MCE535
Thermal Power and Propulsive Systems

Lecture 02: 19/09/2017

Dr. Ayokunle O. Balogun
balogun.ayokunle@lmu.edu.ng

Class: Thursday (3 – 5 pm)

Etiquettes and MOP

- Attendance is a requirement.
- There may be class assessments, during or after lecture.
- Computational software will be employed in solving problems
- Conceptual understanding will be tested
- Lively discussions are integral part of the lectures.

Lecture content

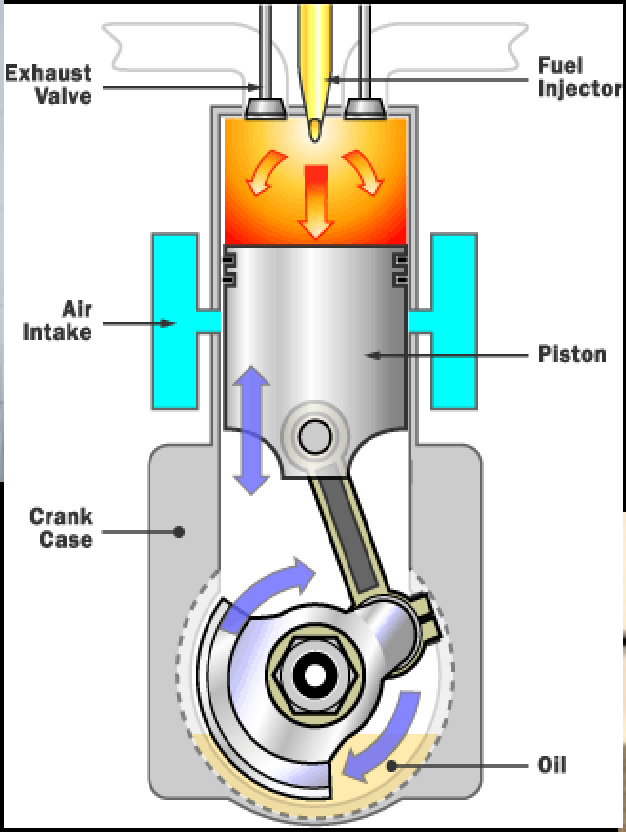
Mass and Energy Analysis of Control volumes

- Mass and volume flow rates
- Conservation of mass for control volume
- Flow work and energy of flowing fluid
- Conservation of energy for control volume

Recommended Textbook:

- Thermodynamics: An Engineering Approach by Cengel Y.A. & Boles M.A. 8th Edition

Conceptual Understanding



How would you analyse these devices?

Conservation of Energy for Control volumes

- The conservation of mass and energy principles for control volumes apply to systems having mass crossing the system boundary.

- The ***mass*** and ***energy*** content of the open system may change when mass enters or leaves the control volume.

