CHAPTER

4

The First Law of Thermodynamics for *Control Volumes*

Conservation of mass: Mass, like energy, is a conserved property, and it cannot be created or destroyed during a process.

Closed systems: The mass of the system remain constant during a process.

Control volumes: Mass can cross the boundaries, and so we must keep track of the amount of mass entering and leaving the control volume.

Mass is conserved even during chemical reactions.

Mass m and energy E can be converted to each other according to $E = mc^2$

where c is the speed of light in a vacuum, which is $c = 2.9979 \times 10^8$ m/s.

The mass change due to energy change is absolutely negligible.

Copyright © The McGraw-Hill Companies, Inc. Permission required for reproduction or display.

Conservation of mass principle

Control volume can be thought of a region of space through which mass flows.

$$\left\{\begin{matrix}\textbf{Total mass}\\ \textbf{entering}\\ \textbf{CV}\end{matrix}\right\} - \left\{\begin{matrix}\textbf{Total mass}\\ \textbf{leaving CV}\end{matrix}\right\} = \left\{\begin{matrix}\textbf{Net change}\\ \textbf{in mass}\\ \textbf{within CV}\end{matrix}\right\}$$

$$\sum m_i - \sum m_e = \Delta m_{\mathrm{CV}}$$

Note: *i*-inlet , *e*-exit , CV-control volume

The rate form $\rightarrow$ $$\sum \dot{m}_i - \sum \dot{m}_e = \Delta \dot{m}_{\mathrm{CV}}$$

where $\dot{m}$ **is mass flow rate, i.e** $\dfrac{dm}{dt}$

Flow through a pipe or duct

The average velocity V_{avg} is defined as the average speed through a cross section.

The volume flow rate is the volume of fluid flowing through a cross section per unit time.

Copyright © The McGraw-Hill Companies, Inc. Permission required for reproduction or display

The mass flow rate through a different area *dA* can be expressed as:

$$d\dot{m} = \rho V_n dA$$

V_n → **Velocity normal to *dA***

$$\dot{m} = \int_A \rho V_n dA \quad (\text{kg/s})$$

$$\dot{m} = \rho V_{avg} A \quad (\text{kg/s})$$

ρ → **density** kg/ m^3

V_{avg} → **average fluid velocity normal to *A*,** m/s

The volume flow rate:

$$\dot{V} = \int_A V_n dA = V_{av} A \left(m^3/s\right)$$

The mass and volume flow rates are related by :

$$\boxed{\dot{m} = \rho \dot{V} = \frac{\dot{V}}{v}}$$

Copyright © The McGraw-Hill Companies, Inc. Permission required for reproduction or display.

Conservation of Energy Principle

Total energy crossing boundary as heat and work + **Total energy of mass entering CV** - **Total energy of mass exiting CV** = **Net change in energy of CV**

$$Q - W + \sum E_{in} - \sum E_{out} = \Delta E_{CV}$$

This equation can also be expressed in the rate form (i.e. quantities per unit time).

When there is no mass flow in and out of the system, the energy equation reduces to that of a closed system:

$$Q - W = \Delta E$$

Copyright © The McGraw-Hill Companies, Inc. Permission required for reproduction or display.

Flow work or flow energy

The energy required to push fluid into or out of a control volume.

The force applied on the fluid element : $F = PA$

The work done in pushing the fluid element into the control volume:

i.e. the flow work : $W_{flow} = F\,L = PAL = PV$ **(kJ)**

On a unit mass basis $w_{flow} = Pv$ **(kJ/kg)**

Copyright © The McGraw-Hill Companies, Inc. Permission required for reproduction or display.

Total Energy of a flowing fluid

For a nonflowing fluid : $e = u + ke + pe = u + \frac{V^2}{2} + gz$ **(kJ/kg)**

For a flowing fluid the total energy $\theta = Pv + e = \underbrace{Pv + u}_{h} + \frac{V^2}{2} + gz$ **(kJ/kg)**

Hence $\theta = h + ke + pe = h + \frac{V^2}{2} + gz$ **(kJ/kg)**

The total energy consists of three parts for a nonflowing fluid and four parts for a flowing fluid.

Copyright © The McGraw-Hill Companies, Inc. Permission required for reproduction or display.

THE STEADY-FLOW PROCESS

Steady flow is defined such that all properties at each point in a system remain constant with respect to time. (e.g. turbines, compressors, and heat exchangers)

Under steady-flow conditions, the mass and energy contents of a control volume remain constant.

Under steady-flow conditions, the fluid properties at an inlet or exit remain constant (do not change with time).

Copyright © The McGraw-Hill Companies, Inc. Permission required for reproduction or display.

