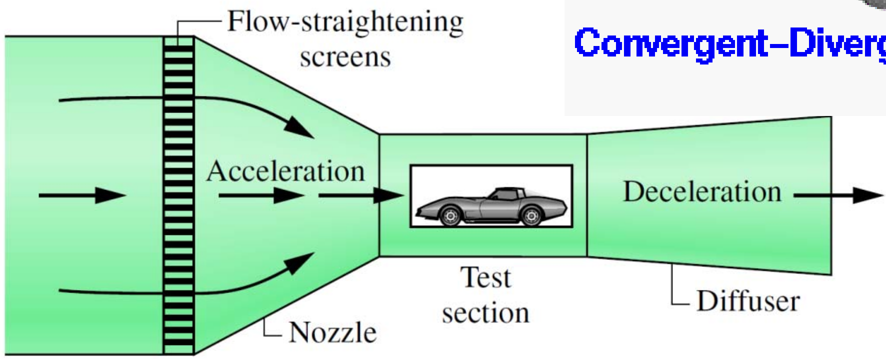

Maneuvering

External Geometry


Convergent


Convergent–Divergent (CD)





Wind-tunnel Test Facility

Analysis

- At steady state the mass and energy rate balances

$$\frac{\cancel{dm_{\text{cv}}}^{\,0}}{dt} = \dot{m}_1 - \dot{m}_2$$

$$\frac{\cancel{dE_{\text{cv}}}^{\,0}}{dt} = \dot{Q}_{\text{cv}} - \cancel{\dot{W}_{\text{cv}}}^{\,0} + \dot{m}_1\left(h_1 + \frac{\text{V}_1^2}{2} + gz_1\right) - \dot{m}_2\left(h_2 + \frac{\text{V}_2^2}{2} + gz_2\right)$$

- where 1 denotes the inlet and 2 the exit.

$$0 = \frac{\dot{Q}_{\text{cv}}}{\dot{m}} + (h_1 - h_2) + \left(\frac{\text{V}_1^2 - \text{V}_2^2}{2}\right)$$

0

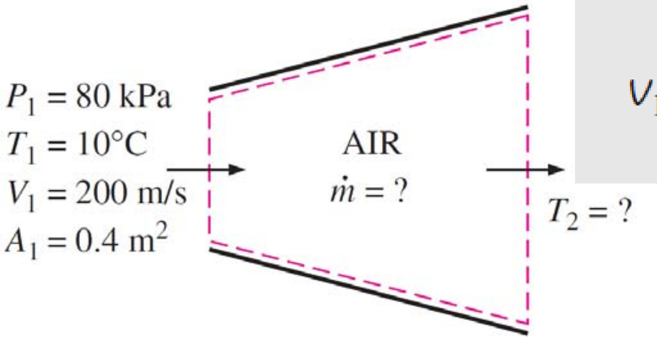
$$\boxed{0 = (h_1 - h_2) + (\frac{\text{V}_1^2 - \text{V}_2^2}{2})}$$

Example 1: Deceleration of Air in a Diffuser

- Air at 10° C and 80 kPa enters the diffuser of a jet engine steadily with a velocity of 200 m/s. The inlet area of the diffuser is 0.4 m^2. The air leaves the diffuser with a velocity that is very small compared with the inlet velocity. Determine

  (a) the mass flow rate of the air.

  (b) the temperature of the air leaving the diffuser.



$$v_1 = \frac{RT_1}{P_1} = \frac{0.287\ \text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(283\ \text{K})}{80\ \text{kPa}} = 1.015\ \text{m}^3/\text{kg}$$

$$\dot{m} = \frac{1}{v_1} V_1 A_1 = \frac{1}{1.015\ \text{m}^3/\text{kg}} (200\ \text{m/s})(0.4\ \text{m}^2) = \mathbf{78.8\ kg/s}$$

Example 1 continued

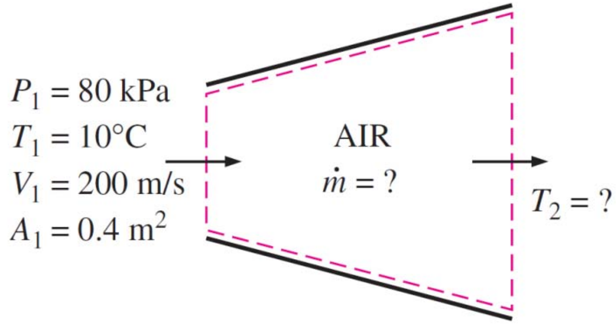
$$0 = \underbrace{\dot{Q}_{\mathrm{cv}}}_{0} - \underbrace{\dot{W}_{\mathrm{cv}}}_{0} + \dot{m}\left[(h_1 - h_2) + \frac{(\mathrm{V}_1^2 - \mathrm{V}_2^2)}{2} + \underbrace{g(z_1 - z_2)}_{0}\right]$$

