ESO 201A: Thermodynamics

2016-2017-I semester

Mass-Energy Analysis: part 5

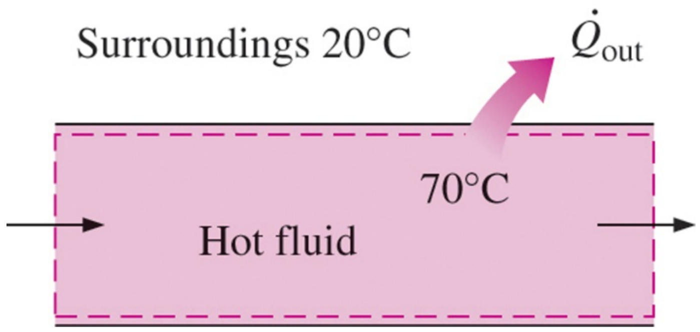
Dr. Jayant K. Singh
Department of Chemical Engineering
Faculty Building 469,
Telephone: 512-259-6141
E-Mail: jayantks@iitk.ac.in
home.iitk.ac.in/~jayantks/ESO201/index.htm

Learning objectives

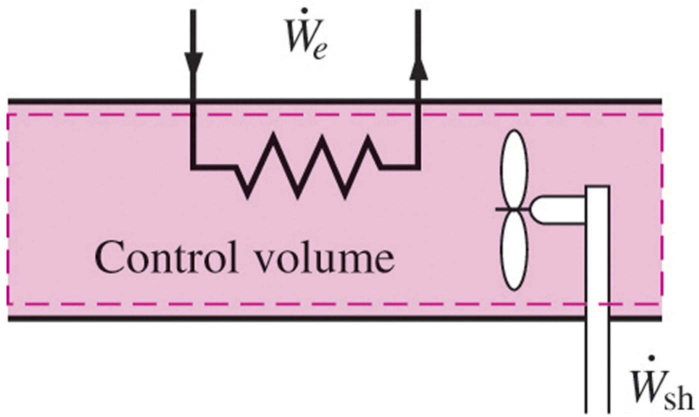
- Develop the conservation of mass principle.
- Apply the conservation of mass principle to various systems including steady- and unsteady-flow control volumes.
- Apply the first law of thermodynamics as the statement of the conservation of energy principle to control volumes.
- Identify the energy carried by a fluid stream crossing a control surface as the sum of internal energy, flow work, kinetic energy, and potential energy of the fluid and to relate the combination of the internal energy and the flow work to the property enthalpy.
- Solve energy balance problems for common steady-flow devices such as nozzles, compressors, turbines, throttling valves, mixers, heaters, and heat exchangers, pipe and duct flow
- Apply the energy balance to general unsteady-flow processes with particular emphasis on the uniform-flow process as the model for commonly encountered charging and discharging processes.

Pipe and duct flow

The transport of liquids or gases in pipes and ducts is of great importance in many engineering applications. Flow through a pipe or a duct usually satisfies the steady-flow conditions.



Heat losses from a hot fluid flowing through an uninsulated pipe or duct to the cooler environment may be very significant.



Pipe or duct flow may involve more than one form of work at the same time.

Example

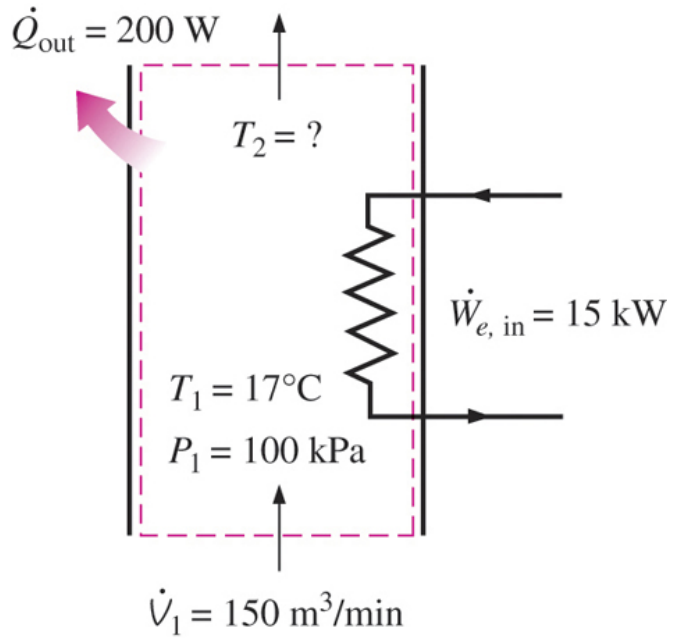
The electric heating systems used in many houses consist of a simple duct with resistance heaters. Air is heated as it flows over resistance wires. Consider a 15-kW electric heating system. Air enters the heating section at 100 kPa and 17ºC with a volume flow rate of 150 m^3/min. If heat is lost from the air in the duct to the surroundings at a rate of 200 W, determine the exit temperature of air.