Example:

Conservation of mass

m_{cv} **= constant for steady-flow process**

$$\sum \dot{m}_i = \sum \dot{m}_e$$

If there is only one inlet and one exit

$$\dot{m}_1 = \dot{m}_2 \text{ (kg/s) or } \rho_1 V_1 A_1 = \rho_2 V_2 A_2 \qquad \textbf{(or } \frac{1}{v_1} V_1 A_1 = \frac{1}{v_2} V_2 A_2 \textbf{)}$$

where $\rho = \text{density (kg/m}^3\text{)}$

$v = \text{specific volume (m}^3\text{/kg)}$

$V = \text{average velocity (m/s)}$

$A = \text{cross-sectional area normal to area (m}^2\text{)}$

Copyright © The McGraw-Hill Companies, Inc. Permission required for reproduction or display.

Conservation of energy for steady flow

$$E_{CV} = \text{constant} \quad \text{or} \quad \Delta E_{CV} = 0$$

$$\dot{Q} - \dot{W} = \sum \dot{E}_{out} - \sum \dot{E}_{in} + \Delta \dot{E}_{cv}$$

$$\Rightarrow \dot{Q} - \dot{W} = \sum \dot{m}_e \theta_e - \sum \dot{m}_i \theta_i$$

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

For one-inlet, one-exit systems(i.e single stream systems):

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

$$\dot{Q} - \dot{W} = \dot{m}\{\underbrace{h_2 - h_1}_{\Delta h} + \underbrace{\frac{V_2 - V_1}{2}}_{\Delta ke} + g\underbrace{(z_2 - z_1)}_{\Delta pe}\}$$

In many cases:

$$\Delta ke = \Delta pe = 0$$

$$\Rightarrow q - w = \Delta h$$

Copyright © The McGraw-Hill Companies, Inc. Permission required for reproduction or display.

Some Steady-Flow Engineering Devices

1.Nozzels and Diffusers

$$\cancelto{0}{q} - \cancelto{0}{w} = \Delta h + \Delta ke + \cancelto{0}{\Delta pe}$$

$$0 = h_2 - h_1 + \frac{V_2^2 - V_1^2}{2}$$

Copyright © The McGraw-Hill Companies, Inc. Permission required for reproduction or display.

2.Turbines and compressors

A modern land-based gas turbine used for electric power production. This is a General Electric LM5000 turbine. It has a length of 6.2 m, it weighs 12.5 tons, and produces 55.2 MW at 3600 rpm with steam injection.

Copyright © The McGraw-Hill Companies, Inc. Permission required for reproduction or display.

2.Turbines and compressors

$$q - w = \Delta h + \Delta ke + \Delta pe$$

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

$$q - w = \Delta h + \cancel{\Delta ke}^{0} + \cancel{\Delta pe}^{0}$$

$$q - w = h_2 - h_1$$

Copyright © The McGraw-Hill Companies, Inc. Permission required for reproduction or display.

Ex: Steam turbine

For steady flow

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

$$\dot{Q} - \dot{W} = \dot{m}\{h_2 - h_1 + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)\}$$

$$\frac{\dot{Q}}{\dot{m}} - \frac{\dot{W}}{\dot{m}} + (h + \frac{V^2}{2} + gz)_1 - (h + \frac{V^2}{2} + gz)_2 = 0$$

$$\dot{m} = \frac{600\, kg/hr}{3600\, sec/hr} = 0.167\, kg/sec$$

$$\dot{Q} = \frac{630\, kg/hr}{3600\, sec/hr} = 0.175 kW$$

$$-\frac{0.175\, kJ/s}{0.167\, kg/s} - \frac{\dot{W}}{0.167\, kg/s} + (3120\, kJ/kg + \frac{(100\, m/s)^2}{2(1000\, J/kJ)} + \frac{9.81\, m/s^2}{1000\, J/kJ}) - (2330\, kJ/kg + \frac{(130\, m/s)^2}{2(1000\, J/kJ)} + 0) = 0$$

$$\Rightarrow -1.05\, kJ/kg - \frac{\dot{W}}{0.167\, kg/s} + (3120\, kJ/kg + 5\, kJ/kg + 0.029\, kJ/kg) - (2330 + 8.45 + 0) = 0$$

$$\Rightarrow \dot{W} = +131.183 kW$$

Copyright © The McGraw-Hill Companies, Inc. Permission required for reproduction or display.

3.Throling Valves

Throttling valves are *any kind of flow-restricting devices* that cause a significant pressure drop in the fluid.

Why there is a pressure drop?

Energy per unit volume before = Energy per unit volume after

$$P_1 + \tfrac{1}{2}\rho v_1^2 + \rho g z_1 = P_2 + \tfrac{1}{2}\rho v_2^2 + \rho g z_2$$

Copyright © The McGraw-Hill Companies, Inc. Permission required for reproduction or display.

3.Throling Valves

What is the difference between a turbine and a throttling valve?

The pressure drop in the fluid is often accompanied by a *large drop in temperature*, and for that reason throttling devices are commonly used in refrigeration and air-conditioning applications.