$\dot{Q} \cong 0$, $\dot{W} = 0$, and $\Delta\mathrm{pe} \cong 0$

$$\dot{m}\left(h_1 + \frac{V_1^2}{2}\right) = \dot{m}\left(h_2 + \frac{V_2^2}{2}\right)$$

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

$V_2 \ll V_1$

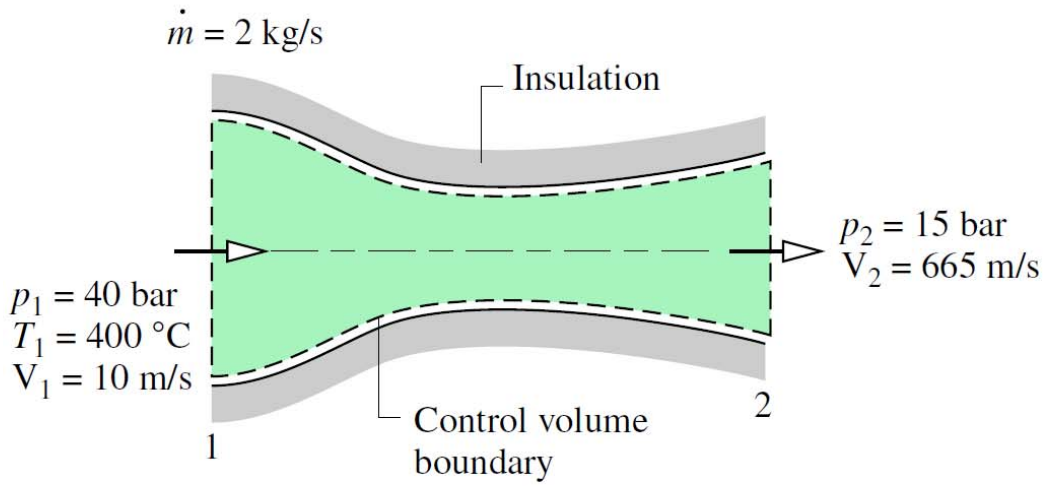


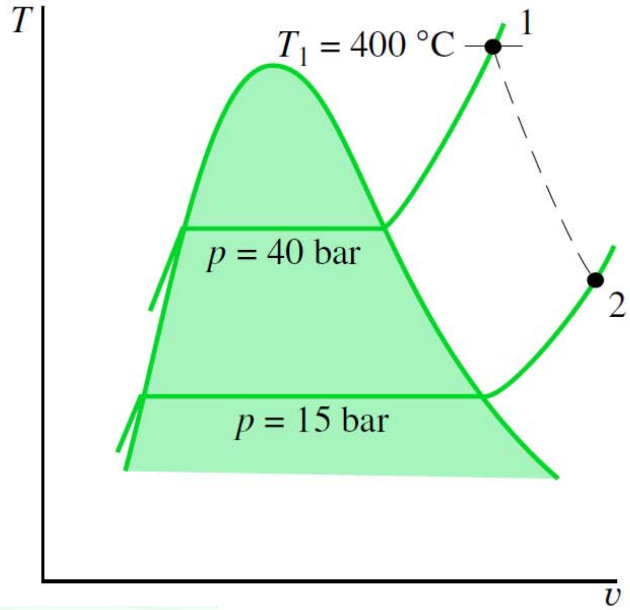
$$h_1 = h_{\,@\,283\ \mathrm{K}} = 283.14\ \mathrm{kJ/kg}$$

$$h_2 = 283.14\ \mathrm{kJ/kg} - \frac{0 - (200\ \mathrm{m/s})^2}{2}\left(\frac{1\ \mathrm{kJ/kg}}{1000\ \mathrm{m^2/s^2}}\right) = 303.14\ \mathrm{kJ/kg}$$

