Outline

- More steady-flow engineering devices
- Turbines and compressors

Turbines

- In steam, gas, or hydroelectric power plants, the device that drives the electric generator is the turbine
- As the fluid passes through the turbine, work is done against the blades, which are attached to the shaft
- As a result, the shaft rotates, and the turbine produces work (positive - done by fluid)

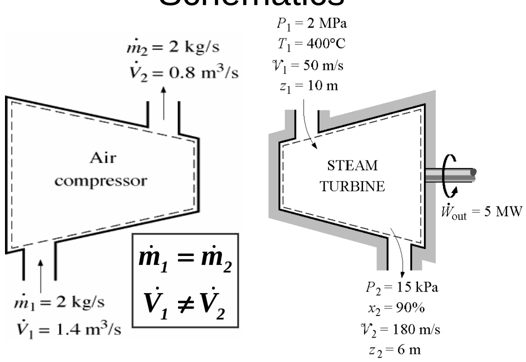
Compressors

- Compressors, also pumps and fans, are devices used to increase the pressure of a fluid
- Work is supplied to these devices from external source through a rotating shaft
- A fan increases pressure of a gas slightly and is mainly used to mobilize a gas
- A compressor is capable of compressing the gas to very high pressures
- Pumps work like compressors but work with liquids

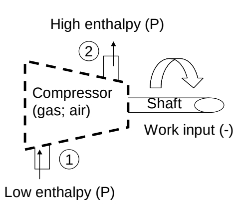
Turbines and compressors

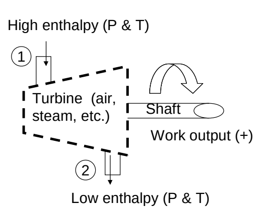
- Turbines produce power output
- Compressors, pumps, and fans require power input
- Heat transfer from turbines is negligible
- Heat transfer from compressors is also negligible unless intentionally cooled
- Changes in kinetic and potential energy are usually small compared to change in enthalpy and are usually neglected

Schematics



Pictures and control volumes





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Governing equations

- Assume steady flow; recall basic equations
- Conservation of mass

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \underset{\text{SISO}}{\rightarrow} \dot{m}_{in} = \dot{m}_{out} \rightarrow V_1 A_1 / \upsilon_1 = \rho_2 V_2 / \upsilon_2 (kg/s)$$

- Conservation of energy (1st law)

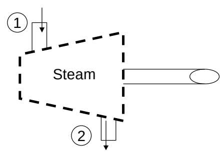
$$\dot{Q} - \dot{W} + \sum \dot{m}_i (h_i + \frac{V_i^2}{2} + gz_i) - \sum \dot{m}_e (h_e + \frac{V_e^2}{2} + gz_e) = 0$$

- Combine mass and energy

$$\div \dot{m} \rightarrow q - w = h_2 - h_1 + \frac{V_2^2 - V_1^2}{2} + g\left(z_2 - z_1\right) \underset{usually}{\Rightarrow} -w = h_2 - h_1$$

Example

- Steam enters an adiabatic turbine at 10 MPa and 500 C at a rate of 3 kg/s and leaves at 20 kPa. If the power output of the turbine is 2 MW, determine the temperature of the steam at the turbine exit. Neglect kinetic energy changes.



Solution

$$\left.\begin{array}{l} P_1 = 10MPa \\ T_1 = 500C \end{array}\right\} h_1 = 3373 kJ/kg \quad \text{(steam tables)}$$

$$\dot{m}_1 = \dot{m}_2 = \dot{m} \quad \text{(Conservation of Mass)}$$

$$-\dot{W} = \dot{m}_2 h_2 - \dot{m}_1 h_1 = \dot{m}(h_2 - h_1) \quad \text{(Conservation of Energy)}$$

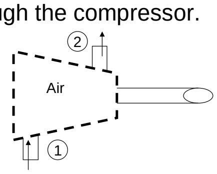
$$-2000 kJ/s = (3kg/s)(h_2 - 3373.7) kJ/kg$$

$$h_2 = 2707 kJ/kg$$

$$\left.\begin{array}{l} P_2 = 20kPa \\ h_2 = 2707 kJ/kg \end{array}\right\} T_2 = 110.8C$$

Example

- Air enters a compressor of a gas-turbine plant at ambient conditions of 100 kPa and 25C with a low velocity and exits at 1MPa and 347C with a velocity of 90m/s. The compressor is cooled at a rate of 1500kJ/min, and the power input to the compressor is 250kW. Determine the mass flow rate of air through the compressor.



