First Law Analysis for a Control Volume

Dr. Md. Zahurul Haq, *Ph.D., CEA, FBSME, FIEB*

Professor
Department of Mechanical Engineering
Bangladesh University of Engineering & Technology (BUET)
Dhaka-1000, Bangladesh

zahurul@me.buet.ac.bd
http://zahurul.buet.ac.bd/

ME 203: Engineering Thermodynamics
`http://zahurul.buet.ac.bd/ME203/`

Steady-State, Steady Flow (SSSF) Processes

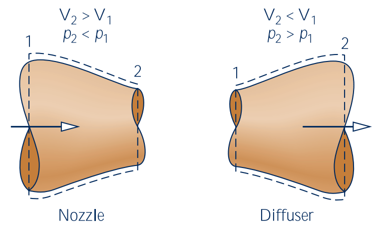
Assumptions:

- Control volume does not move relative to the coordinate frame.
- State of the mass at each point in the control volume does not vary with time.
- As for the mass that flows across the control surface, the mass flux and the state of this mass at each discrete area of flow on the control surface do not vary with time. The rates at which heat and work cross the control surface remain constant.

For example, a centrifugal air compressor that operates with a constant mass rate of flow into and out it, constant properties at each point across the inlet and exit ducts, a constant rate of heat transfer to the surroundings, and a constant power input. At each point in the compressor the properties are constant with time.

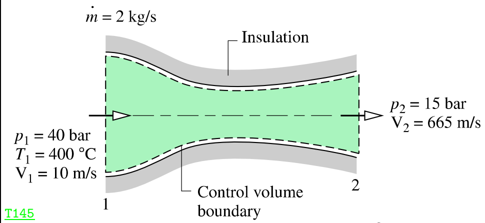
Nozzles & Diffusers

T159



- A nozzle is a flow passage of varying cross-sectional area in which the velocity of a gas or liquid increases in the direction of flow.
- In a diffuser, the gas or liquid decelerates in the direction of flow.
- For a nozzle or diffuser, the only work is *flow work* at locations where mass enters and exits the CV, so the term W_{cv} drops out.
- $\Delta PE \approx 0$

Moran Ex. 4.3: ▷ Converging-diverging Steam Nozzle: Estimate A_2.



T145

- ⇒ Steady state ⇒ $dE_{cv}/dt = 0$
- ⇒ $Z_2 = Z_1$
- ⇒ $\dot{W}_{cv} = 0$ & $\dot{Q} = 0$
- ⇒ $\dot{m}_i = \dot{m}_e = 2$ kg/s

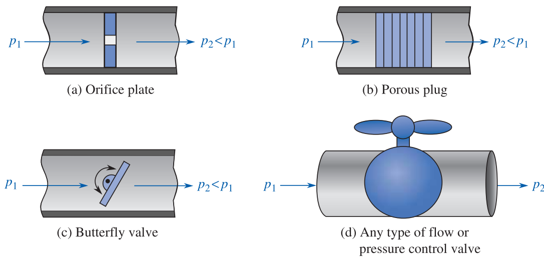
$$\frac{dE_{cv}}{dt} = \dot{Q} - \dot{W}_{cv} + \sum_i \dot{m}_i \left(h_i + \frac{\mathbb{V}_i^2}{2} + gz_i \right) - \sum_e \dot{m}_e \left(h_e + \frac{\mathbb{V}_e^2}{2} + gz_e \right)$$

$$0 = (h_1 - h_2) + \tfrac{1}{2}(\mathbb{V}_1^2 - \mathbb{V}_2^2)$$

- ⇒ $h_2 = h_1 + \frac{1}{2}(\mathbb{V}_1^2 - \mathbb{V}_2^2)$
- ⇒ $\rho_2 = \rho(Steam, P = P_2, h = h_2) = 6.143$ kg/m^3
- ⇒ $\dot{m}_2 = \rho_2 A_2 \mathbb{V}_2 \Rightarrow A_2 = 4.896 \times 10^{-4}$ m^2 ◁

Throttling Devices

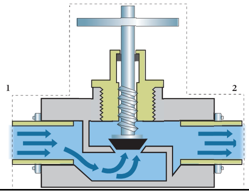
A significant reduction in pressure can be achieved simply by introducing a restriction into a line through which a gas or liquid flows.



T160

- For a control volume enclosing a throttling device, the only work is *flow work* at locations where mass enters and exits the control volume, so the term W_{cv} drops out.
- There is usually no significant heat transfer with the surroundings, and the change in potential energy from inlet to exit is negligible.

Cengel Ex. 5.8: ▷ R-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 x_2 and ΔT.