From Table $T_2 = \mathbf{303\ K}$

Example 2 Calculating Exit Area of a Steam Nozzle



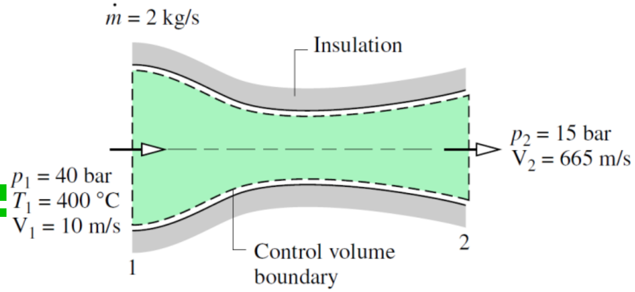


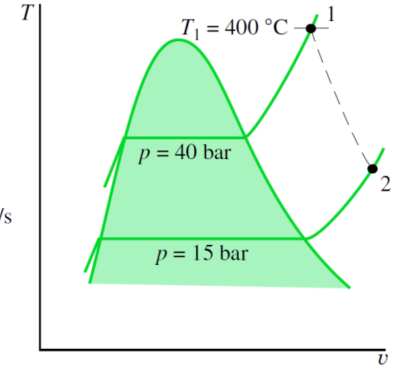
- Find: The exit area.
- Assumptions:
  - » steady state
  - » $\dot{Q}_{cv} = 0$ $\dot{W}_{cv} = 0$
  - » $\Delta PE = 0$

$$A_2 = \frac{\dot{m} v_2}{V_2}$$

?

Example 2 continued





$$0 = \cancel{\dot{Q}_{cv}}^{0} - \cancel{\dot{W}_{cv}}^{0} + \dot{m}\left(h_1 + \frac{V_1^2}{2} + gz_1\right) - \dot{m}\left(h_2 + \frac{V_2^2}{2} + gz_2\right)$$

$$0 = (h_1 - h_2) + \left(\frac{V_1^2 - V_2^2}{2}\right)$$

$$h_2 = h_1 + \left(\frac{V_1^2 - V_2^2}{2}\right)$$

- From Table A-4, h_1=3213.6 kJ/kg

$$h_2 = 3213.6\ \text{kJ/kg} + \left[\frac{(10)^2 - (665)^2}{2}\right]\left(\frac{\text{m}^2}{\text{s}^2}\right)\left|\frac{1\ \text{N}}{1\ \text{kg}\cdot\text{m/s}^2}\right|\left|\frac{1\ \text{kJ}}{10^3\ \text{N}\cdot\text{m}}\right|$$
$$= 3213.6 - 221.1 = 2992.5\ \text{kJ/kg}$$

- Table A-4 at p_2 ＝15 bar， h_2 ＝2992.5 kJ/kg
  - » v_2=0.1627 m3/kg

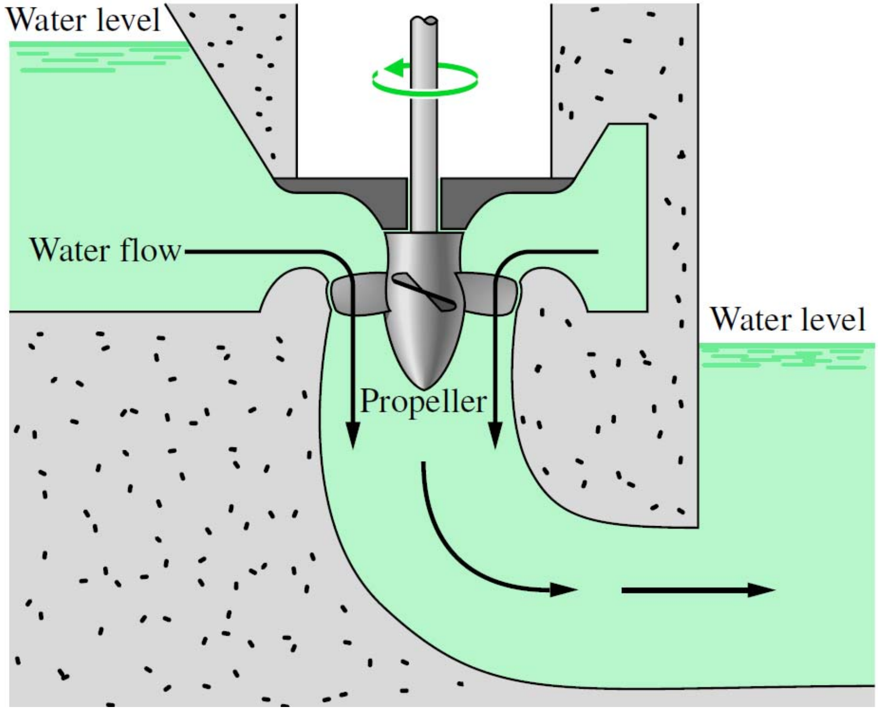
$$A_2 = \frac{\dot{m}v_2}{V_2} = \frac{(2\ \text{kg/s})(0.1627\ \text{m}^3/\text{kg})}{665\ \text{m/s}} = 4.89 \times 10^{-4}\ \text{m}^2$$