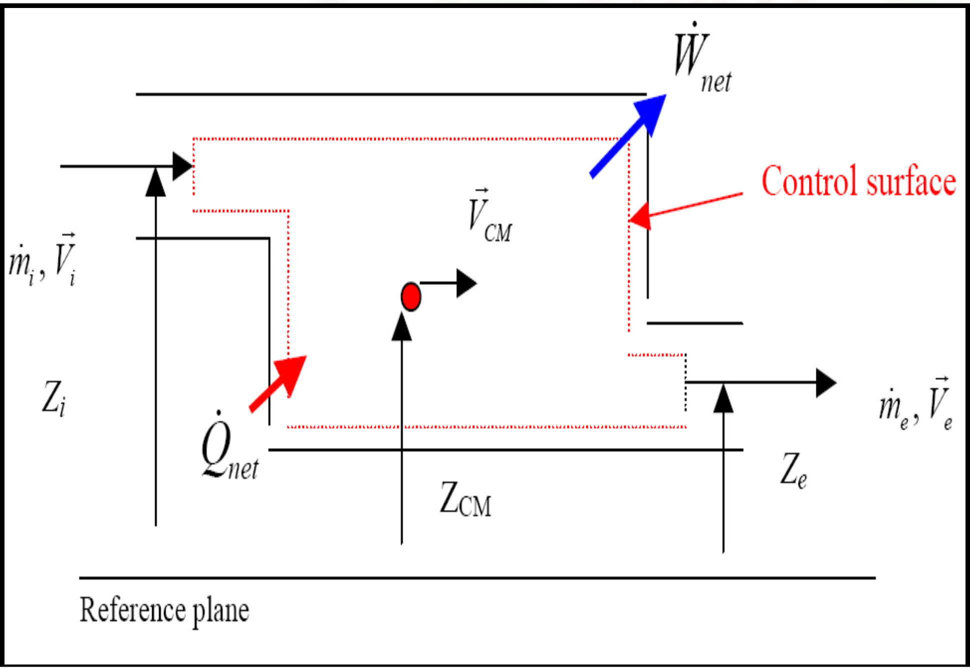
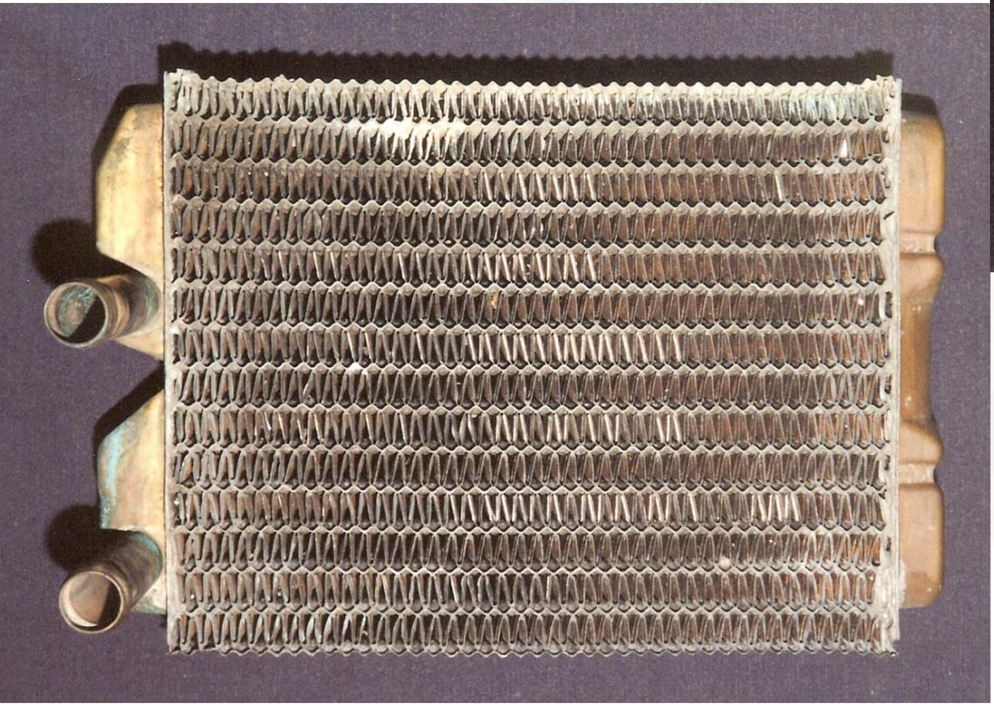


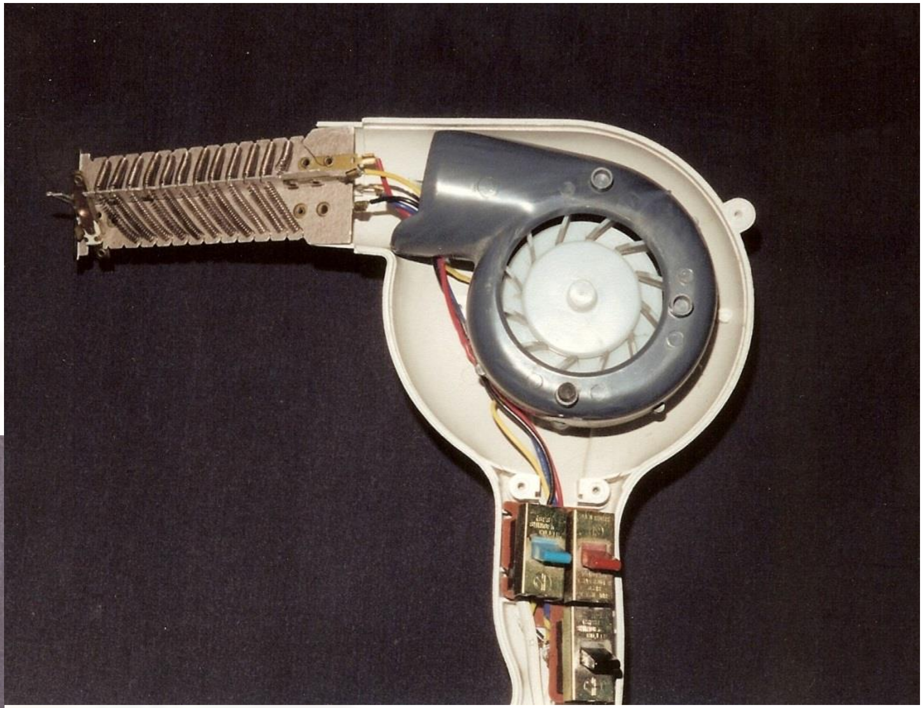
Fig 1: Typical schematic of a control volume or an open system

- Thermodynamic processes involving control volumes can be looked at in two groups: (1) ***steady-flow*** or (2) ***unsteady-flow*** processes.

Conservation of Energy for Control volumes (cont'd)

A heat exchanger, the heater core from a 1966 289 V8 Mustang, is an example of an open system device. Cooling water flows into and out of the tubes and air is forced through the fin structure.