T148

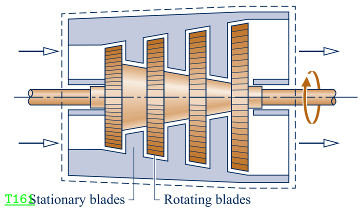
- ⇒ Steady state ⇒ $dE_{cv}/dt = 0$
- ⇒ $Z_2 = Z_1$ & $\mathbb{V}_2 \simeq \mathbb{V}_1$
- ⇒ $\dot{Q} \simeq 0$ & $\dot{W}_{cv} = 0$

$$h_2 \cong h_1$$

- ⇒ $h_1 = h(R134a, P_1 = 0.8\ MPa, x_1 = 0.0)$
- ⇒ $h_1 = h_2 = h_{f,\ 0.12MPa} + x_2 h_{fg,\ 0.12MPa} \Rightarrow x_2 = 0.34 \lhd$
- ⇒ $T_1 = T(R134a, P_1 = 0.8\ MPa, x_1 = 0.0) \Rightarrow T_1 = 31.34^o C$
- ⇒ $T_2 = T(R134a, P_2 = 0.12\ MPa, sat.) \Rightarrow T_2 = -22.31^o C$
- ⇒ $\Delta T = -53.64^o C \lhd$

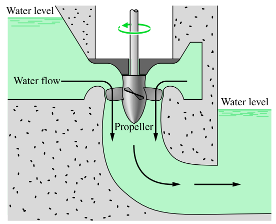
Turbines

A turbine is a device in which power is developed as a result of a gas or liquid passing through a set of blades attached to a shaft free to rotate.



T161

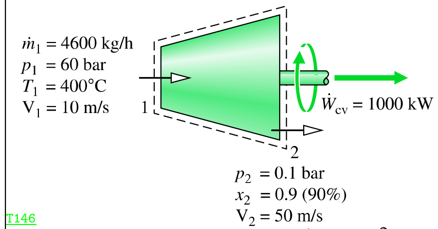
Axial-flow steam or gas turbine.



T162

Hydraulic turbine installed in a dam.

Moran Ex 4.4: ▷ Heat Transfer from Steam Turbine: Determine heat loss, Q.



T146

- ⇒ Steady state ⇒ $dE_{cv}/dt = 0$
- ⇒ $Z_2 = Z_1$
- ⇒ $\dot{m}_i = \dot{m}_e = (4600/3600)$ kg/s

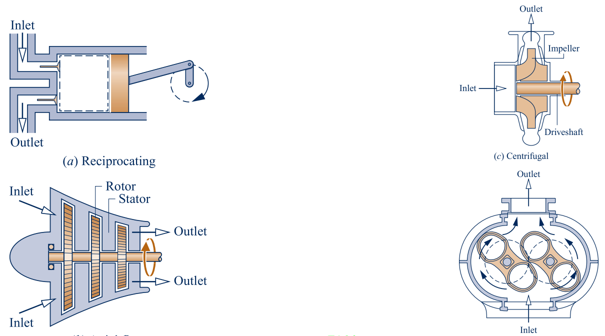
$$\frac{dE_{cv}}{dt} = \dot{Q} - \dot{W}_{cv} + \sum_i \dot{m}_i \left(h_i + \frac{\mathbb{V}_i^2}{2} + gz_i\right) - \sum_e \dot{m}_e \left(h_e + \frac{\mathbb{V}_e^2}{2} + gz_e\right)$$

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

- ⇒ $h_1 = h(Steam, P = P_1, T = T_1)$
- ⇒ $h_2 = h(Steam, P = P_2, x = x_2)$
- ⇒ $\dot{Q}_{cv} = -63.61$ kW (heat loss) $\lhd$

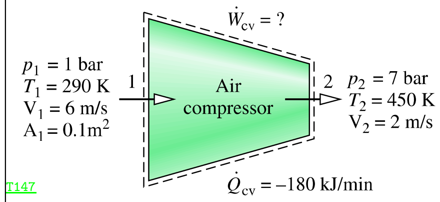
Compressors & Pumps

Compressors and pumps are devices in which work is done on the substance flowing through them in order to increase the pressure and/or elevation. Compressor is used to compress a gas (vapour) and the term pump is used when the substance is a liquid.



T163 T164

Moran Ex. 4.5: ▷ Air Compressor Power: Determine power required, $\dot{W}_{cv}$.