CONCEPTS

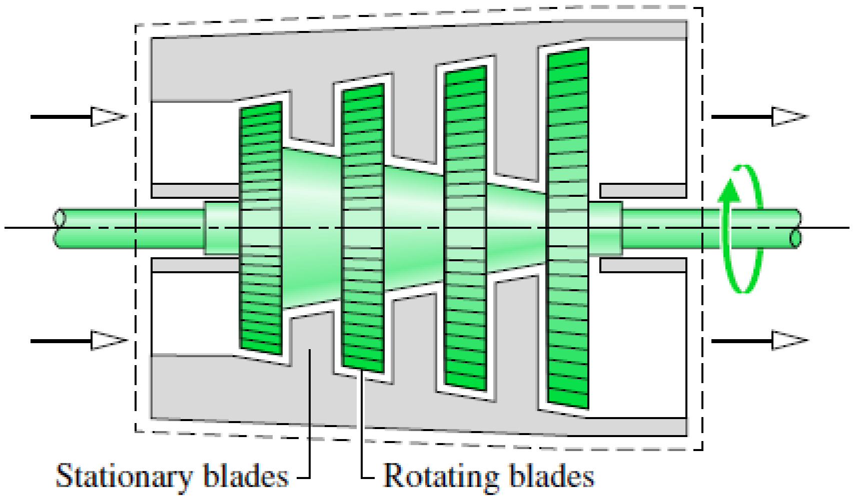
Turbines

- **Turbine :::** a steady-flow engineering device used to produce work output by expansion process
- Features
  - » In a turbine, $\boldsymbol{v}\uparrow$ from inlet to exit as the working fluid expands
  - » Work interaction device – desired output mechanical shaft work due to expansion
  - » $\dot{Q}_{cv} = 0$
  - » $\Delta PE = 0$
  - » May need to consider KE changes if given

Applications



Hydraulic turbine installed in a dam.