Solution

$$T_1 = 25C = 298K \rightarrow h_1 = h_{@298K} = 298.2kJ/kg$$

$$T_2 = 347C = 620K \rightarrow h_2 = h_{@620K} = 628.07kJ/kg$$

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

$$\dot{Q} - \dot{W} = \dot{m}\left(h_2 - h_1 + \frac{V_2^2 - V_1^2}{2}\right) \text{ (Can you derive this?)}$$

$$-1500/60kJ/s + 250kJ/s$$

$$= \dot{m}\left[628.07 - 298.2 + \frac{(90m/s)^2 - 0}{2}\left(\frac{1kJ/kg}{1000m^2/s^2}\right)\right]$$

$$\therefore \dot{m} = 0.674kg/s$$

Summary

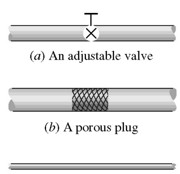
- Consider an adiabatic turbine operating steadily. Does the work output of the turbine have to be equal to the decrease in energy of the steam flowing through it?
- Consider an air compressor operating steadily. How would you compare the volume flow rates of the air at the compressor inlet and exit?
- Will the temperature of air rise as it is compressed by an adiabatic compressor? Why?

Outline

- Throttling valves, mixing chambers
- Heat exchangers, ducts, and pipes

Throttling valves

- Any kind of flow restricting device that causes significant pressure drop in fluid
- Examples include adjustable valves, capillary tubes, and porous plugs
- Unlike turbine, they produce pressure drop without work
- Often pressure drop comes with large temperature drop, hence use in AC and refrigeration


(*a*) An adjustable valve
(*b*) A porous plug
(*c*) A capillary tube

Throttling valve assumptions

- Adiabatic (no time or area (small device))
- No work (pressure drop due to friction)
- Change in potential energy small
- Change in kinetic energy small
- Conservation of mass and energy:

$$\dot{m}_{in} = \dot{m}_{out} \rightarrow \rho_1 V_1 A_1 = \rho_2 V_2 A_2 (kg/s)$$

$$0 = h_2 - h_1 \Rightarrow h_1 \cong h_2$$

Insight

$$h_1 \cong h_2 \therefore u_1 + P_1\upsilon_1 = u_2 + P_2\upsilon_2$$

- Internal energy + Flow energy = constant
- An increase in flow energy implies a decrease in internal energy (temperature) and vice versa
- For ideal gas, h=h(T), above implies inlet and outlet temperatures the same

Examples

- 1. A well-insulated valve is used to throttle steam from 8MPa and 500C to 6MPa. Determine final temperature of steam.
- 2. Air at 200psia and 90F is throttled to the atmospheric pressure of 35psia. Determine the final temperature of the air.

Solutions

- 1

$$\left.\begin{matrix} P_1 = 8MPa \\ T_1 = 500C \end{matrix}\right\} h_1 = 3398.3kJ/kg \ \ (A-6)$$

$$\left.\begin{matrix} P_2 = 6MPa \\ (h_2 = h_1) \end{matrix}\right\} T_2 = 490.1C$$

- 2

$$h_1 = h_2 \underset{\substack{ideal \\ gas, h=h(T)}}{\longrightarrow} T_1 = T_2 = 90F$$

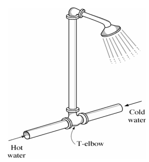
Mixing chambers

- Mixing two streams of fluids common in engineering applications
- Chamber or T-elbow or Y-elbow
- Multiple inlets with a single outlet
- Conservation of mass:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \underset{2I1O}{\rightarrow} \dot{m}_1 + \dot{m}_2 = \dot{m}_3$$

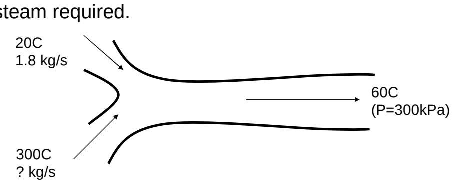
- Conservation of energy:

$$0 = \sum \dot{m}_e h_e - \sum \dot{m}_i h_i \underset{2I1O}{\Rightarrow} \dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3$$



Example

- Liquid water at 300kPa and 20C is heated in a chamber by mixing it with superheated steam at 300kPa and 300C. Cold water enters the chamber at a rate of 1.8kg/s. If the mixture leaves the mixing chamber at 60C, determine the mass flow rate of the superheated steam required.