Energy balance for the pipe flow shown in the figure is

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

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

$$\dot{W}_{e,in} - \dot{Q}_{out} = \dot{m}c_p(T_2 - T_1)$$

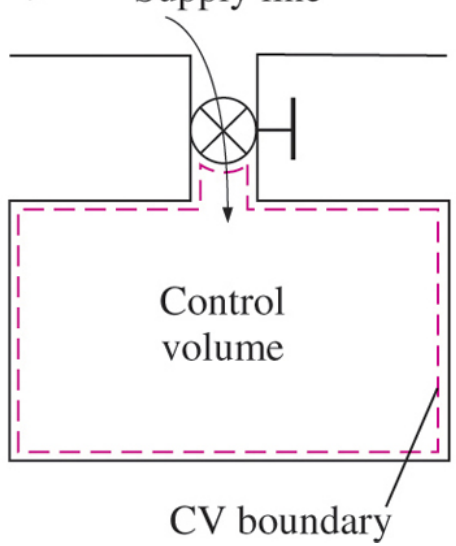


Energy Analysis of Unsteady-Flow Process

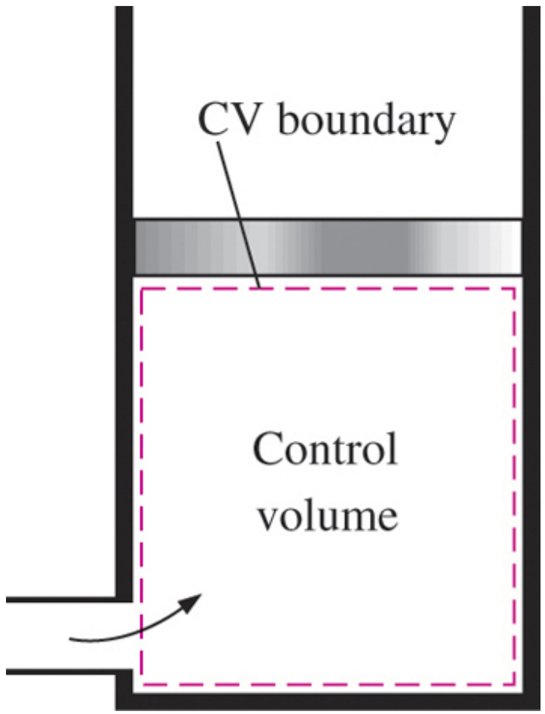
Many processes of interest, however, involve *changes* within the control volume with time. Such processes are called *unsteady-flow,* or *transient-flow,* processes.

- Discharge of a fluid from pressurized vessel.
- Inflating tires or baloons

Charging of a rigid tank from a supply line is an unsteady-flow process since it involves changes within the control volume.



The shape and size of a control volume may change during an unsteady-flow process.



Energy Analysis of Unsteady-Flow Process

Most unsteady-flow processes can be represented reasonably well by the *uniform-flow process*.

Uniform-flow process: The fluid flow at any inlet or exit is uniform and steady, and thus the fluid properties do not change with time or position over the cross section of an inlet or exit. If they do, they are averaged and treated as constants for the entire process.