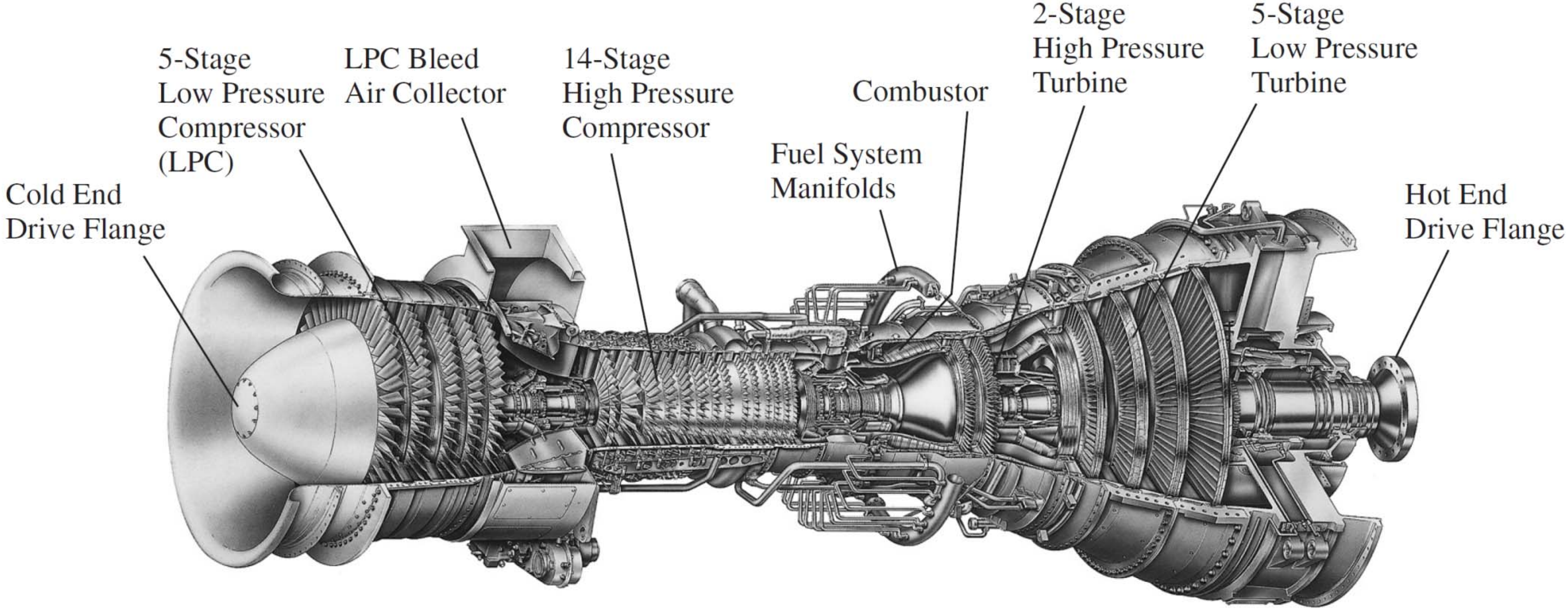


axial- flow turbine

- Turbines are widely used in vapor power plants, gas turbine power plants, and aircraft engines (Chaps. 8 and 9).

Gas Turbine

- A modern land-based gas turbine used for electric power production. This is a General Electric LM5000 turbine. It has a length of 6.2 m, it weighs 12.5 tons, and produces 55.2 MW at 3600 rpm with steam injection.



Analysis

$$0 = \dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}\left[(h_1 - h_2) + \frac{(V_1^2 - V_2^2)}{2} + g(z_1 - z_2)\right]$$

0

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

Example 3 Power Generation by a Steam Turbine

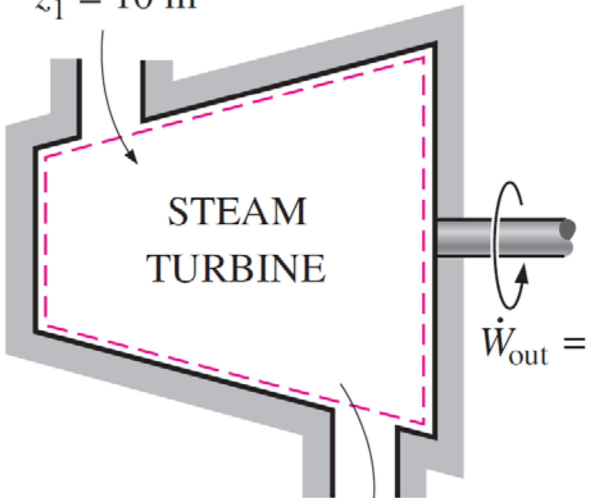
- The power output of an adiabatic steam turbine is 5 MW, and the inlet and the exit conditions of the steam are as indicated in figure

(a) Compare the magnitudes of Δh, Δke, and Δpe.

(b) Determine the work done per unit mass of the steam flowing through the turbine.

(c) Calculate the mass flow rate of the steam.

$P_1 = 2$ MPa
$T_1 = 400°C$
$V_1 = 50$ m/s
$z_1 = 10$ m



$\dot{W}_{out} = 5$ MW

$P_2 = 15$ kPa
$x_2 = 90\%$
$V_2 = 180$ m/s
$z_2 = 6$ m

Known: *The inlet and exit conditions of a steam turbine and its power output are given.*

Find: *The changes in kinetic energy, potential energy, And enthalpy of steam, as well as the work done per unit mass and the mass flow rate of steam are to be determined.*

Example 3

(a) Compare the magnitudes of Δh, Δke, and Δpe
(b) work done per unit mass of the steam
(c) mass flow rate of the steam.

Assumptions: steady-flow process, The system is adiabatic

$$\underbrace{\cancel{\frac{dm_{cv}}{dt}}}_{0} = \sum_i \dot{m}_i - \sum_e \dot{m}_e$$

$$\underbrace{\cancel{\frac{dE_{cv}}{dt}}}_{0} = \underbrace{\cancel{\dot{Q}_{cv}}}_{0} - \dot{W}_{cv} + \sum_i \dot{m}_i\left(h_i + \frac{V_i^2}{2} + gz_i\right) - \sum_e \dot{m}_e\left(h_e + \frac{V_e^2}{2} + gz_e\right)$$

$$\dot{m}_1 = \dot{m}_2 = \dot{m}$$

$$\left.\begin{aligned} P_1 &= 2\text{ MPa} \\ T_1 &= 400°\text{C} \end{aligned}\right\} \quad h_1 = 3248.4\text{ kJ/kg}$$

