CHAPTER

3

Thermodynamics

First Law of Thermodynamics

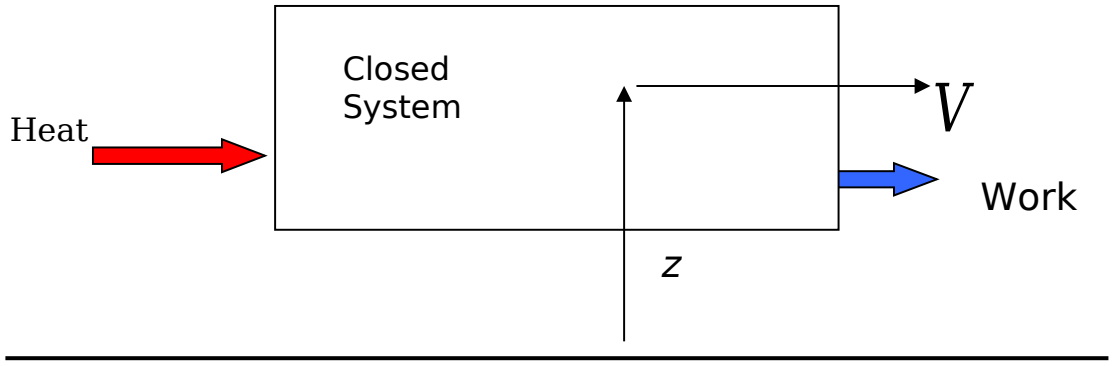
FIRST LAW OF THERMODYNAMICS

ENERGY ANALYSIS OF CLOSED SYSTEM

First Law of Thermodynamics

- The First Law is usually referred to as the Law of Conservation of Energy, i.e. *energy can neither be created nor destroyed, but rather transformed from one state to another*.
- The energy balance is maintained within the system being studied/defined boundary.
- The various energies associated are then being observed as they cross the boundaries of the system.

Energy Balance for Closed System



$$\begin{pmatrix}\text{Total energy}\\ \text{entering the system}\end{pmatrix}-\begin{pmatrix}\text{Total energy}\\ \text{leaving the system}\end{pmatrix}=\begin{pmatrix}\text{The change in total}\\ \text{energy of the system}\end{pmatrix}$$

or

$$E_{in} - E_{out} = \Delta E_{system}$$

- According to classical thermodynamics

$$Q_{net} - W_{net} = \Delta E_{system}$$

- The total energy of the system, E_{system}, is given as

$$E = Internal\ energy + Kinetic\ energy + Potential\ energy$$

$$E = U + KE + PE$$

- The change in stored energy for the system is

$$\Delta E = \Delta U + \Delta KE + \Delta PE$$

- The first law of thermodynamics for closed systems then can be written as

$$Q_{net} - W_{net} = \Delta U + \Delta KE + \Delta PE$$

- If the system does not move with a velocity and has no change in elevation, the conservation of energy equation is reduced to

$$Q_{net} - W_{net} = \Delta U$$

- The first law of thermodynamics can be in the form of

$$q_{net} - w_{net} = \left(u_2 - u_1 + \frac{V_2^2 - V_1^2}{2000} + \frac{g(z_2 - z_1)}{1000} \right) \qquad (kJ/kg)$$

$$Q_{net} - W_{net} = m\left(u_2 - u_1 + \frac{V_2^2 - V_1^2}{2000} + \frac{g(z_2 - z_1)}{1000} \right) \qquad (kJ)$$

- ***For a constant volume process,***

$$Q_{net} - W_{net} = m\left(u_2 - u_1 + \frac{V_2^2 - V_1^2}{2000} + \frac{g(z_2 - z_1)}{1000} \right)$$

$$Q_{net} = m\left(u_2 - u_1 + \frac{V_2^2 - V_1^2}{2000} + \frac{g(z_2 - z_1)}{1000} \right)$$

- ***For a constant pressure process***,

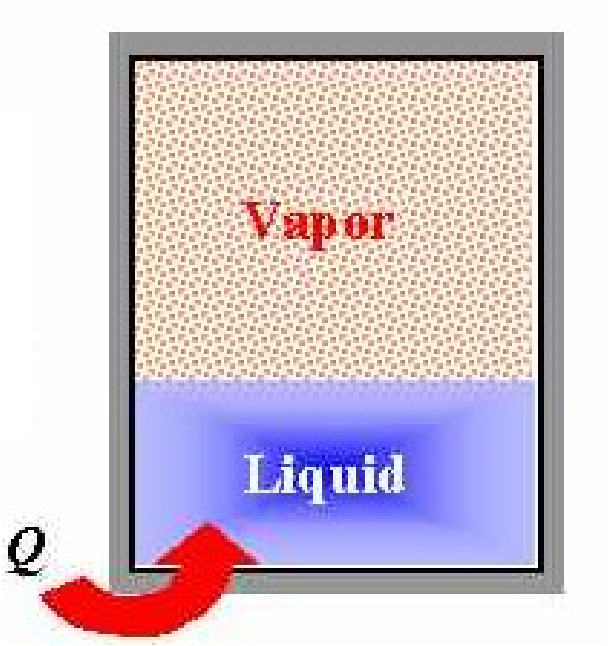
$$Q_{net} - W_{net} = m\left(u_2 - u_1 + \frac{V_2^2 - V_1^2}{2000} + \frac{g(z_2 - z_1)}{1000} \right)$$

$$Q_{net} - P(V_2 - V_1) = m\left(u_2 - u_1 + \frac{V_2^2 - V_1^2}{2000} + \frac{g(z_2 - z_1)}{1000} \right)$$

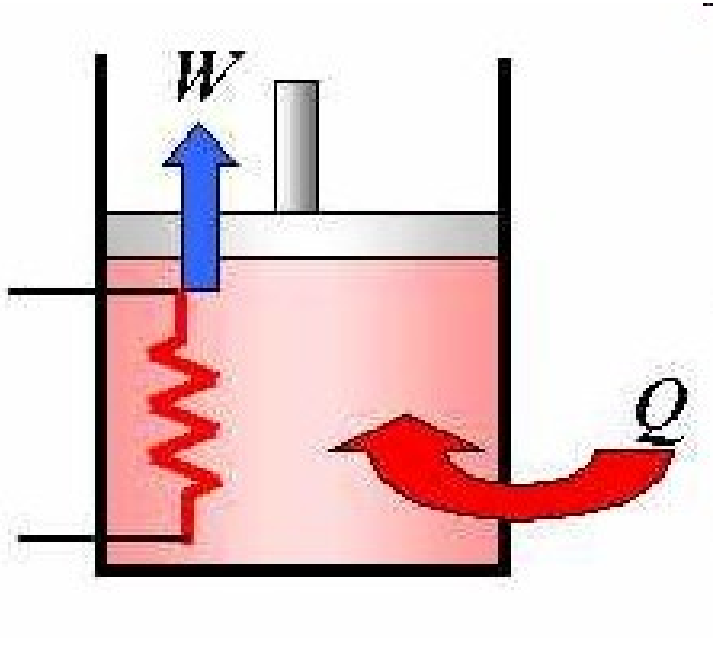
$$Q_{net} = m\left(u_2 - u_1 + P(V_2 - V_1) + \frac{V_2^2 - V_1^2}{2000} + \frac{g(z_2 - z_1)}{1000} \right)$$

$$Q_{net} = m\left(h_2 - h_1 + \frac{V_2^2 - V_1^2}{2000} + \frac{g(z_2 - z_1)}{1000} \right)$$

Example of Closed Systems



Rigid tank



Piston cylinder

Example 3.1

A 2 kg undergoes an adiabatic process. The work done on the system is 30 kJ. The velocity of the system changes from 3 m/s to 15 m/s. During the process, the elevation of the system increases 45 meters. Determine the change in internal energy of the system.

Solution:

- Energy balance,

$$Q_{net} - W_{net} = m\left(u_2 - u_1 + \frac{V_2^2 - V_1^2}{2000} + \frac{g(z_2 - z_1)}{1000} \right)$$

- Rearrange the equation

$$\cancel{Q_{net}} - W_{net} = m\left(u_2 - u_1 + \frac{V_2^2 - V_1^2}{2000} + \frac{g(z_2 - z_1)}{1000} \right)$$

$$-W_{net} = m\left(u_2 - u_1 + \frac{V_2^2 - V_1^2}{2000} + \frac{g(z_2 - z_1)}{1000} \right)$$

$$-(-30) = 2\Delta u + 2\left(\frac{15^2 - 3^2}{2000} \right) + 2\left(\frac{9.81(45)}{1000} \right)$$

$$\Delta u = \underline{\underline{14.451\ kJ}} \quad Ans..$$

Example 3.2

Steam at 1100 kPa and 92 percent quality is heated in a rigid container until the pressure is 2000 kPa. For a mass of 0.05 kg, calculate the amount of heat supply (in kJ) and the total entropy change (in kJ/kg.K).