A hair drier is an example of a one entrance, one exit open system that receives electrical work input to drive the fan and power the resistance heater.

Photo by M. A. Boles

Fig 2: Examples of devices modeled as control volumes

Conservation of Energy for Control volumes (cont'd)

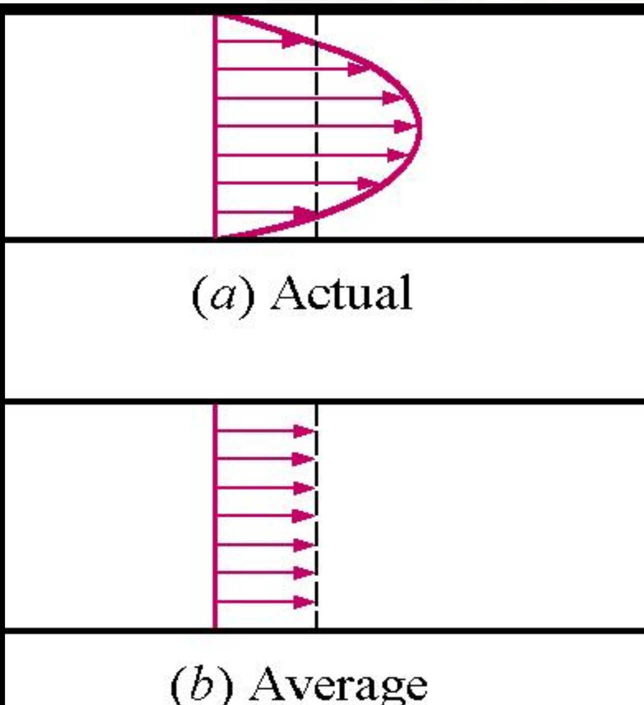
Mass Flow Rate

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

$$\dot{m} = \int_A \rho \vec{V}_n \, dA \qquad (1)$$

where $\vec{V}_n$ is the velocity normal to the cross-sectional flow area.

Fig 3: The average velocity V_{avg} is defined as the average speed through a cross-section



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

$$\dot{m} = \rho \vec{V}_{ave} A = \frac{\vec{V}_{ave} A}{v} \qquad (2)$$

where ρ is density, kg/m^3 (= $1/v$ [*specific volume*]), A is cross-sectional area, m^2; and $\vec{V}_{ave}$ is the average fluid velocity normal to the area, m/s.

Volume Flow Rate

- The fluid volume flowing through a cross-section per unit time is called the volume flow rate $\dot{V}$. The volume flow rate is given by integrating the product of the velocity normal to the flow area and the differential flow area over the flow area.
- If the velocity over the flow area is a constant, the volume flow rate is given by

$$\dot{V} = \vec{V}A \qquad (m^3/s) \qquad (3)$$

- The mass and volume flow rate are related by

$$\dot{m} = \rho\dot{V} = \frac{\dot{V}}{v} \qquad (kg/s) \qquad (4)$$

Example 1

- Refrigerant-134a at 200 kPa, 40% quality, flows through a 1.1-cm inside diameter, *d*, tube with a velocity of 50 m/s. Find the mass flow rate of the refrigerant-134a.

Example 2

- Air at 100 kPa, 50^{o}C, flows through a pipe with a volume flow rate of 40 m^3/min. Find the mass flow rate through the pipe, in kg/s.

Conservation of Mass for General Control Volume

- The conservation of mass principle for the open system or control volume is expressed as

$$\begin{bmatrix}\text{Sum of rate}\\ \text{of mass flowing}\\ \text{into control volume}\end{bmatrix} - \begin{bmatrix}\text{Sum of rate}\\ \text{of mass flowing}\\ \text{from control volume}\end{bmatrix} = \begin{bmatrix}\text{Time rate change}\\ \text{of mass inside}\\ \text{control volume}\end{bmatrix}$$

or

$$\sum \dot{m}_{in} - \sum \dot{m}_{out} = \Delta \dot{m}_{system} \qquad (kg/s) \qquad (5)$$

Steady-State, Steady-Flow Processes

- Most energy conversion devices operate steadily over long periods of time.
- The rates of heat transfer and work as well as states of the mass stream crossing the control surface are constant with time.

Under these conditions the ***mass*** and ***energy*** content of the control volume are constant with time, i.e., they are steady.

$$\frac{dm_{CV}}{dt} = \Delta\dot{m}_{CV} = 0 \qquad (6)$$

Steady-state, Steady-Flow Conservation of Mass:

- Since the mass of the control volume is constant with time during the steady-state, steady-flow process Eq (5) becomes

$$\begin{bmatrix}\text{Sum of rate} \\ \text{of mass flowing} \\ \text{into control volume}\end{bmatrix} = \begin{bmatrix}\text{Sum of rate} \\ \text{of mass flowing} \\ \text{from control volume}\end{bmatrix}$$

or

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \qquad (kg/s) \qquad (7)$$

Special Case: Steady Flow of an Incompressible Fluid

- The mass flow rate is related to volume flow rate and fluid density by

$$\dot{m} = \rho\dot{V} \qquad (8)$$

- For one entrance, one exit steady flow control volume, the mass flow rates are related by

