CH365 Chemical Engineering Thermodynamics

Lesson 7
Enthalpy, Heat Capacity, and Open Systems – Part 2

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Measures of Flow

$$\dot{m} = \text{mass flow rate} \left(\frac{kg}{s}, \frac{lb_m}{hr}, \text{etc.} \right)$$

$$\dot{n} = \text{molar flow rate} \left(\frac{mol}{s}, \frac{lbmol}{s}, \text{etc.} \right)$$

$$\dot{q} = \text{volumetric flow rate} \left(\frac{m^3}{s}, \frac{ft^3}{min}, \text{etc.} \right)$$

$$u = \text{velocity} \left(\frac{ft}{hr}, \frac{m}{s}, \text{etc.} \right)$$

$$\dot{m} = M\dot{n} \qquad M = \text{molar mass} \qquad \text{e.g.,} \ \frac{kg}{s} = \frac{kg}{kmol} \cdot \frac{kmol}{s}$$

$$\dot{m} = uA\rho \qquad A = \text{cross-sectional area} = \frac{\pi D^2}{4} \qquad \rho = \text{density} = \frac{1}{V} \ [=] \ \frac{kg}{m^3}$$

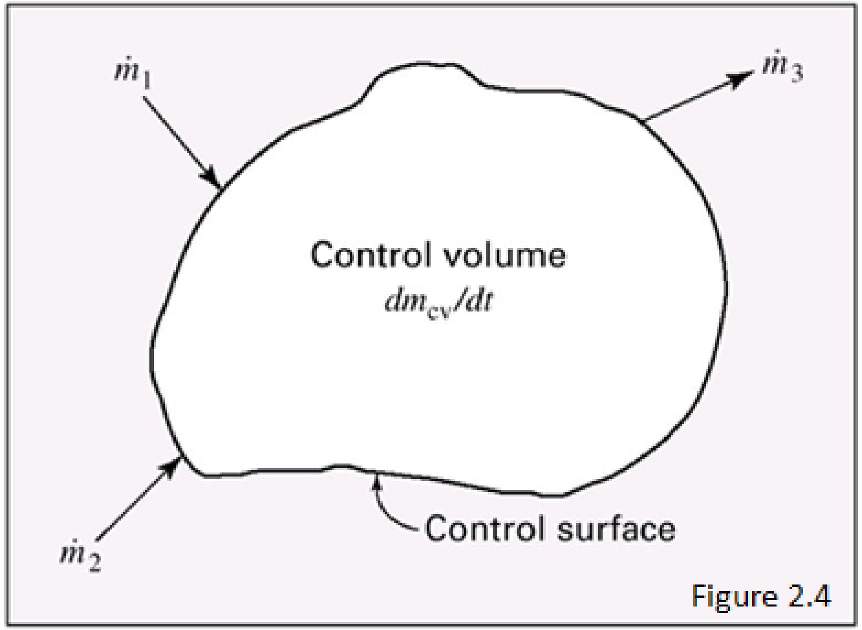
2.23a

$$\text{e.g.,} \ \frac{lb_m}{sec} = \frac{ft}{sec} \cdot ft^2 \cdot \frac{lb_m}{ft^3}$$

$$\dot{n} = uA\rho \cdot \frac{1}{M}$$

2.23b – M is missing on p. 47

Equation of Continuity



This diagram changes in Figure 2.5 in a very important way.

$$\left\{\begin{matrix}\text{mass in}\\ \text{control volume}\\ \text{at time t+}\Delta\text{t}\end{matrix}\right\} = \left\{\begin{matrix}\text{mass in}\\ \text{control volume}\\ \text{at time t}\end{matrix}\right\} + \left\{\begin{matrix}\text{mass entering}\\ \text{control volume}\\ \text{by flow during }\Delta\text{t}\end{matrix}\right\} - \left\{\begin{matrix}\text{mass leaving}\\ \text{control volume}\\ \text{by flow during }\Delta\text{t}\end{matrix}\right\}$$

$$m_{cv}\Big|_{t+\Delta t} = m_{cv}\Big|_{t} + \dot{m}_1\Delta t + \dot{m}_2\Delta t - \dot{m}_3\Delta t$$

$$m_{cv}\Big|_{t+\Delta t} - m_{cv}\Big|_{t} = \dot{m}_1\Delta t + \dot{m}_2\Delta t - \dot{m}_3\Delta t$$

definition of 1st derivative:

$$f'(x) = \frac{df(x)}{dx} = \lim_{\Delta x \to 0} \frac{f(x+\Delta x) - f(x)}{\Delta x}$$

$$\frac{m_{cv}\Big|_{t+\Delta t} - m_{cv}\Big|_{t}}{\Delta t} = \dot{m}_1 + \dot{m}_2 - \dot{m}_3$$