Solution:

$$\boxed{State\ 1}$$

$$at\ P_1 = 1100\,kPa, x_1 = 0.92$$

$$v_1 = v_{f1} + x_1 v_{g1}$$

$$= 0.00113 + 0.92(0.17753 - 0.00113)$$

$$= 0.1634 \frac{m^3}{kg}$$

$$u_1 = u_{f1} + x_1 u_{fg1}$$

$$= 779.78 + 0.92(1805.7)$$

$$= 2441.024 \frac{kJ}{kg}$$

$$s_1 = s_{f1} + x_1 s_{fg1}$$

$$= 2.1785 + 0.92(4.3735)$$

$$= 6.20212 \frac{m^3}{kg}$$

- For a rigid container,
  $v_2 = v_1 = 0.1634\ m^3/kg$

State 2

$v_2 > v_g$ superheated

$at\ P_2 = 2000kPa, v_2 = 0.1634 \frac{m^3}{kg}$

v	u	s
0.15122	2945.9	7.1292
0.1634	u_2	s_2
0.17568	3116.9	7.4337

$$u_2 = 2945.9 + \left(\frac{0.1634 - 0.15122}{0.17568 - 0.15122} \right)(3116.9 - 2945.9)$$

$$= 3030.42 \frac{kJ}{kg}$$

$$s_2 = 7.1292 + \left(\frac{0.1634 - 0.15122}{0.17568 - 0.15122} \right)(7.4337 - 7.1292)$$

$$= 7.2790 \frac{kJ}{kg.K}$$

- Amount of heat supplied, Q

$$Q = m(u_2 - u_1)$$
$$= 0.05(3030.42 - 2441.9)$$
$$= \underline{\underline{29.43 kJ}}$$

- The change in entropy, Δs

$$\Delta s = s_2 - s_1$$
$$= 7.2790 - 6.204$$
$$= \underline{\underline{1.075 \frac{kJ}{kg.K}}}$$

Example 3.5

A rigid tank is divided into two equal parts by a partition. Initially one side of the tank contains 5 kg water at 200 kPa and 25°C, and the other side is evacuated. The partition is then removed, and the water expands into the entire tank. The water is allowed to exchange heat with its surroundings until the temperature in the tank returns to the initial value of 25°C. Determine (a) the volume of the tank (b) the final pressure (c) the heat transfer for this process.

Solution:

$\boxed{State\,1}$

$$\left.\begin{array}{l} P_1 = 200\,kPa, \\ T_1 = 25^oC \end{array}\right\} \begin{array}{l} T_1 < T_{sat} \text{ Comp. liquid} \\ v_1 = v_{f@25^\circ C} = 0.001003 \frac{m^3}{kg} \end{array}$$

initial volume of half resevoir

$$V_1 = mv$$
$$= 5(0.001003)$$
$$\simeq 0.005 m^3$$

- The initial volume for entire tank

$$V_{resevoir} = 2(0.005)$$
$$= \underline{\underline{0.01 m^3}}$$

- The final pressure

$$\boxed{State\,2}$$

$$T_2 = 25^{\circ}C \qquad v_f = 0.001003\,\frac{m^3}{kg}$$

$$v_2 = \frac{0.01}{5} = 0.002\,\frac{m^3}{kg} \qquad v_g = 43.34\,\frac{m^3}{kg}$$

check region!

$v_f < v < v_g \rightarrow$ *saturated mixture*

$$then: P_2 = P_{sat} = \underline{\underline{3.169\,kPa}}$$

- The heat transfer for this process

$$Q_{net} - W_{net} = m(\Delta u + \Delta ke + \Delta Pe)$$

$$Q_{net} - \cancel{W_{net}} = m(\Delta u + \cancel{\Delta ke} + \cancel{\Delta Pe})$$

$$Q_{net} = m\Delta u = m(u_2 - u_1)$$

$$u_1 = u_{f@25^{\circ}C} = 104.83\,\frac{kJ}{kg}$$

$$u_2 = u_{ff} + x_2 u_g$$

$$x_2 = \frac{v_2 - v_f}{v_{fg}}$$

$$= 2.3\times10^{-5}$$

$$\therefore u_2 = 104.83 + 2.3\times10^{-5}(2304.3)$$

$$= 104.88\,\frac{kJ}{kg}$$

Then:

$$Q_{net} = 5\ (104.88\text{-}104.83)$$

$$= \underline{\underline{0.25\,kJ}}$$

- *+ve sign indicates heat transfer into the system.*

Closed System First Law of a Cycle

- Some thermodynamic cycle composes of processes in which the working fluid undergoes a series of state changes such that the final and initial states are identical.
- For such system the change in internal energy of the working fluid is zero.
- The first law for a closed system operating in a thermodynamic cycle becomes

$$Q_{net} - W_{net} = \Delta U_{cycle}$$

$$Q_{net} = W_{net}$$

According to a law of $PV^n = \text{constant}$

No	Value of n	Process	Description	Result of IGL
1	∞	iso***cho***ric	constant volume ($V_1 = V_2$)	$\frac{P_1}{T_1} = \frac{P_2}{T_2}$
2	0	iso***bar***ic	constant pressure ($P_1 = P_2$)	$\frac{V_1}{T_1} = \frac{V_2}{T_2}$
3	1	iso***ther mal***	constant temperature ($T_1 = T_2$)	$P_1V_1 = P_2V_2$
4	1<n< γ	polytropi c	-none-	$\frac{P_1}{P_2} = \left(\frac{V_2}{V_1}\right)^n = \left(\frac{T_1}{T_2}\right)^{\frac{n}{n-1}}$
5	γ	i***sentrop i***c	constant entropy ($S_1 = S_2$)	

- Various forms of work are expressed as follows

Process	Boundary Work
iso***cho***ric	$W_{12} = P(V_2 - V_1) = 0$
iso***bar***ic	$W_{12} = P(V_2 - V_1)$
iso***thermal***	$W_{12} = P_1 V_1 \ln \frac{V_2}{V_1}$
polytropic	$W_{12} = \frac{P_2 V_2 - P_1 V_1}{1 - n}$
i***sentropi***c	

Example 3.4

Sketch a P-V diagram showing the following processes in a cycle

Process 1-2: isobaric work output of 10.5 kJ from an initial volume of 0.028 m^3 and pressure 1.4 bar,
Process 2-3: isothermal compression, and
Process 3-1: isochoric heat transfer to its original volume of 0.028 m^3 and pressure 1.4 bar.

Calculate (a) the maximum volume in the cycle, in m^3, (b) the isothermal work, in kJ, (c) the net work, in kJ, and (d) the heat transfer during isobaric expansion, in kJ.

Solution:

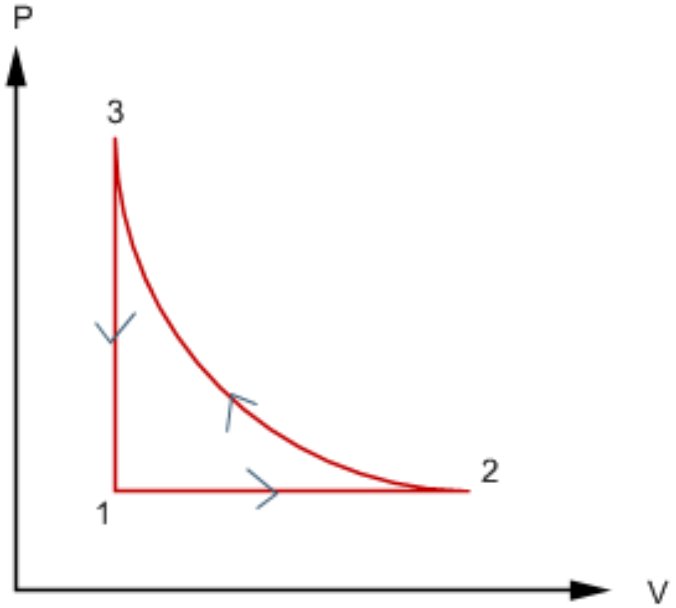
- Process by process analysis,

Section 1- 2 (isobaric)

$$W_{12} = P(V_2 - V_1) = 10.5$$

$$140(V_2 - 0.028) = 10.5$$

$$V_2 = \underline{\underline{0.103 m^3}}$$



- The isothermal work

Section 2- 3 (isothermal)

$$P_2V_2 = P_3V_3$$

$$P_3 = \left(\frac{0.103}{0.028}\right)(140) = 515 kPa$$

$$\rightarrow W_{23} = P_2V_2 \ln\frac{V_3}{V_2}$$

$$= 140(0.103)\ln\left(\frac{0.028}{0.103}\right)$$

$$= \underline{\underline{-18.78 kJ}}$$

- The net work

Section 3- 1(isochoric)

$$W_{31} = 0$$

$$\therefore W_{net} = W_{12} + W_{23} + W_{31}$$

$$= 10.5 - 18.78$$

$$= \underline{\underline{-8.28 kJ}}$$

Example 3.5

A fluid at 4.15 bar is expanded reversibly according to a law PV = constant to a pressure of 1.15 bar until it has a specific volume of 0.12 m^3/kg. It is then cooled reversibly at a constant pressure, then is cooled at constant volume until the pressure is 0.62 bar; and is then allowed to compress reversibly according to a law PV^n = constant back to the initial conditions. The work done in the constant pressure is 0.525 kJ, and the mass of fluid present is 0.22 kg. Calculate the value of n in the fourth process, the net work of the cycle and sketch the cycle on a P-V diagram.