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

$$\rho_{\text{in}}\dot{V}_{\text{in}} = \rho_{\text{out}}\dot{V}_{\text{out}}$$

$$\rho_{\text{in}} = \rho_{\text{out}} \quad \text{incompressible assumption}$$

$$\dot{V}_{\text{in}} = \dot{V}_{\text{out}}$$

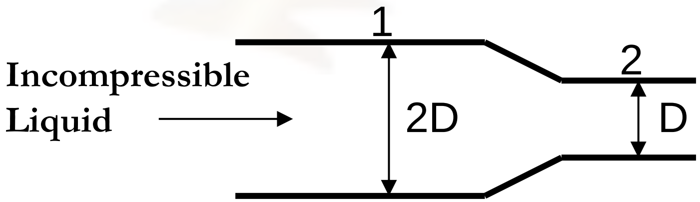
$$\vec{V}_{\text{in}}A_{\text{in}} = \vec{V}_{\text{out}}A_{\text{out}}$$

Word of caution: This result applies only to incompressible fluids. Most thermodynamic systems deal with processes involving compressible fluids such as ideal gases, steam, and the refrigerants for which the above relation **will not apply**.

Example 3 Geometry Effects on Fluid Flow

- An incompressible liquid flows through the pipe shown in the figure. The velocity at location 2 is

A) $\frac{1}{4}\vec{V}_1$ B) $\frac{1}{2}\vec{V}_1$ C) $2\vec{V}_1$ D) $4\vec{V}_1$



Flow work and the energy of a flowing fluid

- Energy flows into and from the control volume with the mass. The energy required to push the mass into or out of the control volume is known as the ***flow work*** or ***flow energy***.

- The fluid upstream of the control surface acts as a piston to push a unit of mass into or out of the control volume as shown in Fig 4.

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

$$W_{flow} = F\,L = F\,L\frac{A}{A} = PV = Pmv$$

$$w_{flow} = \frac{W_{flow}}{m} = Pv \qquad (9)$$

The term ***Pv*** is the ***flow work*** done on the unit of mass as it crosses the boundary

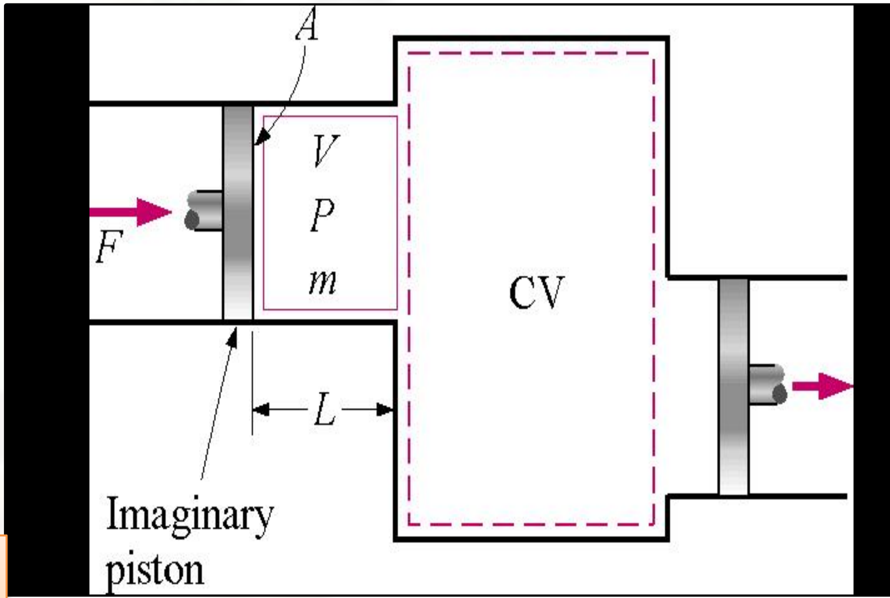


Fig 4: Schematic for flow work

The total energy of 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*, and *kinetic energy*.

$$\theta = u + Pv + \frac{\vec{V}^2}{2} + gz \qquad \text{kJ/kg} \qquad (10)$$

$$= h + \frac{\vec{V}^2}{2} + gz$$

- Here we have used the definition of enthalpy, ***h* = *u* + *Pv***.

Energy transport by mass

- Amount of energy transport across a control surface:

$$E_{mass} = m\theta = m\left(h + \frac{\vec{V}^2}{2} + gz\right) \quad \text{(kJ)} \qquad (11)$$

- Rate of energy transport across a control surface:

$$\dot{E}_{mass} = \dot{m}\theta = \dot{m}\left(h + \frac{\vec{V}^2}{2} + gz\right) \quad (kW) \qquad (12)$$

Example 4

- Steam is leaving a 4-L pressure cooker whose operating pressure is 150 kPa. It is observed that the amount of liquid in the cooker has decreased by 0.6 L in 40 min after the steady operating conditions are established, and the cross-sectional area of the exit opening is 8 mm^2.