→ Energy balance

$$\overset{0}{\cancel{q}} - \overset{0}{\cancel{w}} = \Delta h + \overset{0}{\cancel{\Delta ke}} + \overset{0}{\cancel{\Delta pe}}$$

$$\Rightarrow h_2 = h_1$$

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

Internal energy + Flow energy = Constant

During a throttling process, the enthalpy of a fluid remains constant. But internal and flow energies may be converted to each other.

Copyright © The McGraw-Hill Companies, Inc. Permission required for reproduction or display.

3.Throttling Valves

$$h_2 \cong h_1$$

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

Internal energy +flow =const.
If $P_2 v_2$ increase then u_2 decreases $\longrightarrow$ drop in temperature
If $P_1 v_1$ decrease then u_1 increases $\longrightarrow$ increase in temperature
For an ideal gas, h=h(T) and since $h_1 = h_2$, the temperature does not change $T_1 = T_2$.

Copyright © The McGraw-Hill Companies, Inc. Permission required for reproduction or display.

4. Heat exchangers

Mass flow rate of fluid A: $\dot{m}_i = \dot{m}_e = \dot{m}_A$

Mass flow rate of fluid B: $\dot{m}_i = \dot{m}_e = \dot{m}_B$

Energy equation for blue CV:

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

$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e$$

$$\dot{m}_B h_{Bi} + \dot{m}_A h_{Ai} = \dot{m}_B h_{Be} + \dot{m}_A h_{Ae}$$

Energy equation for red CV: $\longrightarrow$ single stream

$$\dot{Q} - \cancelto{0}{\dot{W}} = \dot{m}_A (\Delta h + \cancelto{0}{\Delta ke} + \cancelto{0}{\Delta pe})$$

$$\dot{Q} = \dot{m}_A (h_2 - h_1)$$

Copyright © The McGraw-Hill Companies, Inc. Permission required for reproduction or display.

5.Mixing Chambers

$$\sum \dot{m}_i = \sum \dot{m}_2$$

$$\dot{m}_1 + \dot{m}_2 = \dot{m}_3 \rightarrow \frac{\dot{m}_1}{\dot{m}_2} + 1 = \frac{\dot{m}_3}{\dot{m}_2}$$

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

$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e$$

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

Divide by $\dot{m}_2$ **and let** $y = \dfrac{\dot{m}_1}{\dot{m}_2} \therefore y\, h_1 + h_2 = (y+1)\, h_3$

The T-elbow of an ordinary shower serves as the mixing chamber for the hot- and the cold-water streams.

Copyright © The McGraw-Hill Companies, Inc. Permission required for reproduction or display.

6.Pipe and Duct Flow

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

$$\dot{Q} - \dot{W} = \dot{m}\,(\Delta h + \Delta ke + \Delta pe)$$

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

When air treated as ideal gas

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

$$v_1 = \frac{RT_1}{P_1}$$

$$\dot{m} = \frac{\dot{V}_1}{v_1}$$

$$\Rightarrow \dot{Q} - \underbrace{\dot{W}}_{(-\dot{W}_e - W_{sh})} = \dot{m}C_p(T_2 - T_1)$$

Copyright © The McGraw-Hill Companies, Inc. Permission required for reproduction or display.

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

$$V_1 = \frac{\dot{m}}{\rho_1 A_1} \qquad (m/s)$$

$$V_2 = \frac{\dot{m}}{\rho_2 A_2} \qquad (m/s)$$

Enthalpy change for incompressible substance:

$$h_2 - h_1 = (u_2 + P_2 v_2) - (u_1 + P_1 v_1)$$

$$= (u_2 - u_1) + v(P_2 - P_1)$$

$$= \underbrace{C(T_2 - T_1)}_{\Delta u} + v(P_2 - P_1)$$

Copyright © The McGraw-Hill Companies, Inc. Permission required for reproduction or display.

Energy equation becomes:

$$\dot{Q} - \dot{W}_{sh} = \dot{m}\{ C\,(T_2 - T_1) + v\,(P_2 - P_1) + \frac{\vartheta_2^2 - \vartheta_1^2}{2} + g\,(z_2 - z_1)\}$$

$$\Rightarrow \dot{W}_{sh} = -\dot{m}\,\{ \frac{\vartheta_2^2 - \vartheta_1^2}{2} + g\,(z_2 - z_1)\}$$

where ϑ is velocity

$$\dot{W}_{fluid} = \dot{V}\,(P_i - P_o)$$

This is the power required to produce a fluid pressure rise across a pump

In the energy equation potential and kinetic energy differences are small, heat transfer is small and the internal energy changes are negligible

$$\eta_P = \frac{\dot{W}_{fluid}}{\dot{W}_{sh}}$$

$$\therefore \dot{W}_{sh} = \frac{\dot{V}(P_i - P_o)}{\eta}$$

Electric Pump