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

(a)

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

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

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

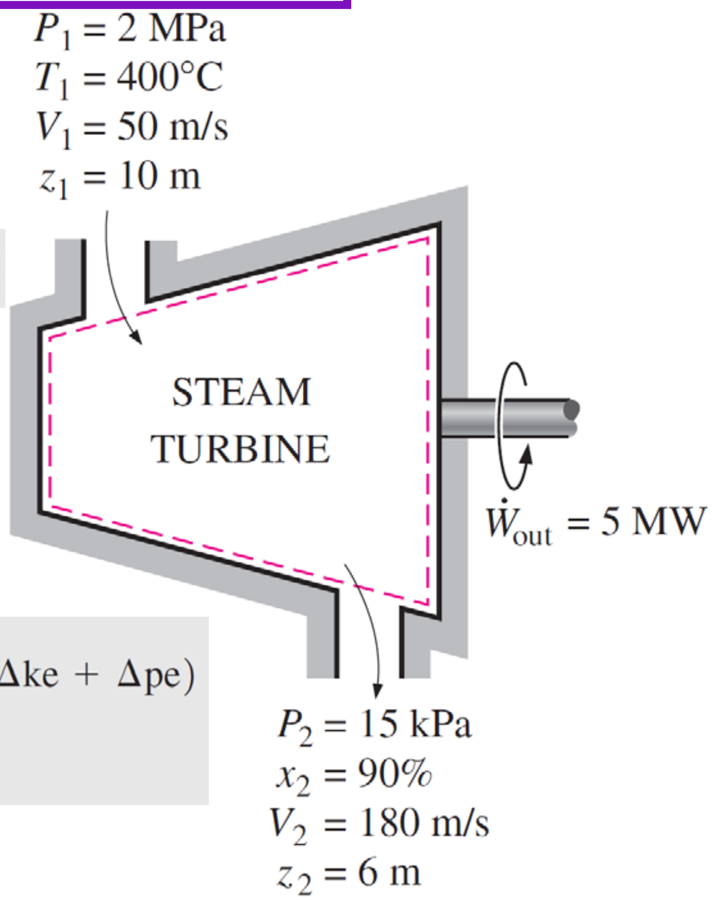
(b)

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

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

(c)

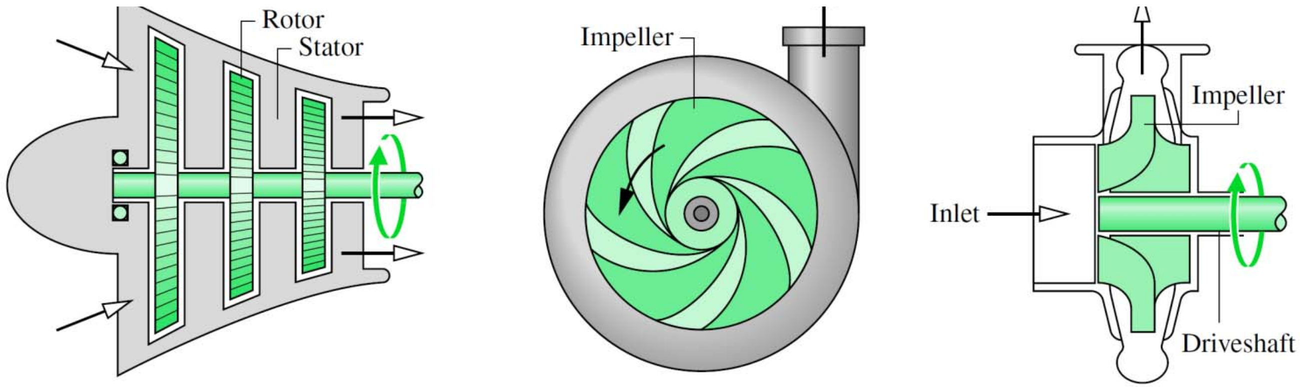
$$\dot{m} = \frac{\dot{W}_{out}}{w_{out}} = \frac{5000\text{ kJ/s}}{872.48\text{ kJ/kg}} = \mathbf{5.73\ kg/s}$$