Determine

(a) the mass flow rate of the steam and the exit velocity
(b) the total and flow energies of the steam per unit mass, and
(c) the rate at which energy leaves the cooker by steam.

Conservation of Energy for General Control Volume

- The conservation of energy principle (*first law*) for the control volume in terms of rate of energy transfers is expressed as Eq 13

$$\begin{bmatrix}\text{Sum of rate}\\ \text{of energy flowing}\\ \text{into control volume}\end{bmatrix} - \begin{bmatrix}\text{Sum of rate}\\ \text{of energy flowing}\\ \text{from control volume}\end{bmatrix} = \begin{bmatrix}\text{Time rate change}\\ \text{of energy inside}\\ \text{control volume}\end{bmatrix}$$

or

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\substack{\text{Rate of net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{\Delta\dot{E}_{system}}_{\substack{\text{Rate change in internal, kinetic,}\\ \text{potential, etc., energies}}} \quad (kW) \qquad (13)$$

- Energy flows into and from the control volume with the mass, energy enters because net heat is transferred to the control volume, and energy leaves because the control volume does net work on its surroundings, thus the first law for the control volume becomes

$$\dot{Q}_{net} + \sum \underbrace{\dot{m}_i\theta_i}_{\text{for each inlet}} - \dot{W}_{net} - \sum \underbrace{\dot{m}_e\theta_e}_{\text{for each exit}} = \frac{dE_{CV}}{dt} \qquad (kW) \qquad (14)$$

- NOTE: the composition of θ as in Eq 10.

$$\dot{E}_{in} - \dot{E}_{out} = \Delta\dot{E}_{CV}$$

$$\dot{Q}_{net} + \underbrace{\sum \dot{m}_i\left(h_i + \frac{\vec{V}_i^{\,2}}{2} + gz_i\right)}_{\text{for each inlet}} - \dot{W}_{net} - \underbrace{\sum \dot{m}_e\left(h_e + \frac{\vec{V}_e^{\,2}}{2} + gz_e\right)}_{\text{for each exit}} = \Delta\dot{E}_{CV} \qquad (15)$$

- Where the time rate change of the energy of the control volume has been written as $\Delta\dot{E}_{CV}$

Steady-State, Steady-Flow Processes

- Since most energy conversion devices operate steadily over long periods of time. The ***mass*** and ***energy*** content of the control volume may be viewed as constant with time, thus, implying Eq (16)

$$\frac{dm_{CV}}{dt} = \Delta\dot{m}_{CV} = 0$$
$$\frac{dE_{CV}}{dt} = \Delta\dot{E}_{CV} = 0 \qquad (16)$$

Steady-state, Steady-Flow Conservation of Mass:

As a result of Eq. (16), Eqs (17) and (18) respectively emerges for *mass* and *energy* contents

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \qquad (kg/s) \qquad (17)$$

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

$$\underbrace{\dot{E}_{in}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work, and mass} \\ \text{into the system}}} = \underbrace{\dot{E}_{out}}_{\substack{\text{Rate of energy transfer} \\ \text{by heat, work, and mass} \\ \text{from the system}}}$$

- With the flow of mass across the control surface, energy as heat is transferred to the control volume, and leaves the control volume as work done on its surroundings, and the steady-state, steady-flow first law becomes

$$\dot{Q}_{in} + \dot{W}_{in} + \underbrace{\sum \dot{m}_i \left(h_i + \frac{\vec{V}_i^2}{2} + gz_i \right)}_{\text{for each inlet}} = \dot{Q}_{out} + \dot{W}_{out} + \underbrace{\sum \dot{m}_e \left(h_e + \frac{\vec{V}_e^2}{2} + gz_e \right)}_{\text{for each exit}} \qquad (18)$$

Often this result is written as

$$\dot{Q}_{net} - \dot{W}_{net} = \underbrace{\sum \dot{m}_e \left(h_e + \frac{\vec{V}_e^2}{2} + gz_e \right)}_{\text{for each exit}} - \underbrace{\sum \dot{m}_i \left(h_i + \frac{\vec{V}_i^2}{2} + gz_i \right)}_{\text{for each inlet}} \qquad (19)$$

where

$$\dot{Q}_{net} = \sum \dot{Q}_{in} - \sum \dot{Q}_{out}$$

$$\dot{W}_{net} = \sum \dot{W}_{out} - \sum \dot{W}_{in}$$

Steady-state, steady-flow for one entrance and one exit

- Thermodynamic devices such as pumps, fans, compressors, turbines, nozzles, diffusers, and heaters operate with one entrance and one exit. The steady-state, steady-flow conservation of mass and first law of thermodynamics for these systems reduce to

$$\dot{m}_1 = \dot{m}_2 \qquad (kg/s) \qquad (20)$$

$$\frac{1}{v_1}\vec{V}_1 A_1 = \frac{1}{v_2}\vec{V}_2 A_2 \qquad (21)$$

$$\dot{Q} - \dot{W} = \dot{m}\left[h_2 - h_1 + \frac{\vec{V}_2^2 - \vec{V}_1^2}{2} + g(z_2 - z_1) \right] \qquad (kW) \qquad (22)$$