$$\frac{dm_{cv}}{dt} = \dot{m}_1 + \dot{m}_2 - \dot{m}_3 \qquad 2.24$$

Mass Balance for Open Systems

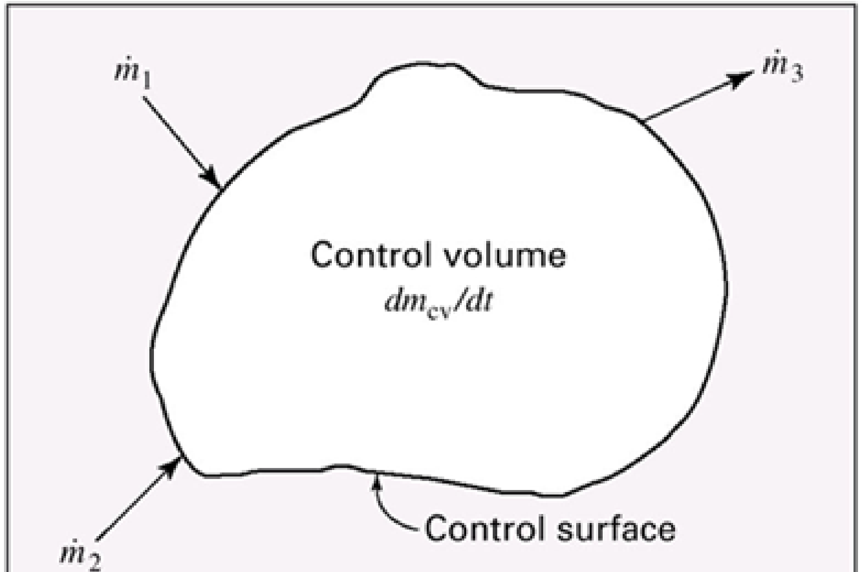


Figure 2.4

This diagram changes in Figure 2.5 in a very important way with the addition of frictionless pistons, but there is no explanation of this in the textbook.

$$\frac{dm_{cv}}{dt} + \Delta(\dot{m})_{fs} = 0 \qquad 2.24$$

$$\Delta(\dot{m})_{fs} = \dot{m}_3 - \dot{m}_1 - \dot{m}_2$$

$$\dot{m} = uA\rho$$

2.23a

$$\frac{dm_{cv}}{dt} + \Delta(\rho u A)_{fs} = 0 \qquad 2.25$$

$$\Delta(\rho u A)_{fs} = 0 \qquad \text{steady state } \frac{dm_{cv}}{dt} = 0$$

$$\rho_2 u_2 A_2 - \rho_1 u_1 A_1 = 0 \qquad \text{(single entrance and single exit)}$$