Solution

$T < T_{sat@300kPa} = 133.55C \therefore$ cold water and mixture are compressed liquid. So use sat. liq. at same temp.

$$h_1 \approx h_{f@20} = 83.96kJ/kg$$

$$h_3 \approx h_{f@60} = 251.13kJ/kg$$

$$\left.\begin{array}{l} P_2 = 300kPa \\ T_2 = 300C \end{array}\right\} h_2 = 3069.3kJ/kg$$

$$\dot{m}_{in} = \dot{m}_{out} \rightarrow \dot{m}_1 + \dot{m}_2 = \dot{m}_3$$

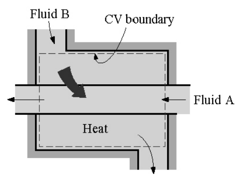
$$\dot{E}_{in} = \dot{E}_{out} \rightarrow \dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3$$

$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = \left(\dot{m}_1 + \dot{m}_2\right) h_3$$

$$\dot{m}_2 = \frac{h_1 - h_3}{h_3 - h_2}\dot{m}_1 = \frac{83.96 - 251.13}{251.13 - 3069.3}(1.8kg/s) = 0.107kg/s$$

Heat exchangers (HEs)

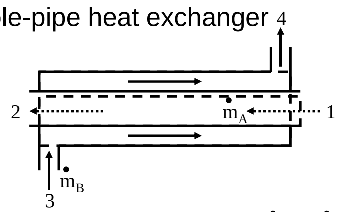
- Device where two moving fluids streams exchange heat without mixing
- E.g. double-tube (tube-in-shell) (see below) – indirect contact HE
- Two choices for control volume
  - Treat each stream separately; so mass flow in equals mass flow out and there is heat transfer
  - Treat entire HE as system to total mass/energy in equals total mass/energy out; adiabatic



(a) System: Entire heat exchanger ($Q_{CV} = 0$)

Analysis

- Double-pipe heat exchanger



Fluid A $\dot{Q}_{1\text{-}2} = \dot{m}_A (h_2 - h_1)$

Fluid B $\dot{Q}_{3\text{-}4} = \dot{m}_B (h_4 - h_3)$

$\dot{Q}_{1\text{-}2} + \dot{Q}_{3\text{-}4} = 0$

$\dot{m}_A (h_2 - h_1) + \dot{m}_B (h_4 - h_3) = 0$

Example

- Steam enters the condenser of a steam power plant at 20kPa and a quality of 95% with a mass flow rate of 20,000kg/h. It is to be cooled by water from a nearby river circulating the water through tubes within the condenser. To prevent thermal pollution, the river water is not allowed to experience a temperature rise above 10C. If the steam is to leave the condenser as saturated liquid at 20kPa, determine the mass flow rate of the cooling water required (see figure in text).

Solution

$$\left.\begin{array}{l} P_3 = 20kPa \\ x_3 = 0.95 \end{array}\right\} h_3 = h_f + x_3 h_{fg} = 251.40 + 0.95(2358.3) = 2491.8kJ/kg$$

$$\left.\begin{array}{l} P_4 = 20kPa \\ sat.liq. \end{array}\right\} h_4 \approx h_{f\,@20kPa} = 251.40kJ/kg$$

$$\dot{m}_{in} = \dot{m}_{out} \rightarrow \dot{m}_1 = \dot{m}_2 = \dot{m}_w; \dot{m}_3 = \dot{m}_4 = \dot{m}_s$$

$$\dot{m}_1 h_1 + \dot{m}_3 h_3 = \dot{m}_2 h_2 + \dot{m}_4 h_4 \ni \dot{m}_w \left(h_2 - h_1\right) = \dot{m}_s \left(h_3 - h_4\right)$$

$$\dot{m}_w = \frac{\left(h_3 - h_4\right)}{\left(h_2 - h_1\right)} \dot{m}_s \cong \frac{\left(h_3 - h_4\right)}{C_P \left(T_2 - T_1\right)} \dot{m}_s$$

$$= \frac{(2491.8 - 251.4)kJ/kg}{(4.18kJ/kg - C)(10C)} (20,000/3600kg/s) =$$

$$298kg/s = 17,866kg/\min$$

Summary

- During a throttling process, the temperature of a fluid drops from 30 to -20C. Can this process occur adiabatically?
- Would you expect the temperature of air to drop as it undergoes a steady-flow throttling process?
- When two fluid streams are mixed in a mixing chamber, can the mixture temperature be lower than the temperature of both streams? Explain.
- Consider a steady-flow mixing process. Under what conditions will the energy transported into the control volume by the incoming streams be equal to the energy transported out of it by the outgoing stream?