- Oftentimes the KE and PE are neglected, thus the energy conservation equation yields Eq (23)

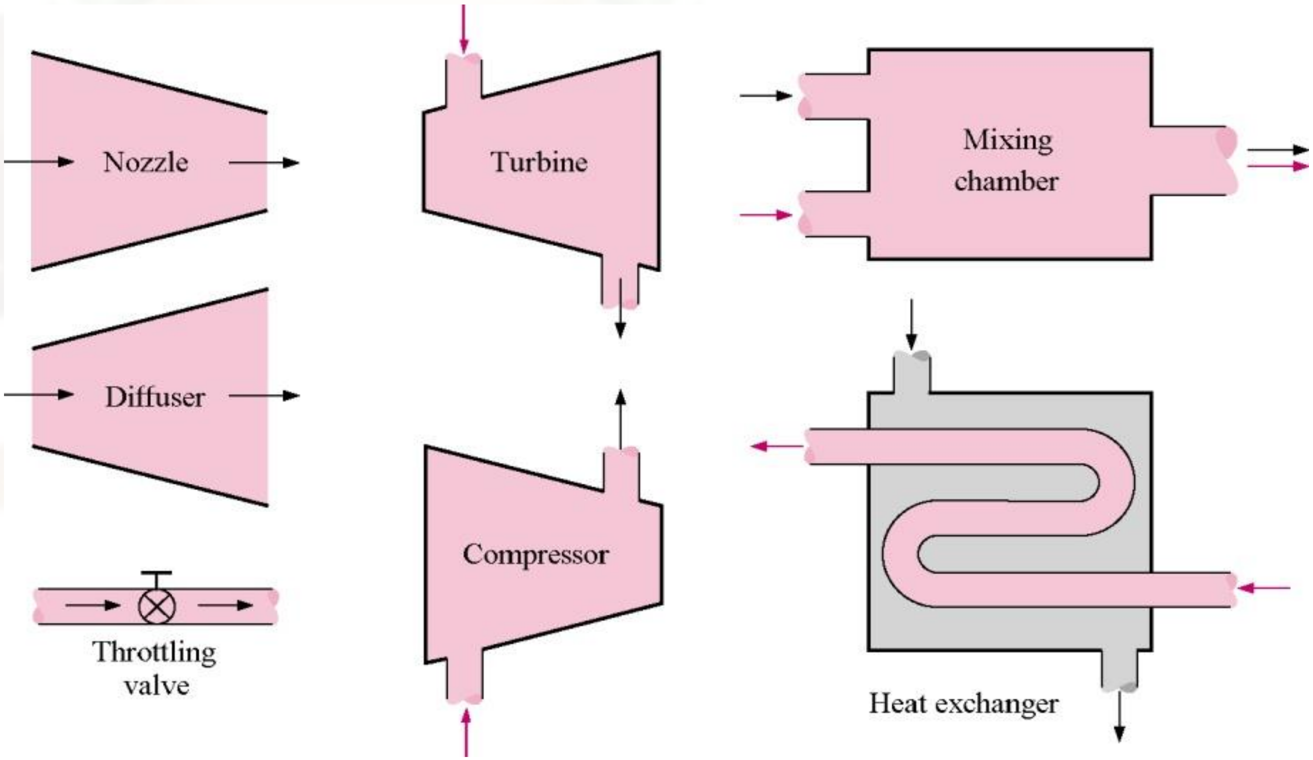
$$\dot{Q} - \dot{W} = \dot{m}(h_2 - h_1) \qquad (kW) \tag{23}$$

- Eq (23) is often written per unit mass flow as Eq (24)

$$q - w = (h_2 - h_1) \qquad (kJ / kg) \tag{24}$$

where $q = \frac{\dot{Q}}{\dot{m}}$ and $w = \frac{\dot{W}}{\dot{m}}$.