$$\dot{m} = \rho_2 u_2 A_2 = \rho_1 u_1 A_1 = \text{constant}$$

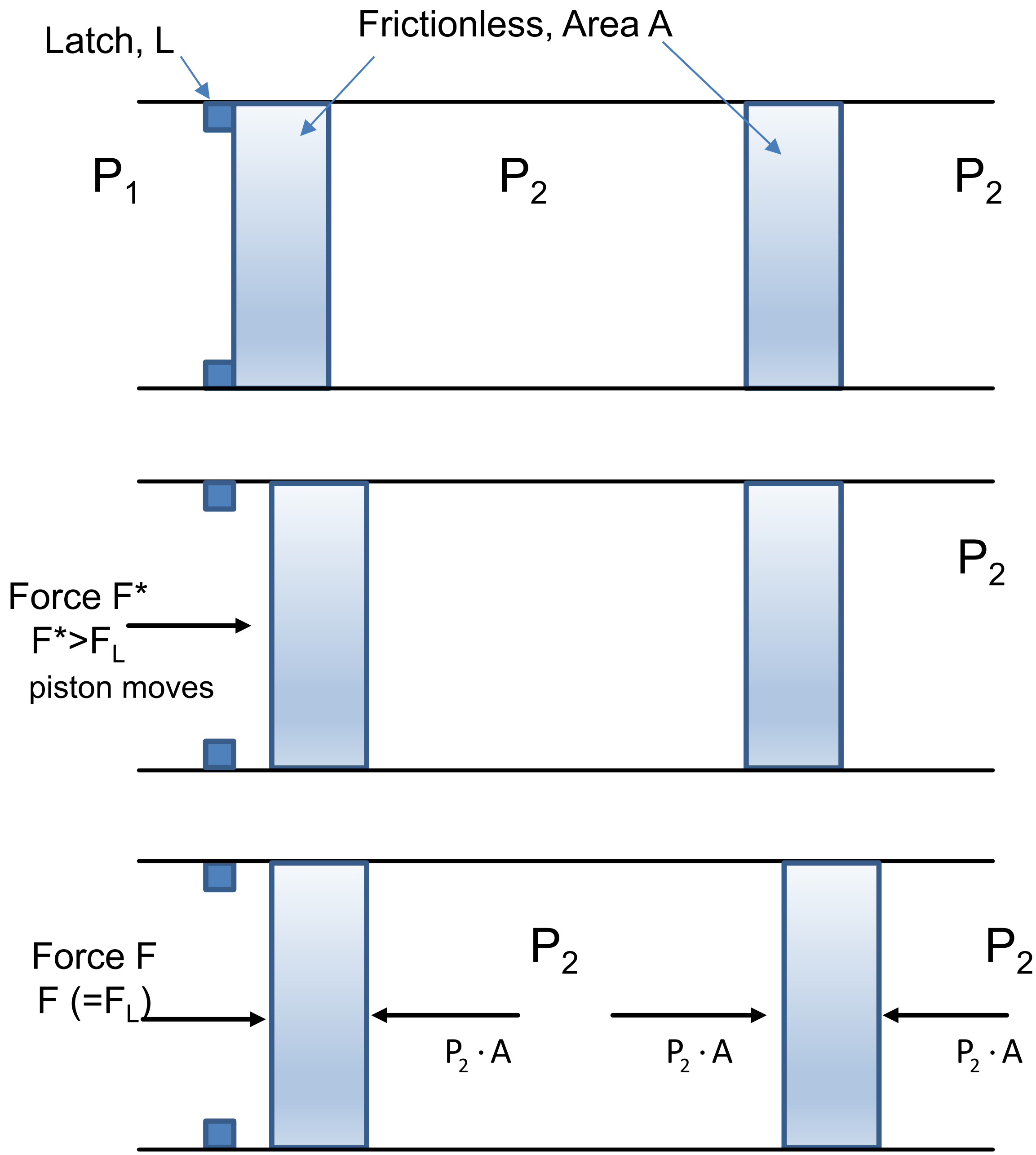
$$\dot{m} = \frac{u_1 A_1}{V_1} = \frac{u_2 A_2}{V_2} \qquad 2.26$$

(specific volume is the reciprocal of density)

Frictionless "Double Piston"

Understanding the "pistons" in figure 2.5

Initially at rest, how does the system respond to a push?



Reversible

$P_2 > P_1$

Static equilibrium
(all forces balanced)

General Energy Balance

Shaft work is not illustrated in Figure 2.5 but is used in the equations.

Question: How does the system respond to a "push" on the left-hand piston?

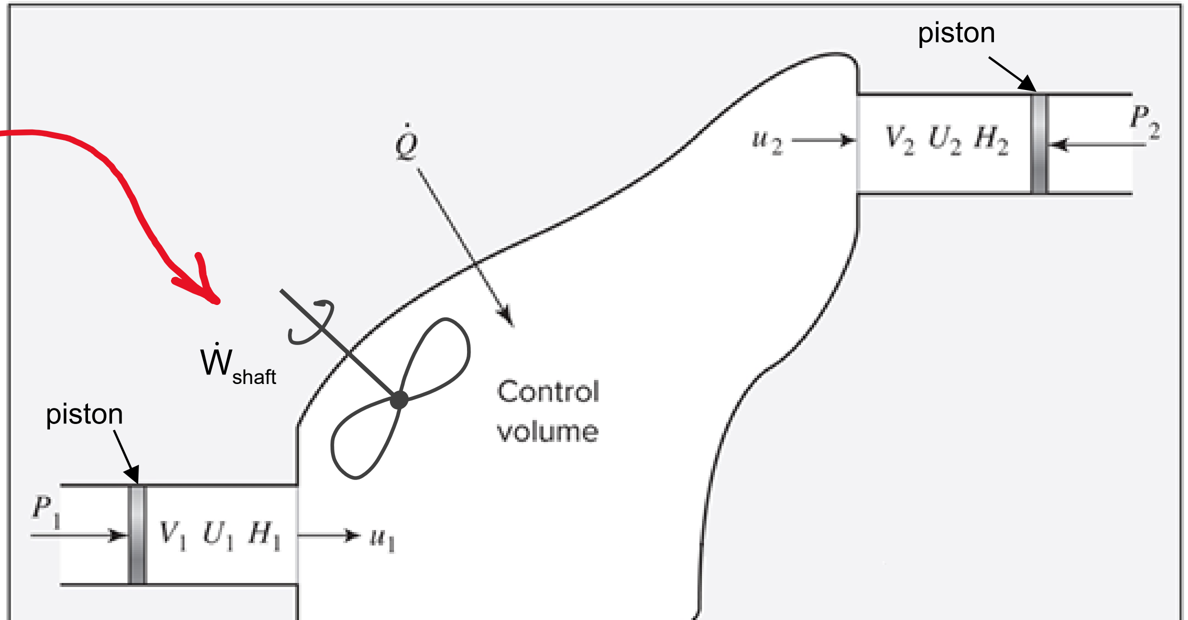


Figure 2.5

$$\frac{d(mU)_{cv}}{dt} = -\Delta\left[\left(U + \frac{1}{2}u^2 + zg\right)\dot{m}\right]_{fs} + \dot{Q} + \dot{W}_{tot}$$