Solution:

- Process by process analysis,

Section 1- 2 (isothermal)

$$P_1V_1 = P_2V_2$$

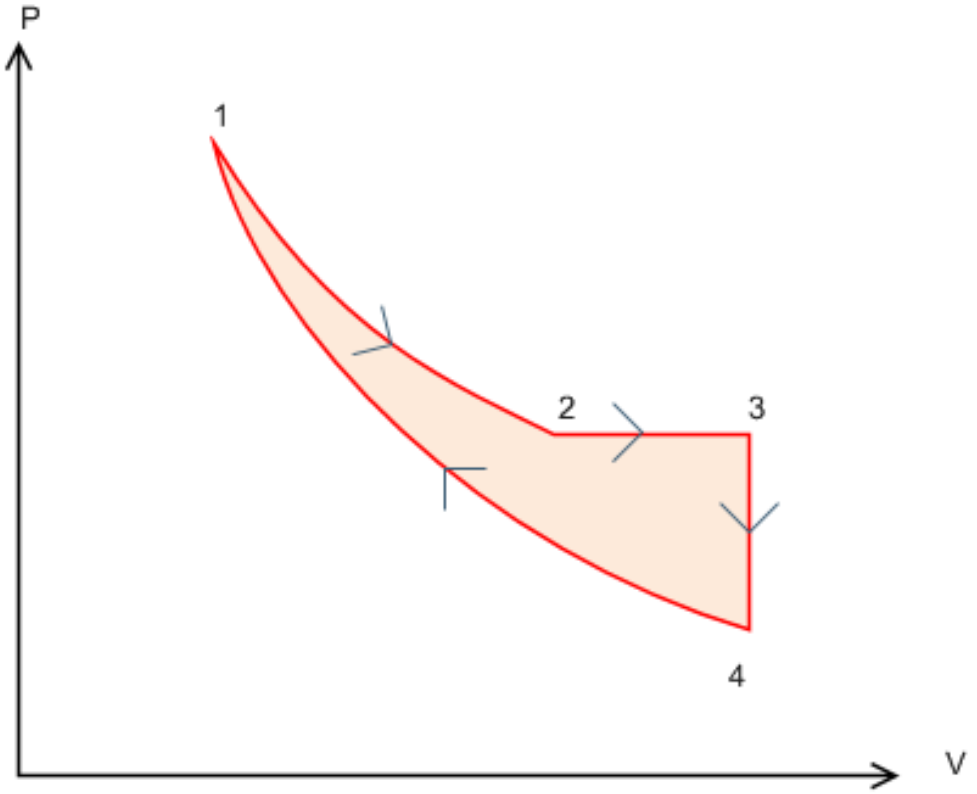
$$V_1 = \left(\frac{115}{415}\right)0.22(0.12)$$

$$= 0.00732\,m^3$$

$$W_{12} = P_1V_1 \ln\frac{V_2}{V_1}$$

$$= 415(0.00732)\ln\frac{0.0264}{0.00732}$$

$$= 3.895\,kJ$$



Section 2- 3(isobaric)

$$W_{23} = P(V_3 - V_2) = 0.525kJ$$

$$V_3 = \frac{0.525}{115} + 0.0264$$

$$= 0.03097m^3$$

Section 3- 4(isochoric)

$$W_{34} = 0$$

Section 4- 1(PolytroPic)

$$\frac{P_4}{P_1} = \left(\frac{V_1}{V_4}\right)^n$$

$$\frac{62}{415} = \left(\frac{0.00732}{0.03097}\right)^n$$

$$\ln 0.1494 = n \ln 0.2364$$

$$n = \underline{\underline{1.3182}}$$

$$W_{41} = \frac{P_1V_1 - P_4V_4}{1 - n}$$

$$= \frac{415(0.0072) - 62(0.03097)}{1 - 1.3182}$$

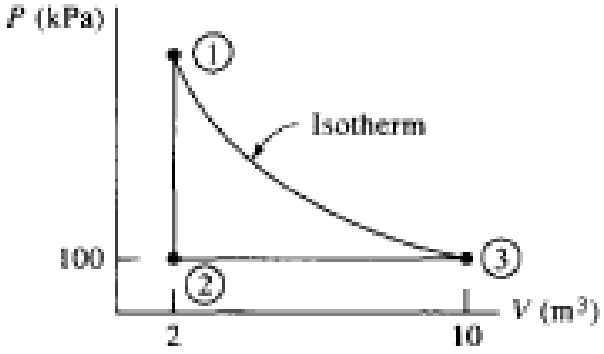
$$= -3.5124kJ$$

- The net work of the cycle

$$W_{net} = W_{12} + W_{23} + W_{34} + W_{41}$$

$$= \underline{\underline{0.9076kJ}}$$

3. Two kg of air experiences the three-process cycle shown in Fig. 3-14. Calculate the net work.



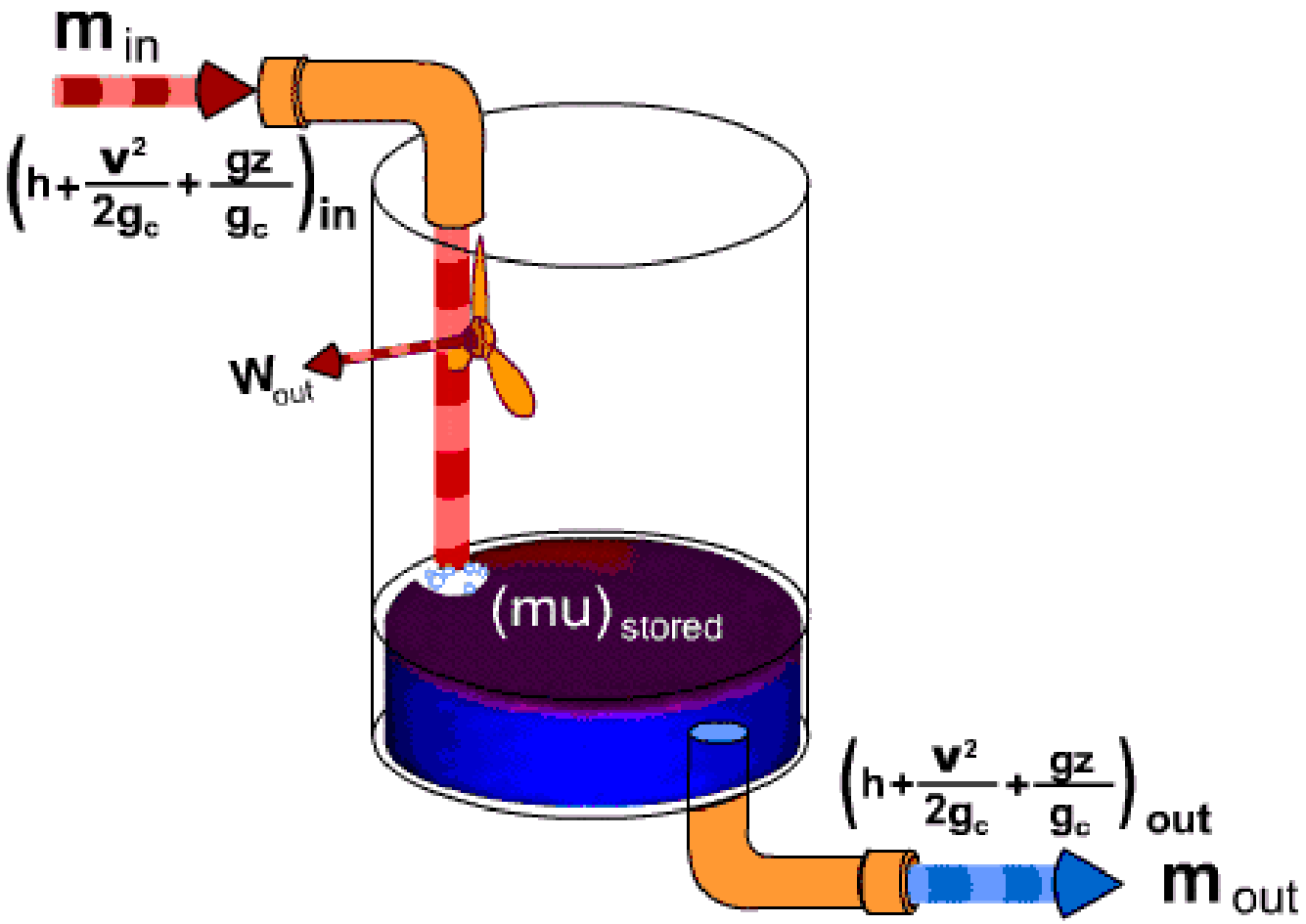
4. A system contains 0.15 m^3 of air pressure of 3.8 bars and 150^o C. It is expanded adiabatically till the pressure falls to 1.0 bar. The air is then heated at a constant pressure till its enthalpy increases by 70 kJ. Sketch the process on a P-V diagram and determine the total work done.