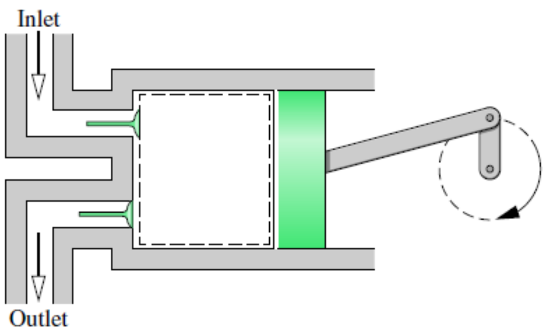
CONCEPTS

Compressor and Pumps

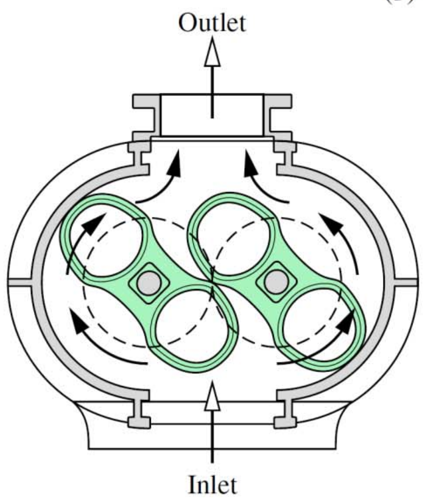
- **Compressor:::** device in which work is done on a **gas** passing through them in order to **raise the pressure**.
- **Pumps :::** the work input is used to **raise the pressure** of a **liquid**



(*a*) (*b*)



Reciprocating compressor



Rotating compressors
(a) Axial flow.
(b) Centrifugal.
(c) Roots type

Compressor and Pumps

$$\boxed{\frac{dE_{\text{cv}}}{dt} = \underbrace{\cancel{\dot{Q}_{\text{cv}}}}_{0} - \dot{W}_{\text{cv}} + \sum_i \dot{m}_i\left(h_i + \frac{V_i^2}{2} + \underbrace{\cancel{gz_i}}_{0}\right) - \sum_e \dot{m}_e\left(h_e + \frac{V_e^2}{2} + \underbrace{\cancel{gz_e}}_{0}\right)}$$

- Work interaction device – desired output increase in pressure due to compression
- In a **compressor**, ***v*** ↓ from inlet to exit as the working fluid is compressed
- In a **pump**, **$\Delta v \cong 0$**
- $\dot{Q}_{\text{cv}} = 0$
- $\Delta PE \cong 0$
- may need to consider KE changes if given

Example 4 Compressing Air by a Compressor

- Air at 100 kPa and 280 K is compressed steadily to 600 kPa and 400 K. The mass flow rate of the air is 0.02 kg/s, and a heat loss of 16 kJ/kg occurs during the process. determine the necessary power input to the compressor.
- Assumptions: 1. *steady-flow process* , 2. *Air is an ideal gas 3. ΔKE=ΔPE=0*

$$\boxed{\frac{\underset{0}{\cancel{dm_{\mathrm{cv}}}}}{dt} = \sum_i \dot{m}_i - \sum_e \dot{m}_e}$$

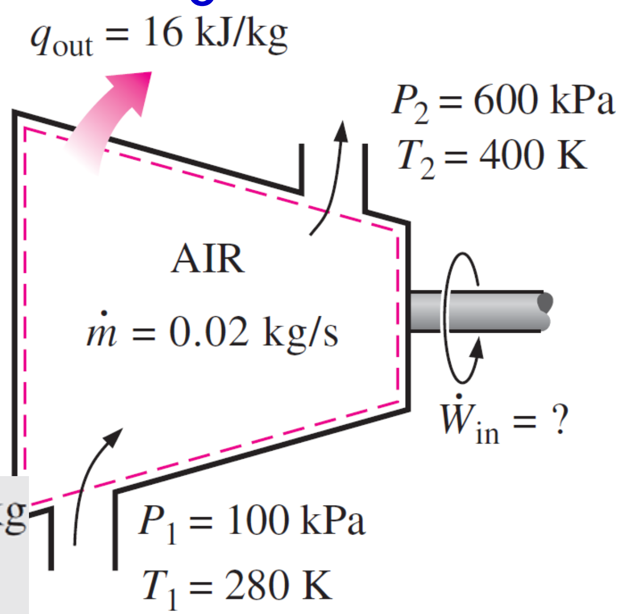
$$\boxed{\frac{\underset{0}{\cancel{dE_{\mathrm{cv}}}}}{dt} = \dot{Q}_{\mathrm{cv}} - \dot{W}_{\mathrm{cv}} + \sum_i \dot{m}_i\left(h_i + \underset{0}{\cancel{\frac{V_i^2}{2}}} + \underset{0}{\cancel{gz_i}}\right) - \sum_e \dot{m}_e\left(h_e + \underset{0}{\cancel{\frac{V_e^2}{2}}} + \underset{0}{\cancel{gz_e}}\right)}$$