Some Steady-Flow Engineering Devices



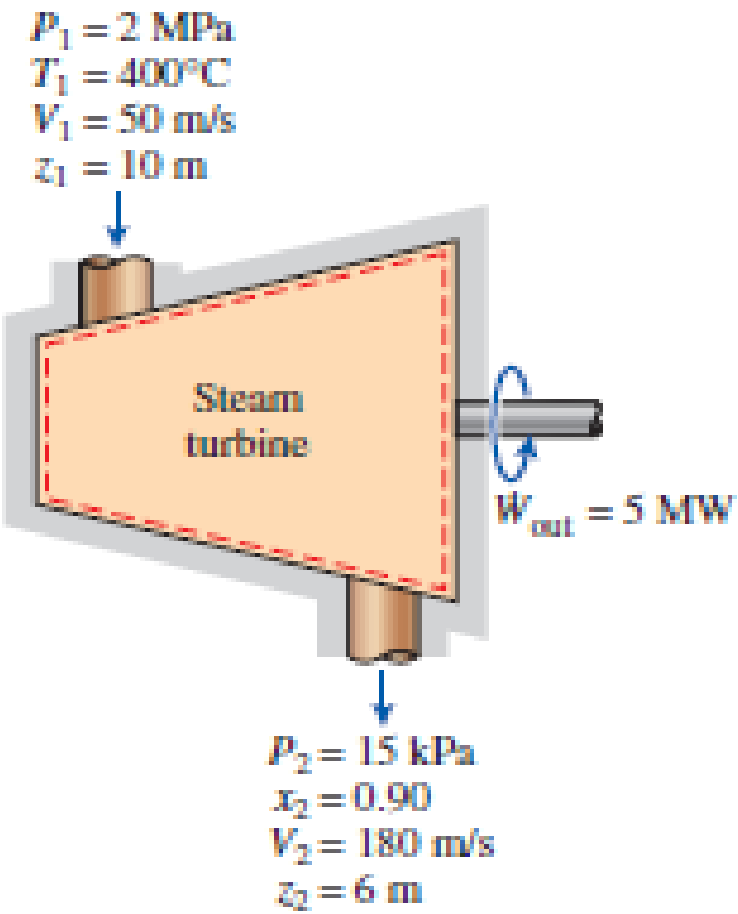
Example 5

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 Fig. below.

(*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.



- The Throttle may be a simple as the *expansion tube* used in automobile air conditioning systems to cause the refrigerant pressure drop between the exit of the condenser and the inlet to the evaporator.

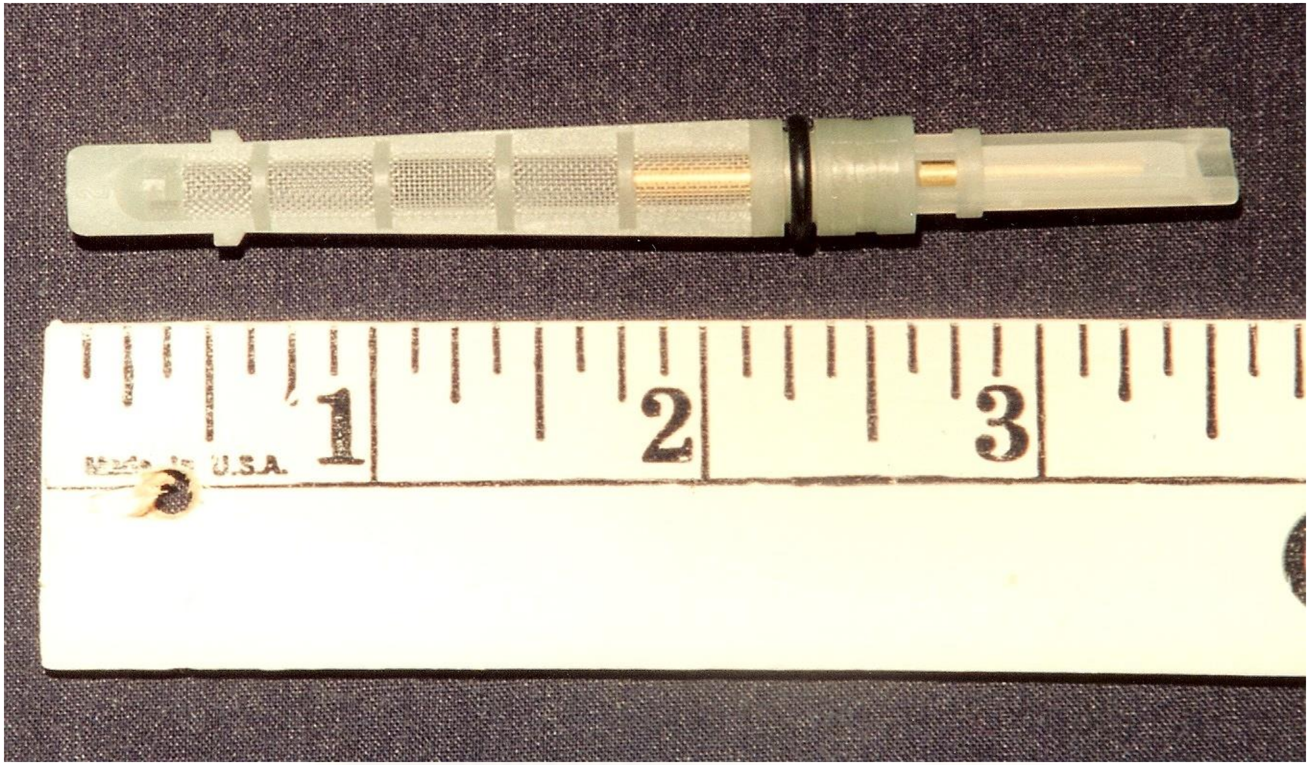
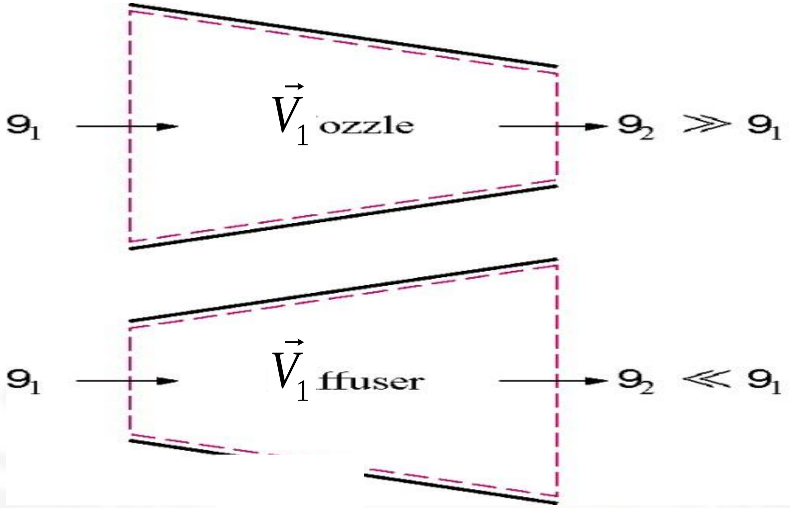