Use c_p=1.005 kJ/kg.K and c_v=0.714 kJ/kg.K

FIRST LAW OF THERMODYNAMICS

MASS & ENERGY ANALYSIS OF CONTROL VOLUME

Applications that show the use of the **principles of conservation of mass and energy, together with relationships among properties for the analysis of control volumes at steady state.**


$\dot{m}_{in}$
$\left(h+\frac{v^2}{2g_c}+\frac{gz}{g_c}\right)_{in}$
$\dot{W}_{out}$
$(mu)_{stored}$
$\left(h+\frac{v^2}{2g_c}+\frac{gz}{g_c}\right)_{out}$
$\dot{m}_{out}$

Conservation of Mass

- Conservation of mass is one of the most fundamental principles in nature. We are all familiar with this principle, and it is not difficult to understand it!
- For closed system, the conservation of mass principle is implicitly used since the mass of the system remain constant during a process.
- However, for control volume, mass can cross the boundaries. So the amount of mass entering and leaving the control volume must be considered.

Mass and Volume Flow Rates

- Mass flow through a cross-sectional area per unit time is called the mass flow rate. Note the dot over the mass symbol indicates a time rate of change. It is expressed as

$$\dot{m} = \int \rho V . dA$$

- If the fluid density and velocity are constant over the flow cross-sectional area, the mass flow rate is

$$\dot{m} = \rho AV = \frac{AV}{v}$$

$$where \quad v = \frac{1}{\rho}$$

v *is called specific volume*

Principal of Conservation of Mass

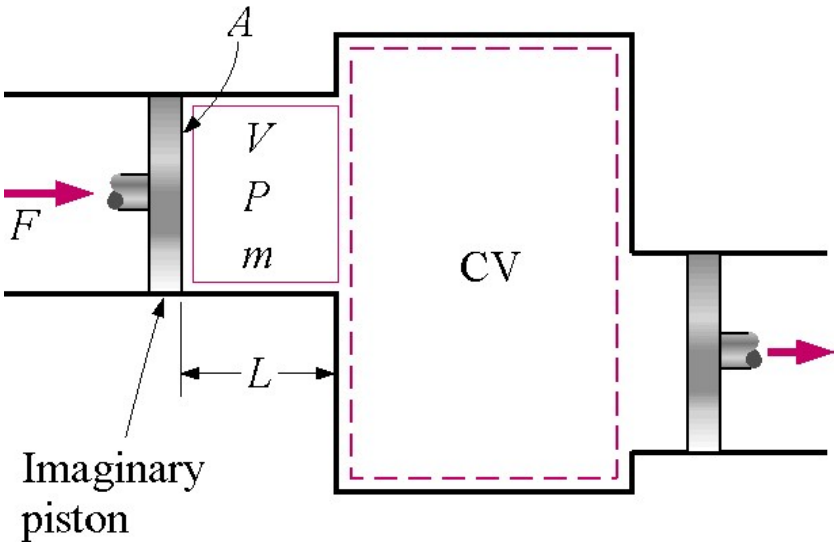
- The conservation of mass principle for a control volume can be expressed as

$$\dot{m}_{in} - \dot{m}_{out} = \dot{m}_{CV}$$

- For a steady state, steady flow process the conservation of mass principle becomes

$$\dot{m}_{in} = \dot{m}_{out} \quad (\text{kg/s})$$

Flow Work & The Energy of a Flowing Fluid



- As the fluid upstream pushes mass across the control volume, work done on that unit of mass is

$$\delta W_{flow} = F dL = F dL \frac{A}{A} = P dV = Pv\delta m$$

$$\delta w_{flow} = \frac{\delta W_{flow}}{\delta m} = Pv$$

Total Energy of a Flowing Fluid

- The total energy carried by a unit of mass as it crosses the control surface is the sum of the internal energy + flow work + potential energy + kinetic energy

$$\sum energy = u + Pv + \frac{V^2}{2} + gz = h + \frac{V^2}{2} + gz$$

The first law for a control volume can be written as

$$\dot{Q}_{net} - \dot{W}_{net} = \sum_{out} \dot{m}_{out} \left(h_{out} + \frac{V_{out}^2}{2} + gz_{out} \right) - \sum_{in} \dot{m}_{in} \left(h_{in} + \frac{V_{in}^2}{2} + gz_{in} \right)$$

Total Energy of a Flowing Fluid

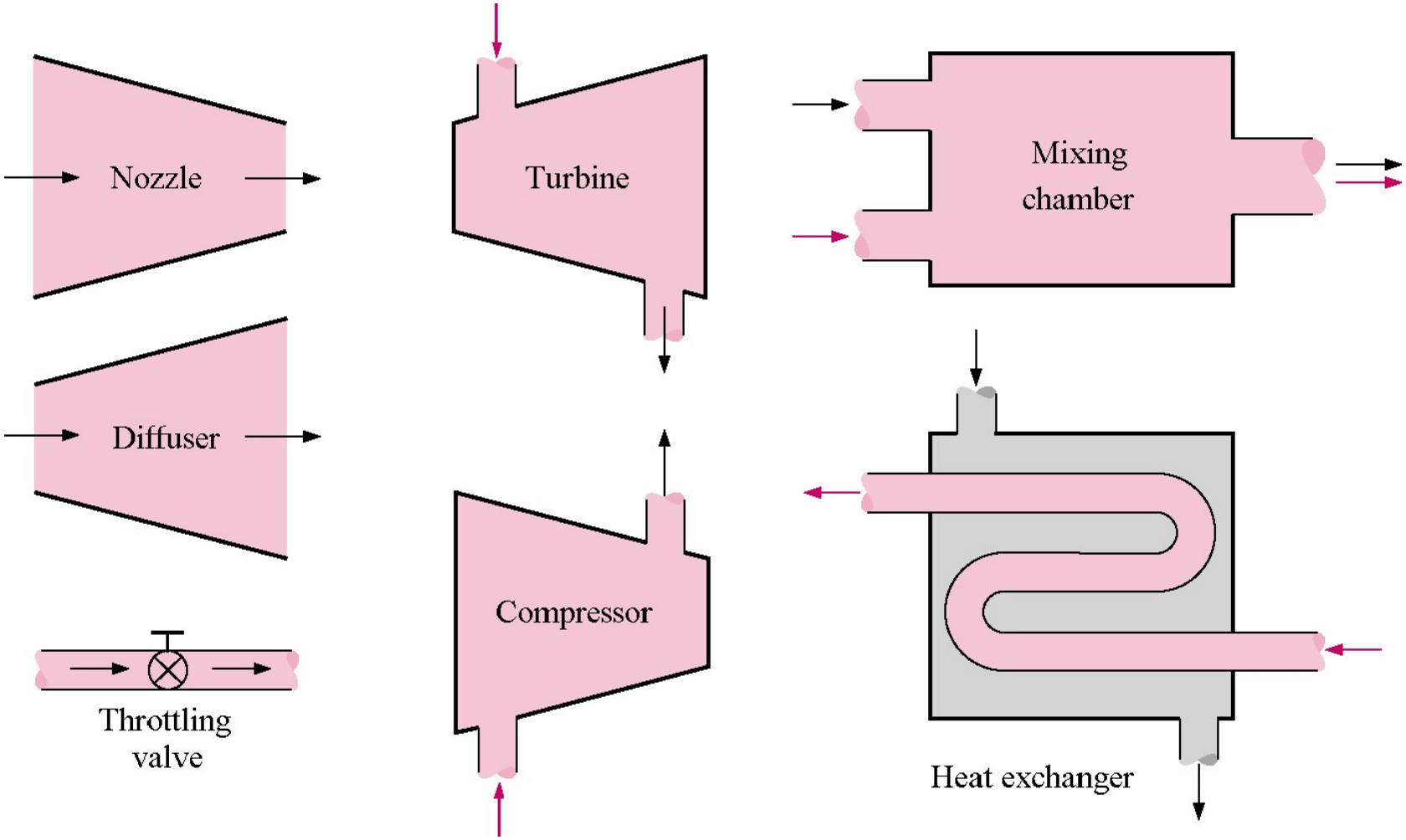
- The steady state, steady flow conservation of mass and first law of thermodynamics can be expressed in the following forms

$$q_{net} - w_{net} = \left(h_2 - h_1 + \frac{V_2^2 - V_1^2}{2000} + \frac{g(z_2 - z_1)}{1000} \right) \qquad (kJ/kg)$$

$$Q_{net} - W_{net} = m\left(h_2 - h_1 + \frac{V_2^2 - V_1^2}{2000} + \frac{g(z_2 - z_1)}{1000} \right) \qquad (kJ)$$