T147

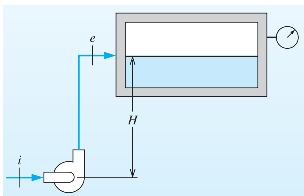
- ⇒ Steady state ⇒ $dE_{cv}/dt = 0$
- ⇒ $Z_2 = Z_1$
- ⇒ $\dot{Q}_{cv} = -180 kJ/min = -3.0$ kW
  - $\dot{m} = \rho A \mathbb{V}$
  - $\rho = P/RT$

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

$$\boxed{\dot{W}_{cv} = \dot{Q} + \dot{m} \left[(h_1 - h_2) + \left(\frac{\mathbb{V}_1^2 - \mathbb{V}_2^2}{2} \right) \right]}$$

- ⇒ $h_1 - h_2 = C_p(T_1 - T_2) = -160.8$ kJ/kg
- ⇒ $\rho_1 = P_1/RT_1 = 1.20$ m^3/kg
- ⇒ $\dot{m} = \rho_1 A_1 \mathbb{V}_1 = 0.72$ kg/s
- ⇒ $\dot{W}_{cv} = -119.4$ kW (work input required) ◁

Borgnakke Ex. 4.6: ▷ A water pump is located 15 m down in a well, taking water in at 10°C, 90 kPa at a rate of 1.5 kg/s. The exit line is a pipe of diameter 0.04 m that goes up to a receiver tank maintaining a gauge pressure of 400 kPa. Assume that the process is adiabatic, with the same inlet and exit velocities, and the water stays at 10°C. Find the required pump work.



T442

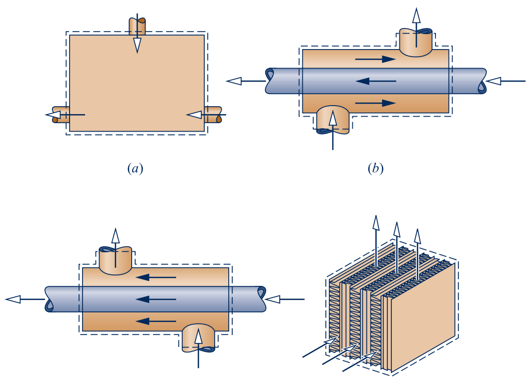
- ⇒ Steady state ⇒ $dE_{cv}/dt = 0$
- ⇒ $\dot{Q} = 0, \; V_i = V_e, \; T_i = T_e$
- ⇒ $P_i = 90$ kPa, $P_e = 501.325$ kPa.
- ⇒ $z_e - z_i = 15.0$ m
- ⇒ $\dot{m} = 1.5$ kg/s

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

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

$\dot{W}_{cv} = -0.822$ kW (work input required) ◁ : $\langle h_1 - h_2 = \frac{P_1 - P_2}{\rho}$, if ρ & T are constant.$\rangle$

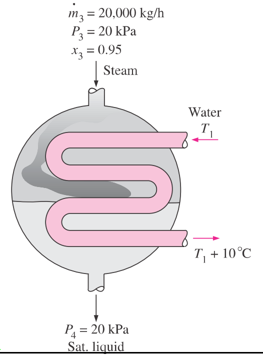
Heat Exchangers



T166

Common heat exchanger types. (a) Direct contact heat exchanger. (b) Tube-within a-tube counterflow heat exchanger. (c) Tube-within-a-tube parallel flow heat exchanger. (d) Cross-flow heat exchanger.

Cengel P5-85: ▷ Condenser Cooling Water: Determine $\dot{m}_{water}$.



T149

$\Rightarrow$ $\dot{W} = 0,\ \dot{Q} = 0,\ \Delta(KE) = 0,\ \Delta(PE) = 0$

$\Rightarrow$ $\dot{m}_3 = (20000/3600)$ kg/s

$\Rightarrow$ $\dot{m}_1 = \dot{m}_2$ & $\dot{m}_3 = \dot{m}_4$

$\Rightarrow$ $h_1 = h(H_2O,\ P = 100 \text{ kPa},\ T = 20)$

$\Rightarrow$ $h_2 = h(H_2O,\ P = 100 \text{ kPa},\ T = 30)$

$\Rightarrow$ $h_3 = h(H_2O,\ P = 20 \text{ kPa},\ x = 0.95)$

$\Rightarrow$ $h_4 = h(H_2O,\ P = 20 \text{ kPa},\ x = 0)$

$$0 = \sum(\dot{m}h)_i - \sum(\dot{m}h)_e$$

$\Rightarrow$ $(\dot{m}_3 h_3 + \dot{m}_1 h_1) = (\dot{m}_4 h_4 + \dot{m}_2 h_2)$

$\Rightarrow$ $m_{water} = m_1 = 297.4$ kg/s ◁