Photo by M. A. Boles

Nozzles and Diffusers



$$\vec{V}_2 >> \vec{V}_1$$

$$\vec{V}_2 << \vec{V}_1$$

- For flow through nozzles, the heat transfer, work, and potential energy are normally neglected, and nozzles have one entrance and one exit. The conservation of energy becomes

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

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

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

$$\dot{Q}_{net} + \underbrace{\sum \dot{m}_i \left(h_i + \frac{\vec{V}_i^2}{2} + gz_i \right)}_{\text{for each inlet}} = \dot{W}_{net} + \underbrace{\sum \dot{m}_e \left(h_e + \frac{\vec{V}_e^2}{2} + gz_e \right)}_{\text{for each exit}}$$

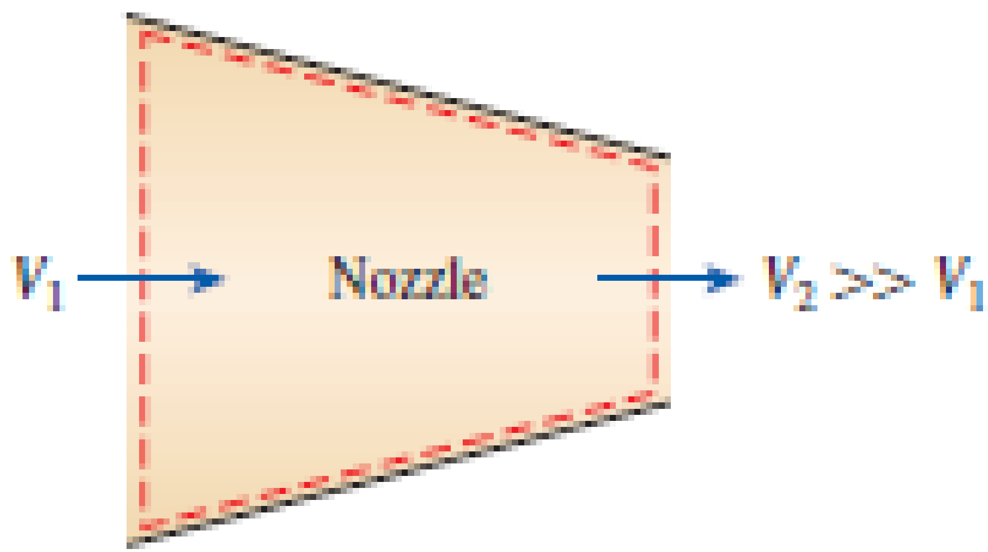
$$\dot{m}\left(h_1 + \frac{\vec{V}_1^2}{2} \right) = \dot{m}\left(h_2 + \frac{\vec{V}_2^2}{2} \right)$$

Solving for $\vec{V}_2$

$$\vec{V}_2 = \sqrt{2(h_1 - h_2) + \vec{V}_1^2}$$

Example 6

- Steam at 0.4 MPa, 300 °C, enters an adiabatic nozzle with a low velocity and leaves at 0.2 MPa with a quality of 90%. Find the exit velocity, in m/s.



Assignment

Thermodynamics: An Engineering Approach by Cengel Y.A. & Boles M.A. 8th Edition

From the above textbook, pp. 254-255 answer 1-4

1. Question 5-17C to 5-18C
2. Question 5-23C to 5-25C
3. Question 5-35 & 5-36
4. Question 5-46 to 5-47