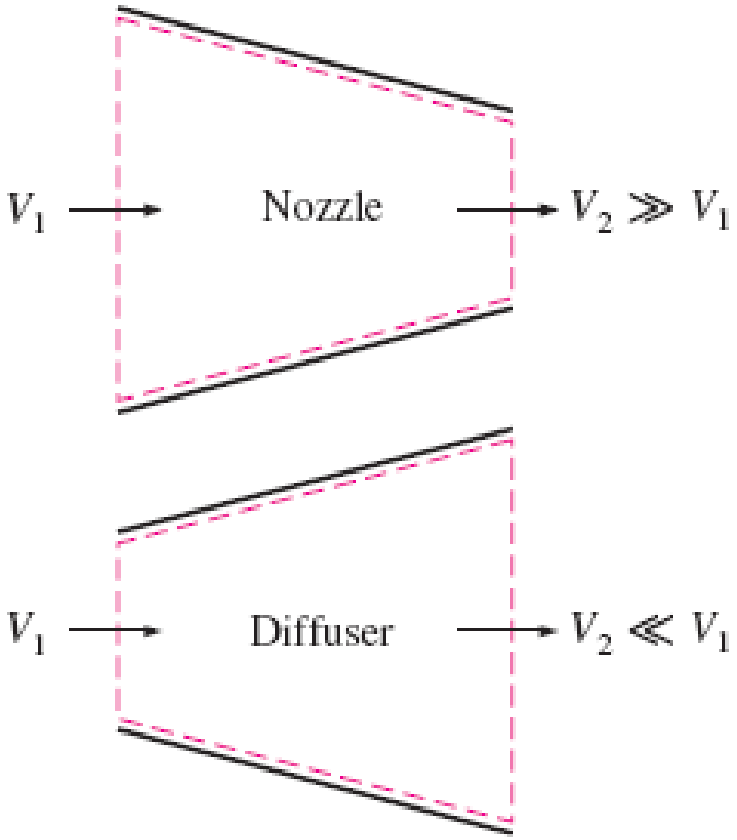
$$\dot{Q}_{net} - \dot{W}_{net} = \dot{m}\left(h_2 - h_1 + \frac{V_2^2 - V_1^2}{2000} + \frac{g(z_2 - z_1)}{1000} \right) \qquad (kW)$$

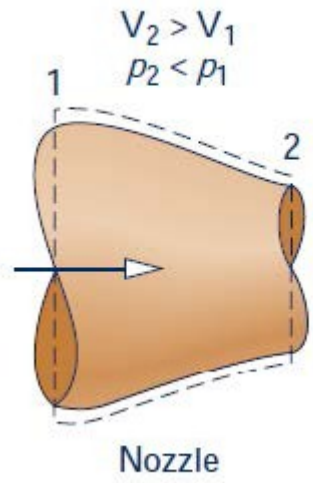
Steady-flow Engineering Devices

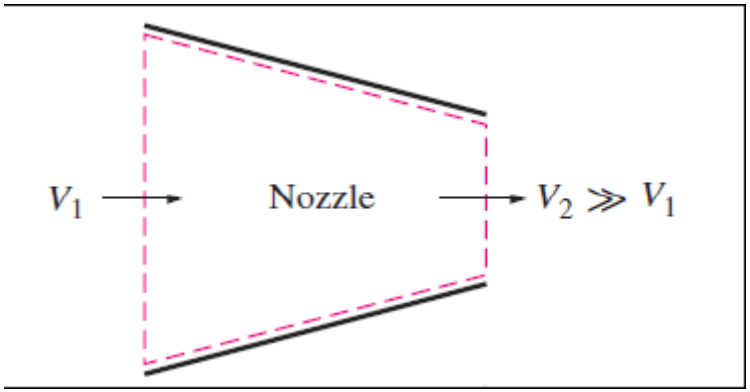


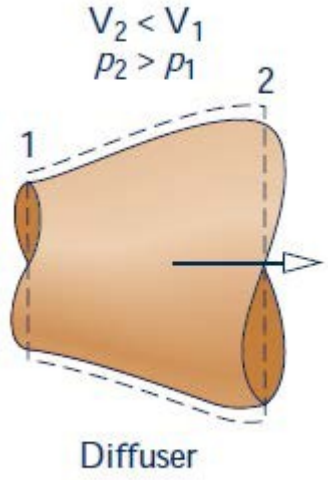
Nozzle & Diffuser

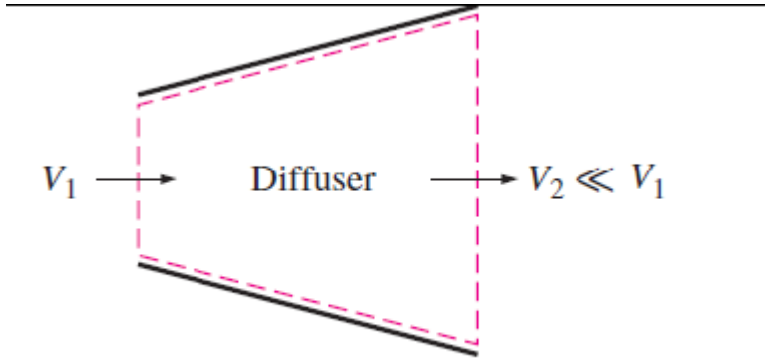
- **Nozzle** - device that increases the velocity fluid at the expense of pressure.
- **Diffuser** - device that increases pressure of a fluid by slowing it down.
- Commonly utilized in jet engines, rockets, space-craft and even garden hoses.
- $Q \approx 0$ (heat transfer from the fluid to surroundings very small
- $W = 0$ and $\Delta PE = 0$




$V_2 > V_1$
$p_2 < p_1$
1
2
Nozzle


V_1
Nozzle
$V_2 \gg V_1$


$V_2 < V_1$
$p_2 > p_1$
1
2
Diffuser


V_1
Diffuser
$V_2 \ll V_1$

- Energy balance (nozzle & diffuser):

$$\dot{Q}_{in} + \dot{W}_{in} + \sum_{in} \dot{m}_{in}\left(h_{in} + \frac{V_{in}^{2}}{2} + gz_{in} \right) = \dot{Q}_{out} + \dot{W}_{out} + \sum_{out} \dot{m}_{out}\left(h_{out} + \frac{V_{out}^{2}}{2} + gz_{out} \right)$$

$$\dot{m}_{in}\left(h_{in} + \frac{V_{in}^{2}}{2} \right) = \dot{m}_{out}\left(h_{out} + \frac{V_{out}^{2}}{2} \right)$$

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

$$\dot{Q}_{cv} \approx 0$$

$$\Delta PE = 0$$

$$\dot{W}cv = O$$

$$\Delta KE \neq 0$$

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

Example 3.6

Steam at 0.4 MPa, 300ºC, enters an adiabatic nozzle with a low velocity and leaves at 0.2 MPa with a quality of 90%. Find the exit velocity.

Solution:

State 1	State 2
$P_1 = 0.4 MPa$	$P_2 = 0.2 MPa$
$T_1 = 300^o C$	$x_2 = 0.9$
$V_1 \simeq 0$	

- Simplified energy balance:

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

$State\ 1$

$$\left.\begin{array}{l} P_1 = 0.4 MPa \\ T_1 = 300^o C \end{array}\right\} \begin{array}{l} h_1 = 3067.1 \frac{kJ}{kg} \\ (superheated) \end{array}$$

$State\ 2$

$$\left.\begin{array}{l} P_2 = 0.2 MPa \\ x_2 = 0.9 \end{array}\right\} \begin{array}{l} h_2 = h_{ff} + x_2 h_g \\ h_2 = 2486.1 \frac{kJ}{kg} \end{array}$$

- Exit velocity:

$$V_2 = \sqrt{2000(3067.1 - 2486.1)}$$

$$= 1078 m/s$$

Example 3.7

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

State 1 *State 2*

$P_1 = 80 kPa$ $V_2 \simeq 0$

$T_1 = 10^o C$

$V_1 = 200 m/s$

$A_1 = 0.4 m^2$

Solution:

- Simplified energy balance:

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

- From Ideal Gas Law:

$$v_1 = \frac{RT_1}{P_1} = 1.015 \frac{m^3}{kg}$$

- Mass flow rate

$$\dot{m} = \frac{1}{v_1} V_1 A_1$$
$$= \left(\frac{1}{1.015} \right) (200)(0.4)$$
$$= \underline{\underline{78.8 \frac{kg}{s}}}$$

- Enthalpy at state 1

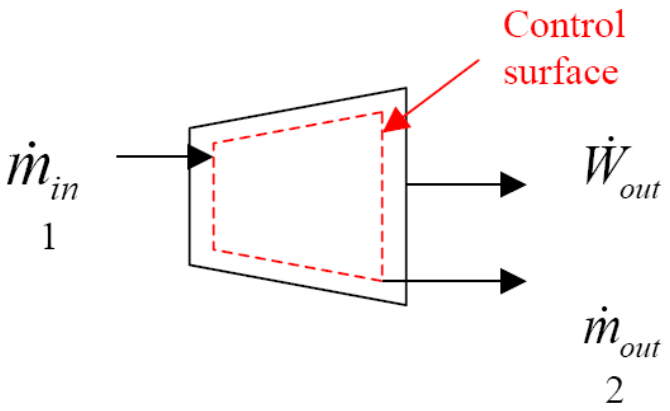
$$h_1 = C_p T_1 = 1.005(283)$$
$$= 284.42 \frac{kJ}{kg}$$

- From energy balance:

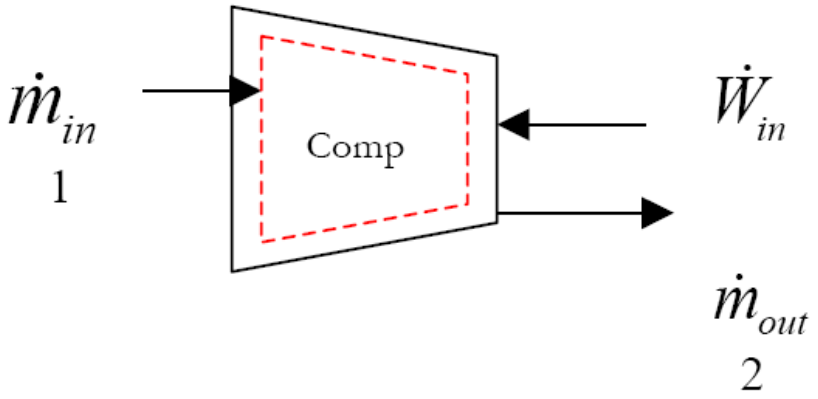
$$h_2 = h_1 + \frac{V_1^2}{2000}$$
$$= 284.42 + \frac{200^2}{2000}$$
$$= 304.42 \frac{kJ}{kg}$$

$$T_2 = \frac{h_2}{C_p}$$
$$= \frac{304.42}{1.005}$$
$$= \underline{\underline{302.9 K}}$$

Turbine & Compressor



Turbine control volume



Steady-Flow Compressor

- **Turbine** – a work producing device through the expansion of a fluid.
- **Compressor** (as well as pump and fan) - device used to increase pressure of a fluid and involves work input.
- Q = 0 (well insulated), ΔPE = 0, ΔKE = 0 (very small compare to Δenthalpy).