Mass balance

$$m_{\text{in}} - m_{\text{out}} = \Delta m_{\text{system}} \qquad \text{(kg)}$$

$$\Delta m_{\text{system}} = m_{\text{final}} - m_{\text{initial}}$$

$$m_i - m_e = (m_2 - m_1)_{\text{CV}}$$

i = inlet, e = exit, 1 = initial state, and 2 = final state

Energy Analysis of Unsteady-Flow Process

Energy balance

$$\underbrace{E_{\text{in}} - E_{\text{out}}}_{\substack{\text{Net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{\text{system}}}_{\substack{\text{Change in internal, kinetic,}\\ \text{potential, etc., energies}}} \quad \text{(kJ)}$$

$$\left(Q_{\text{in}} + W_{\text{in}} + \sum_{\text{in}} m\theta\right) - \left(Q_{\text{out}} + W_{\text{out}} + \sum_{\text{out}} m\theta\right) = (m_2e_2 - m_1e_1)_{\text{system}}$$

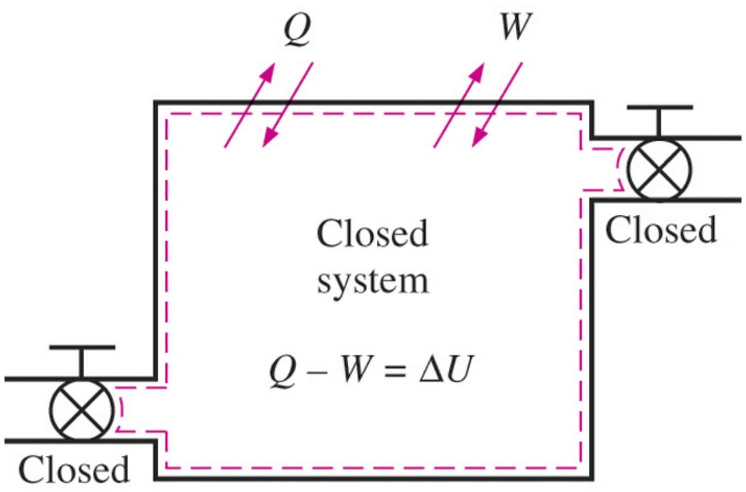
$$\theta = h + \text{ke} + \text{pe}$$

$$e = u + \text{ke} + \text{pe}$$

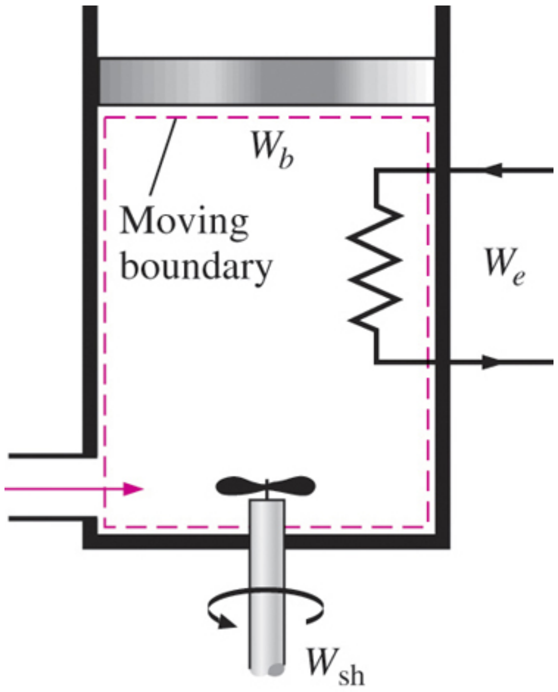
Assuming ke, pe changes of fluid steams and CV are negligible:

$$Q - W = \sum_{\text{out}} mh - \sum_{\text{in}} mh + (m_2u_2 - m_1u_1)_{\text{system}}$$