$$\dot{W}_{\mathrm{in}} + \dot{m}h_1 = \dot{Q}_{\mathrm{out}} + \dot{m}h_2$$

$$\dot{W}_{\mathrm{in}} = \dot{m}q_{\mathrm{out}} + \dot{m}(h_2 - h_1)$$

$$h_1 = h_{@\,280\ \mathrm{K}} = 280.13\ \mathrm{kJ/kg}$$

$$h_2 = h_{@\,400\ \mathrm{K}} = 400.98\ \mathrm{kJ/kg}$$



$$\dot{W}_{\mathrm{in}} = (0.02\ \mathrm{kg/s})(16\ \mathrm{kJ/kg}) + (0.02\ \mathrm{kg/s})(400.98 - 280.13)\ \mathrm{kJ/kg}$$
$$= \mathbf{2.74\ kW}$$

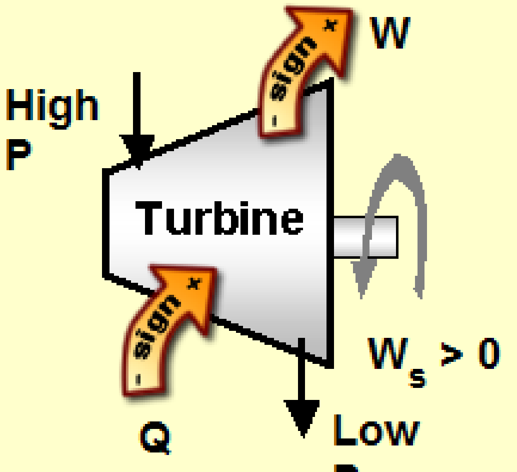
Turbine and Compressor

1st Law, Open System
Steady-State, SISO

$$\cancel{\dot{Q}}^{\,0} - \dot{W}_s = \dot{m}\left[\Delta\hat{H} + \cancel{\frac{\Delta v^2}{2g_c}}^{\,0} + \frac{g}{g_c}\cancel{\Delta z}^{\,0}\right]$$

Only if Adiabatic

Not Always !

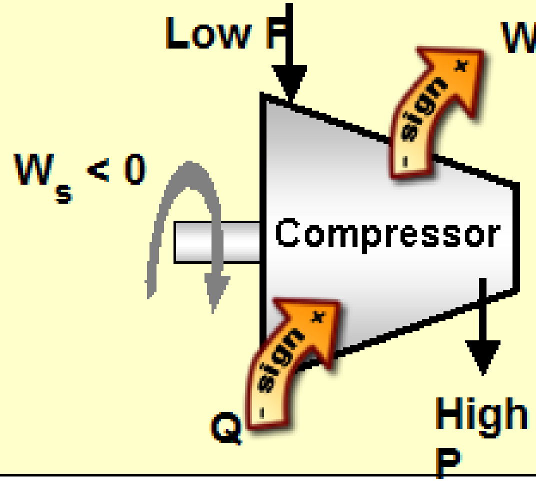


- **Q** and $\mathbf{\Delta E_k}$ are often, but not always negligible.
- Enthalpy decreases, $\mathbf{\Delta H < 0}$.
- **P** decreases dramatically and **T** usually decreases as well.

$$\boxed{\dot{W}_s = -\dot{m}\,\Delta\hat{H}}$$

Turbines & Compressors

- **Q** and $\mathbf{\Delta E_k}$ are often, but not always negligible.
- Enthalpy increases, $\mathbf{\Delta H > 0}$.
- **P** increases dramatically and **T** usually increases as well



Summary

- Open system at **steady state one-inlet one-outlet** (Control Volume system)

  » **Mass balance** **Energy balance**

$$\boxed{\dot{m}_1 = \dot{m}_2}$$

$$\boxed{0 = \dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}\left[(h_1 - h_2) + \frac{(V_1^2 - V_2^2)}{2} + g(z_1 - z_2)\right]}$$

nozzles

diffusers

$$\boxed{\dot{Q}_{cv} = 0}$$

$$\boxed{W_{CV} = 0}$$

$$\boxed{0 = (h_1 - h_2) + \left(\frac{V_1^2 - V_2^2}{2}\right)}$$

turbines

compressors

pumps

$$\boxed{\dot{Q}_{cv} = 0}$$

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