- Energy balance: for turbine

$$\dot{Q}_{in} + \dot{W}_{in} + \sum_{in} \dot{m}_{in}\left(h_{in} + \frac{V_{in}^{2}}{2} + gz_{in} \right) = \dot{Q}_{out} + \dot{W}_{out} + \sum_{out} \dot{m}_{out}\left(h_{out} + \frac{V_{out}^{2}}{2} + gz_{out} \right)$$

$$\dot{m}_{in}(h_{in}) = \dot{W}_{out} + \dot{m}_{out}(h_{out})$$

$$\dot{W}_{out} = \dot{m}(h_1 - h_2)$$

Energy balance: for compressor, pump and fan

$$\dot{Q}_{in} + \dot{W}_{in} + \sum_{in} \dot{m}_{in}\left(h_{in} + \frac{V_{in}^{2}}{2} + gz_{in} \right) = \dot{Q}_{out} + \dot{W}_{out} + \sum_{out} \dot{m}_{out}\left(h_{out} + \frac{V_{out}^{2}}{2} + gz_{out} \right)$$

$$\dot{W}_{in} + \dot{m}_{in}(h_{in}) = \dot{m}_{out}(h_{out})$$

$$\dot{W}_{in} = \dot{m}(h_2 - h_1)$$

Example 3.8

The power output of an adiabatic steam turbine is 5 MW. Compare the magnitudes of Δh, Δke, and Δpe. Then determine the work done per unit mass of the steam flowing through the turbine and calculate the mass flow rate of the steam.

Data : Inlet (P = 2 MPa, T = 400ºC,v = 50 m/s, z = 10 m)

Exit (P = 15 kPa, x = 90%, v = 180 m/s, z = 6m)

Solution:

State 1

$$\left.\begin{array}{l} p_1 = 2\,MPa \\ T_1 = 400^{o}C \end{array}\right\} \begin{array}{l} \text{superheated} \\ h_1 = 3248.4\ \frac{kJ}{kg} \end{array}$$

State 2

$$\left.\begin{array}{l} P_2 = 15\,kPa \\ x_2 = 0.9 \end{array}\right\} sat.mixture$$

$$h_2 = h_{ff2} + x_2 h_{g2}$$

$$= 225.94 + 0.9\ (2372.3)$$

$$= 2361.0\ \frac{kJ}{kg}$$

- From energy balance:

$$\cancel{\dot{Q}_{in}} + \cancel{\dot{W}_{in}} + \sum_{in} \dot{m}_{in}\left(h_{in} + \frac{V_{in}^{2}}{2} + gz_{in}\right) =$$

$$\dot{Q}_{out} + \dot{W}_{out} + \sum_{out} \dot{m}_{out}\left(h_{out} + \frac{V_{out}^{2}}{2} + gz_{out}\right)$$

- Solve the equation:

$$\Delta h = h_2 - h_1 = -887.39\ \frac{kJ}{kg}$$

$$\Delta KE = \frac{V_2^{2} - V_1^{2}}{2000} = 14.95\ \frac{kJ}{kg}$$

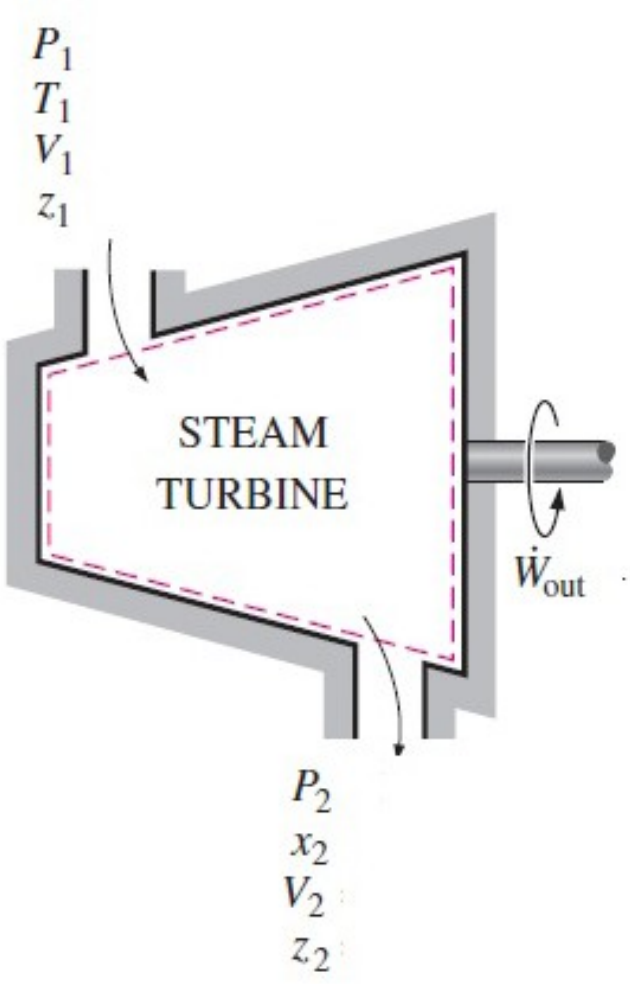
$$\Delta PE = \frac{g(z_2 - z_1)}{1000} = -0.04\ \frac{kJ}{kg}$$

- the work done per unit mass

$$W_{out} = \left[(h_1 - h_2) + \left(\frac{V_1^2 - V_2^2}{2000} \right) + \left(\frac{g(z_1 - z_2)}{1000} \right) \right]$$

$$= 887.39 + 14.95 + 0.04$$

$$= \underline{\underline{872.48 \frac{kJ}{kg}}}$$



- The mass flow rate

$$\dot{m} = \frac{\dot{W}_{out}}{W_{out}} = \frac{5000}{872.48} = \underline{\underline{5.73 \frac{kg}{s}}}$$

Example 3.9

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. Assuming the changes in kinetic and potential energies are negligible, determine the necessary power input to the compressor.

Solution:

- simplified energy balance:

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

$$= \dot{m}(h_2 - h_1) + \dot{m}q_{out}$$

State 1

$$\left.\begin{array}{l} P_1 = 100\,kPa \\ T_1 = 280\,K \end{array}\right\} \begin{array}{l} air \\ h_1 = 280.13 \frac{kJ}{kg} \end{array}$$

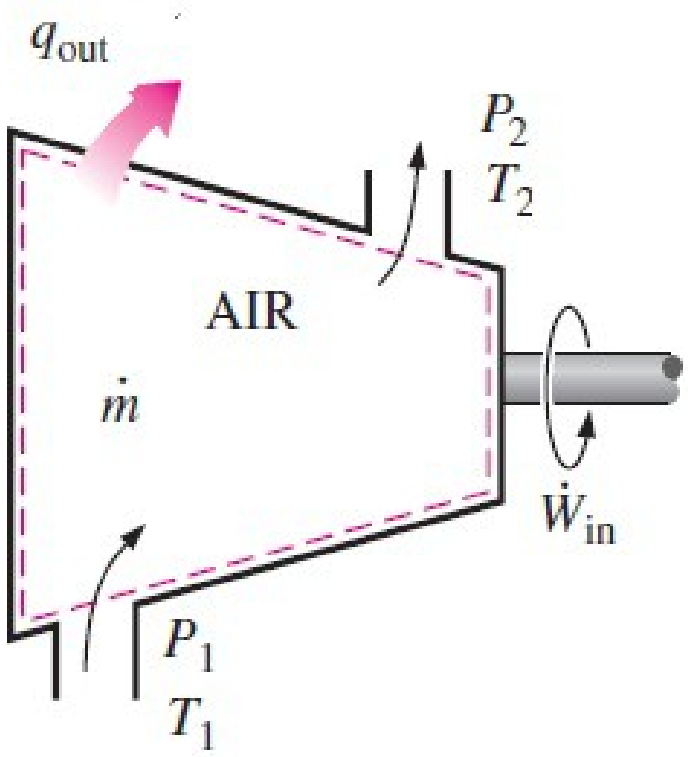
State 2

$$\left.\begin{array}{l} P_2 = 600\,kPa \\ T_2 = 400\,K \end{array}\right\} \begin{array}{l} air \\ h_2 = 400.98 \frac{kJ}{kg} \end{array}$$