Energy Analysis of Unsteady-Flow Process



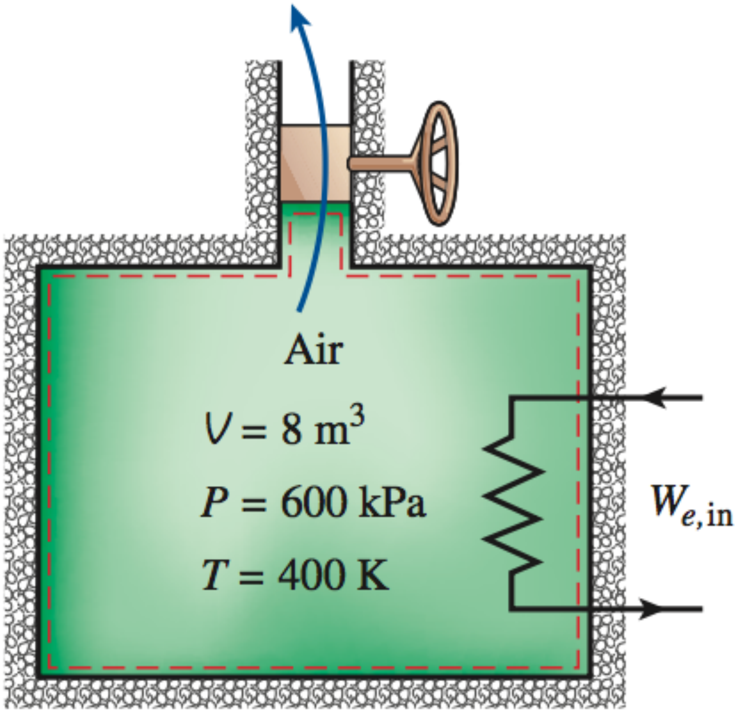
The energy equation of a uniform-flow system reduces to that of a closed system when all the inlets and exits are closed.



A uniform-flow system may involve electrical, shaft, and boundary work all at once.

Example

An insulated 8-m^3 rigid tank contains air at 600 kPa and 400 K. A valve connected to the tank is now opened, and air is allowed to escape until the pressure inside drops to 200 kPa. The air temperature during the process is maintained constant by an electric resistance heater placed in the tank. Determine the electrical energy supplied to air during this process.



Mass balance: $m_{in} - m_{out} = \Delta m_{system} \rightarrow m_e = m_1 - m_2$

Energy balance: $\underbrace{E_{in} - E_{out}}_{\substack{\text{Net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{system}}_{\substack{\text{Change in internal, kinetic,}\\ \text{potential, etc., energies}}}$

$$W_{e,in} - m_e h_e = m_2 u_2 - m_1 u_1 \quad (\text{since } Q \cong \text{ke} \cong \text{pe} \cong 0)$$

The gas constant of air is $R = 0.287$ kPa·m^3/kg·K (Table A-1). The initial and final masses of air in the tank and the discharged amount are determined from the ideal gas relation to be

$$m_1 = \frac{P_1V_1}{RT_1} = \frac{(600\text{ kPa})(8\text{ m}^3)}{(0.287\text{ kPa·m}^3/\text{kg·K})(400\text{ K})} = 41.81\text{ kg}$$

$$m_2 = \frac{P_2V_2}{RT_2} = \frac{(200\text{ kPa})(8\text{ m}^3)}{(0.287\text{ kPa·m}^3/\text{kg·K})(400\text{ K})} = 13.94\text{ kg}$$

$$m_e = m_1 - m_2 = 41.81 - 13.94 = 27.87\text{ kg}$$

The enthalpy and internal energy of air at 400 K are $h_e = 400.98$ kJ/kg and $u_1 = u_2 = 286.16$ kJ/kg (Table A-17). The the electrical energy supplied to air is determined from the energy balance to be

$$\begin{aligned} W_{e,\text{in}} &= m_e h_e + m_2 u_2 - m_1 u_1 \\ &= (27.87\text{ kg})(400.98\text{ kJ/kg}) + (13.94\text{ kg})(286.16\text{ kJ/kg}) \\ &\quad - (41.81\text{ kg})(286.16\text{ kJ/kg}) \\ &= 3200\text{ kJ} = \mathbf{0.889\text{ kWh}} \end{aligned}$$

since 1 kWh = 3600 kJ.

Summary

- Conservation of mass
  - Mass and volume flow rates
  - Mass balance for a steady-flow process
  - Mass balance for incompressible flow
- Flow work and the energy of a flowing fluid
  - Energy transport by mass
- Energy analysis of steady-flow systems
- Some steady-flow engineering devices
  - Nozzles and Diffusers
  - Turbines and Compressors
  - Throttling valves
  - Mixing chambers and Heat exchangers
  - Pipe and Duct flow
- Energy analysis of unsteady-flow processes