$$\frac{d(mU)_{cv}}{dt} = -\Delta\left[\left(U + \frac{1}{2}u^2 + zg\right)\dot{m}\right]_{fs} + \dot{Q} - \Delta\left[(PV)\dot{m}\right]_{fs} + \dot{W}_{shaft}$$

$$\frac{d(mU)_{cv}}{dt} = -\Delta\left[\left(U + PV + \frac{1}{2}u^2 + zg\right)\dot{m}\right]_{fs} + \dot{Q} + \dot{W}_{shaft}$$

$$\frac{d(mU)_{cv}}{dt} + \Delta\left[\left(H + \frac{1}{2}u^2 + zg\right)\dot{m}\right]_{fs} = \dot{Q} + \dot{W}_{shaft} \qquad 2.27$$

$$\frac{d(mU)_{cv}}{dt} + \Delta\left[H\dot{m}\right]_{fs} = \dot{Q} + \dot{W}_{shaft}$$

2.28 (ignores changes in PE and KE)

There are two mechanisms to add or remove work:

$$\dot{W}_{tot} = \dot{W}_{expansion} + \dot{W}_{shaft}$$

$$\dot{W}_{expansion} = -P\Delta V\dot{m}$$

$$bar \cdot \frac{10^5 \frac{kg}{m \cdot s^2}}{bar} \cdot \frac{m^3}{kg} \cdot \frac{kg}{s}$$

$$= \frac{kg \cdot m^2}{s^3} = \frac{J}{s} = \text{Watts}$$

Steady-State Systems

$$\Delta\left[\left(H+\frac{u^2}{2}+gz\right)\dot{m}\right]_{fs}=\dot{Q}+\dot{W}_S$$

2.29

general open system steady-state energy balance

$$\Delta\left(H+\frac{u^2}{2}+gz\right)\dot{m}=\dot{Q}+\dot{W}_S$$

2.30

constant flow open system energy balance (constant density) with one inlet and one outlet.

SI units: $$\Delta H+\frac{\Delta\left(u^2\right)}{2}+g\Delta z=Q+W_S$$

English units: $$\Delta H+\frac{\Delta\left(u^2\right)}{2g_c}+\frac{g}{g_c}\Delta z=Q+W_S$$

2.31

First law of thermodynamics for steady-state, steady flow, constant density process with one inlet and one outlet

all properties are energy per mass

$$\frac{\dot{Q}}{\dot{m}}=Q \qquad \frac{\dot{W}_S}{\dot{m}}=W_S$$

$$\Delta H=Q+W_S$$

2.32

Ignoring kinetic and potential energy changes

Problem 2.38

Carbon dioxide gas enters a water-cooled compressor at conditions $P_1 = 15$ (psia) and $T_1 = 50$ (degF), and is discharged at conditions $P_2 = 520$ (psia) and $T_2 = 200$ (degF). The entering CO_2 flows through a 4-inch-diameter pipe with a velocity of 20 (ft) $(s)^{-1}$, and is discharged through a 1-inch-diameter pipe. The shaft work supplied to the compressor is 5,360 (Btu) $(\text{lb mol})^{-1}$. What is the heat-transfer rate from the compressor in (Btu) $(\text{hr})^{-1}$?

Additional Information:

$H_1 = 307$ (Btu) $(\text{lb}_m)^{-1}$ and $V_1 = 9.25$ $(\text{ft})^3$ $(\text{lb}_m)^{-1}$

$H_2 = 330$ (Btu) $(\text{lb}_m)^{-1}$ and $V_2 = 0.28$ $(\text{ft})^3$ $(\text{lb}_m)^{-1}$

Problem 2.28

Nitrogen flows at steady state through a horizontal, insulated pipe with inside diameter of 1.5 (in). A pressure drop results from flow through a partially opened valve. Just upstream from the valve the pressure is 100 (psia), the temperature is 120 (degF), and the average velocity is 20 (ft)$(s)^{-1}$. If the pressure just downstream from the valve is 20 (psia), what is the temperature? Assume for nitrogen that PV/T is constant, Cv=(5/2)R, and Cp=(7/2)R. (Values of R are given in App. A.)