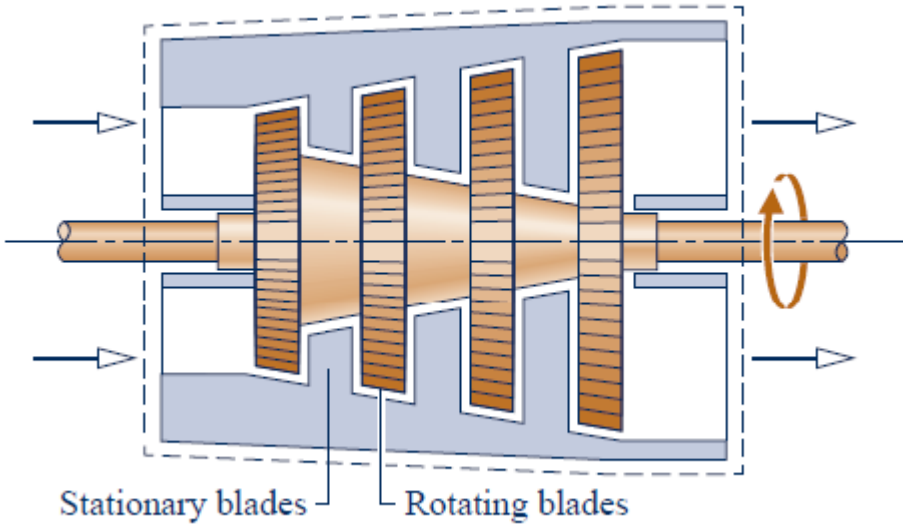
❖ Thus

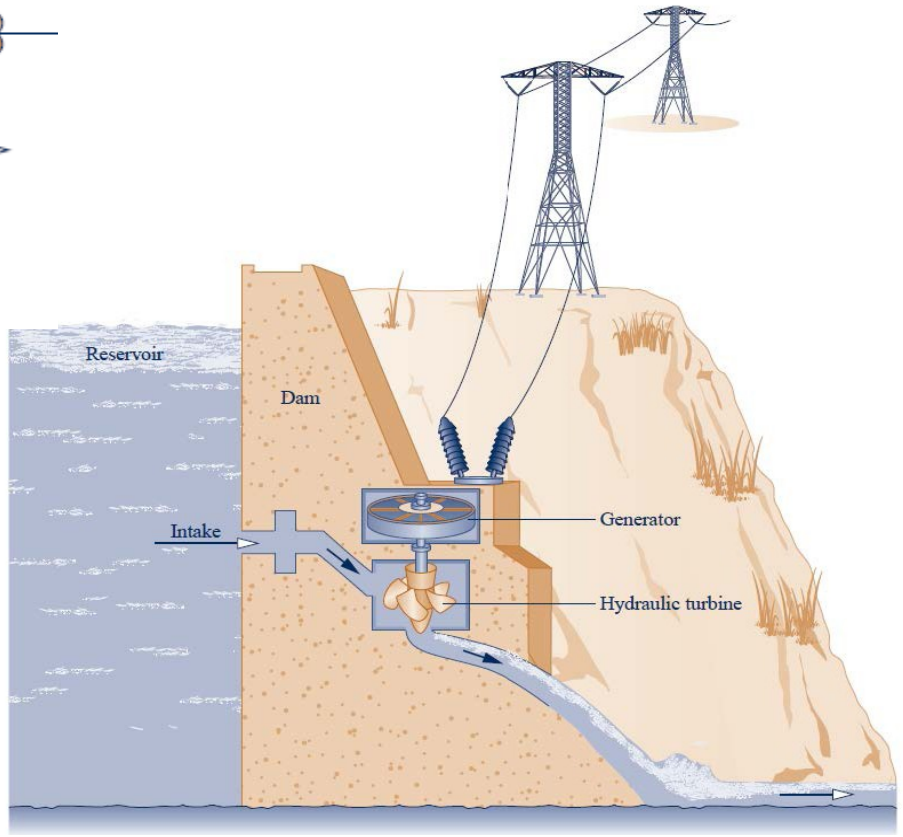
$$\dot{W}_{in} = 0.02\left[(400.98 - 280.13) + 16\right]$$

$$= \underline{\underline{2.74 kW}}$$

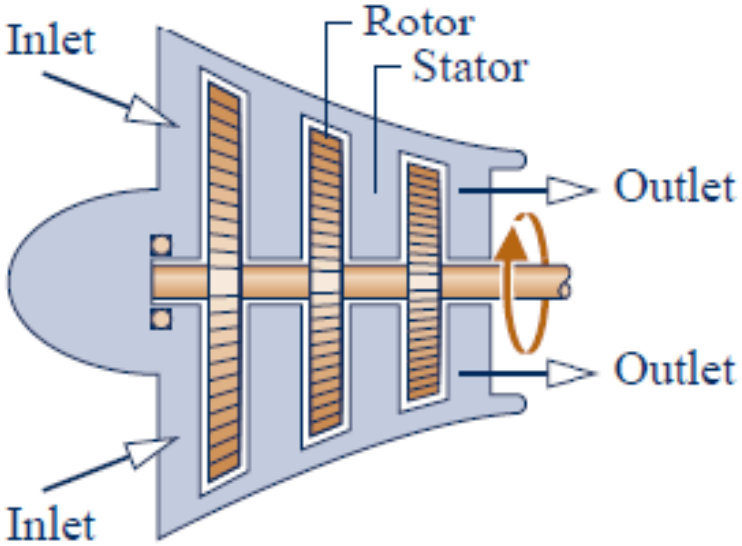


Hydraulic turbine



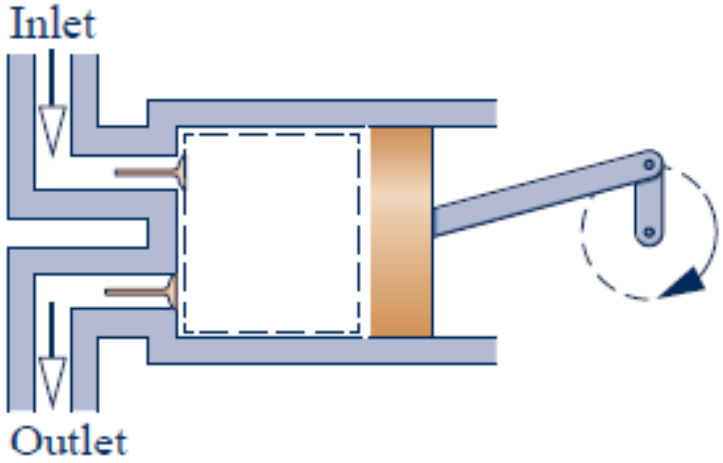


Compressor



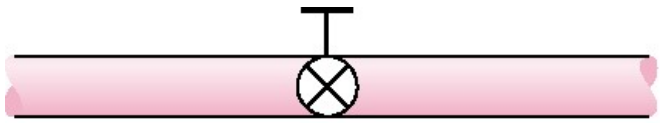
(*b*) Axial flow

$$\dot{W}_{cv} = \dot{m}(h_1 - h_2)$$



(*a*) Reciprocating

Throttling Valve



(*a*) An adjustable valve



(*b*) A porous plug



(*c*) A capillary tube

Flow-restricting devices that cause a significant pressure drop in the fluid.

Some familiar examples are ordinary adjustable valves and capillary tubes.

Assumptions

Adiabatic,no work done, (ΔPE & ΔKE) both zero. Therefore

Conservation of energy

$$u_1 + P_1 v_1 = u_2 + P_2 v_2$$

Example 3.10

Steam enters a throttling valve at 8000 kPa and 300°C and leaves at a pressure of 1600 kPa. Determine the final temperature and specific volume of the steam.

State 1

$$\left.\begin{array}{l} P_1 = 8000\,kPa \\ T_1 = 300^{o}C \end{array}\right\} \begin{array}{l} superheated \\ h_1 = 2786.5\,\frac{kJ}{kg} \end{array}$$

State 2

$$\left.\begin{array}{l} P_2 = 1600\,kPa \\ h_2 = h_1 \end{array}\right\} make\ interpolation$$

$P(kPa)$	$T(^{o}C)$	v_f	v_g	h_f	h_g
1500	198.29	0.001154	0.131710	844.55	2791
1600	T_2	v_{f2}	v_{g2}	h_{f2}	h_{g2}
1750	205.72	0.001166	0.113440	878.16	2795.2

- At state 2, the region is sat. mixture

$$T_2 = T_{sat} = \underline{\underline{201.3^{o}C}}$$

- Getting the quality at state 2

$$x_2 = \frac{h_2 - h_{f2}}{h_{g2} - h_{f2}}$$

$$= \frac{2786.5 - 857.994}{2792.68 - 857.994}$$

$$= 0.997$$

- Specific volume at state 2

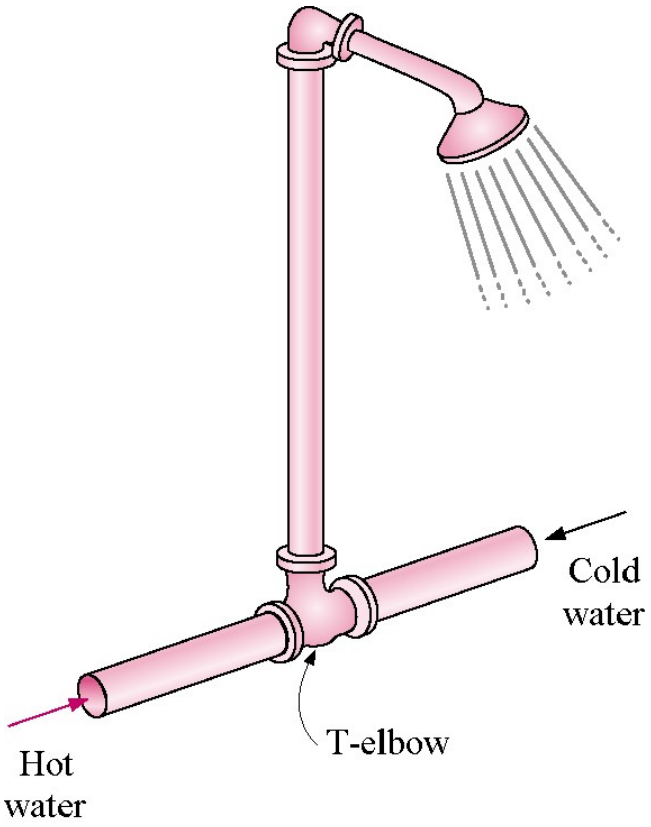
$$v_2 = v_{ff2} + x_2 v_{g2}$$

$$= 0.0011588 +$$

$$0.997(0.124402 - 0.0011588)$$

$$= \underline{\underline{0.1240 \frac{m^3}{kg}}}$$

Mixing Chamber



The section where the mixing process takes place.

An ordinary T-elbow or a Y-elbow in a shower, for example, serves as the mixing chamber for the cold- and hot-water streams.

Assumptions

Adiabatic,no work done, (ΔPE & ΔKE) both zero

Mixing Chamber

- Energy Balance:

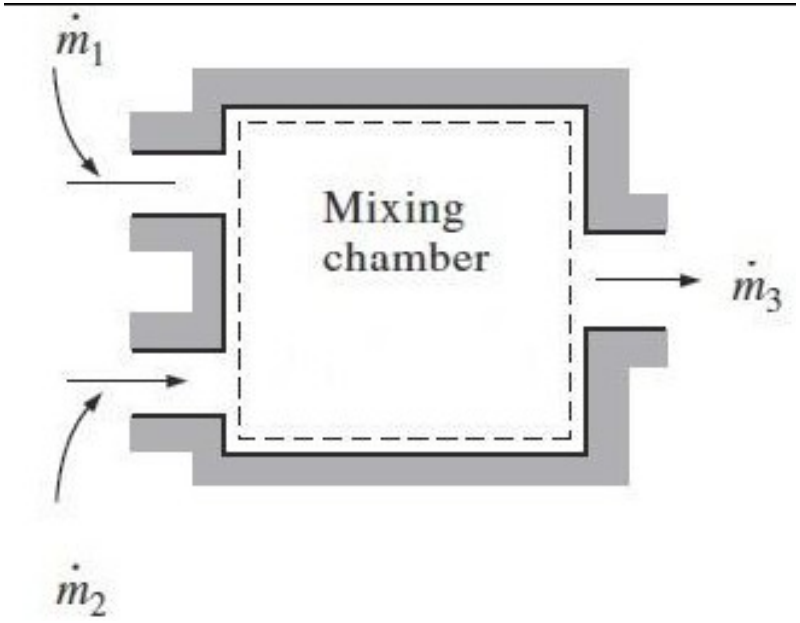
$$\dot{m}_1 h_1 = \dot{m}_2 h_2$$

$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3$$

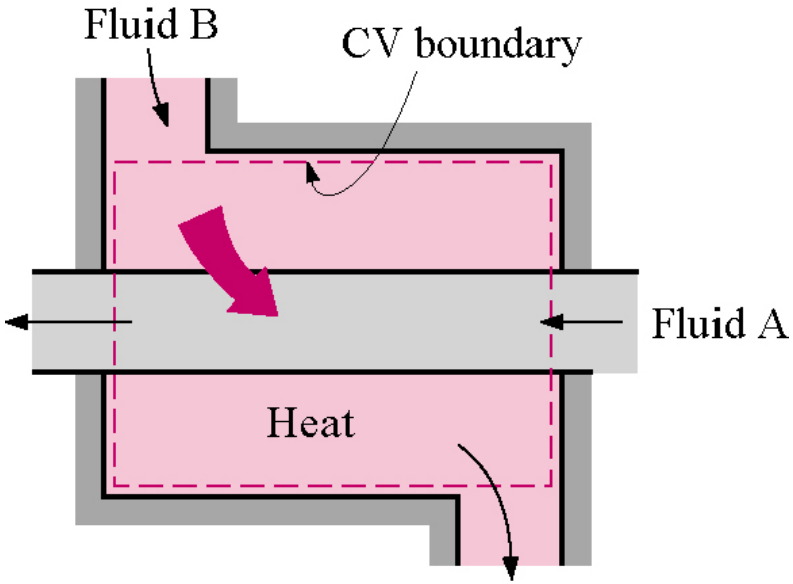
$$\dot{m}_1 h_1 + (\dot{m}_3 - \dot{m}_1) h_2 = \dot{m}_3 h_3$$

$$\dot{m}_1 (h_1 - h_2) = \dot{m}_3 (h_3 - h_2)$$

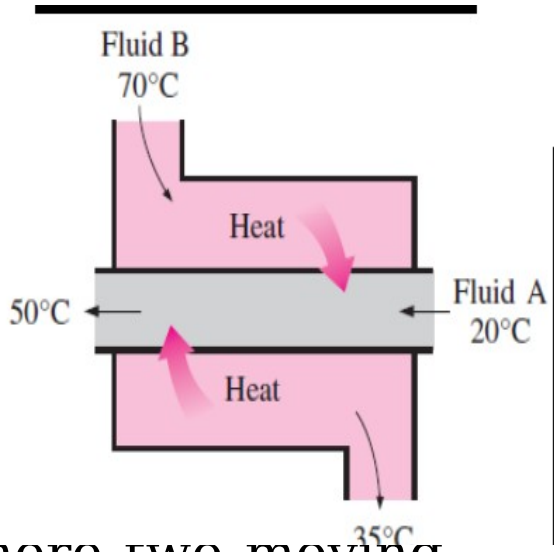
$$\dot{m}_1 = \dot{m}_3 \left(\frac{h_3 - h_2}{h_1 - h_2} \right)$$



Heat Exchanger



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



Devices where two moving fluid streams exchange heat without mixing.

Heat exchangers typically involve no work interactions (w = 0) and negligible kinetic and potential energy changes for each fluid stream.

The conservation of mass principle for a heat exchanger in steady operation can be expressed as : –*Under steady operation, the mass flow rate of each fluid stream flowing through a heat exchanger remains constant*.

Heat exchangers have innumerable domestic and industrial applications;

- **Home heating and cooling systems,**
- Automotive systems,
- Electrical power generation,
- Chemical processing.

In heat exchangers conservation of energy simplifies to
(W, KE, PE are assumed zero)

$$0 = \dot{Q}_{cv} + \sum_i \dot{m}_i h_i - \sum_e \dot{m}_e h_e$$

Example 3.11

Liquid sodium, flowing at 100 kg/s, enters a heat exchanger at 450°C and exits at 350°C. The specific heat of sodium is 1.25 kJ/kg.°C. Water enters at 5000 kPa and 20°C. Determine the minimum mass flux of the water so that the water does not completely vaporize. Neglect the pressure drop through the exchanger. Also, calculate the rate of heat transfer.

Solution:

- simplified energy balance:

$$\dot{m}_s h_{1s} + \dot{m}_w h_{1w} = \dot{m}_s h_{2s} + \dot{m}_w h_{2w}$$

$$\dot{m}_s (h_{1s} - h_{2s}) = \dot{m}_w (h_{2w} - h_{1w})$$

$$\dot{m}_s C_{p,s} (T_{1s} - T_{2s}) = \dot{m}_w (h_{2w} - h_{1w})$$

$$\underline{State\,1: water}$$

$$\left.\begin{array}{l} P_1 = 5000\,kPa \\ T_1 = 20^o C \end{array}\right\} \begin{array}{l} comp.liquid \\ h_{1w} = 88.61 \frac{kJ}{kg} \end{array}$$

$$\underline{State\,2: water}$$

$$P_2 = 5000\,kPa$$

$$h_{2w} = 2794.2 \frac{kJ}{kg}$$

Assume a sat. vapor state to obtain the max. allowable exiting enthalpy.

- the minimum mass flux of the water so that the water does not completely vaporize

$$\dot{m}_w = \frac{m_s C_{p,s}(T_{1s} - T_{2s})}{(h_{2w} - h_{1w})}$$

$$= \frac{100(1.25)(450 - 350)}{2794.2 - 88.61}$$

$$= \underline{\underline{4.62 \frac{kg}{s}}}$$

- the rate of heat transfer

$$\dot{Q}_w = \dot{m}_w (h_{2w} - h_{1w})$$

$$= 4.62(2794.2 - 88.61)$$

$$= \underline{\underline{12.5 MW}}$$