(905212)Chemical Engineering Principles (2)

CHAPTER 7:

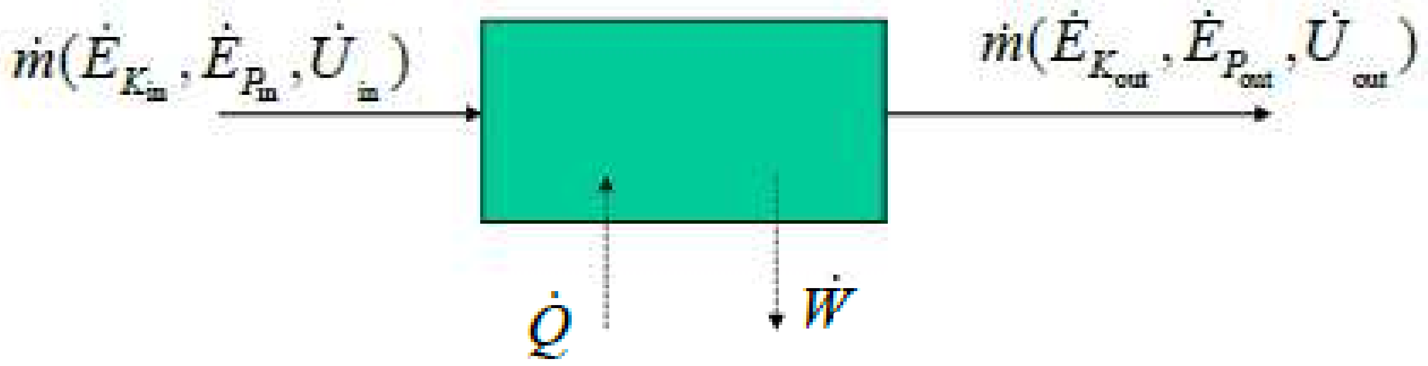
Energy & Energy Balances

Naim M. Faqir
JU Chemical Engineering

Accumulation = In – Out

EB: Continuous (Open) System at Steady-State

Accumulation = 0 !!



$$Energy\ Input = \dot{E}_{K_{in}} + \dot{E}_{P_{in}} + \dot{U}_{in}$$

$$Energy\ Output = \dot{E}_{K_{out}} + \dot{E}_{P_{out}} + \dot{U}_{out}$$

$$Energy\ Transferred = \dot{Q} - (\dot{W}_s + \dot{W}_{fl})$$

7.4aWork

- Work is energy that is transferred between the system and the surroundings, but **work cannot be stored**.
- Work is a force that causes displacement:

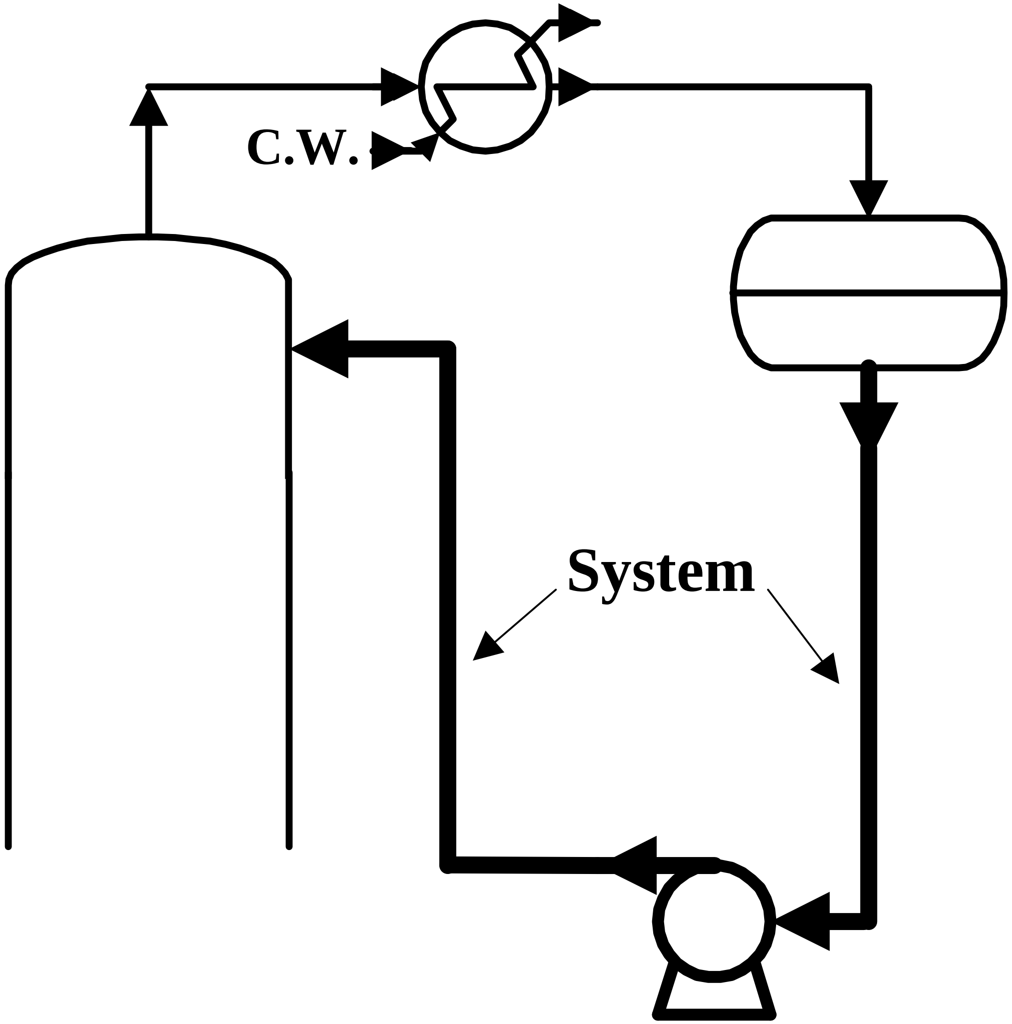
$$W = \int_{State1}^{State2} \vec{F} . d\vec{s}$$

- Work is a path dependent variable.

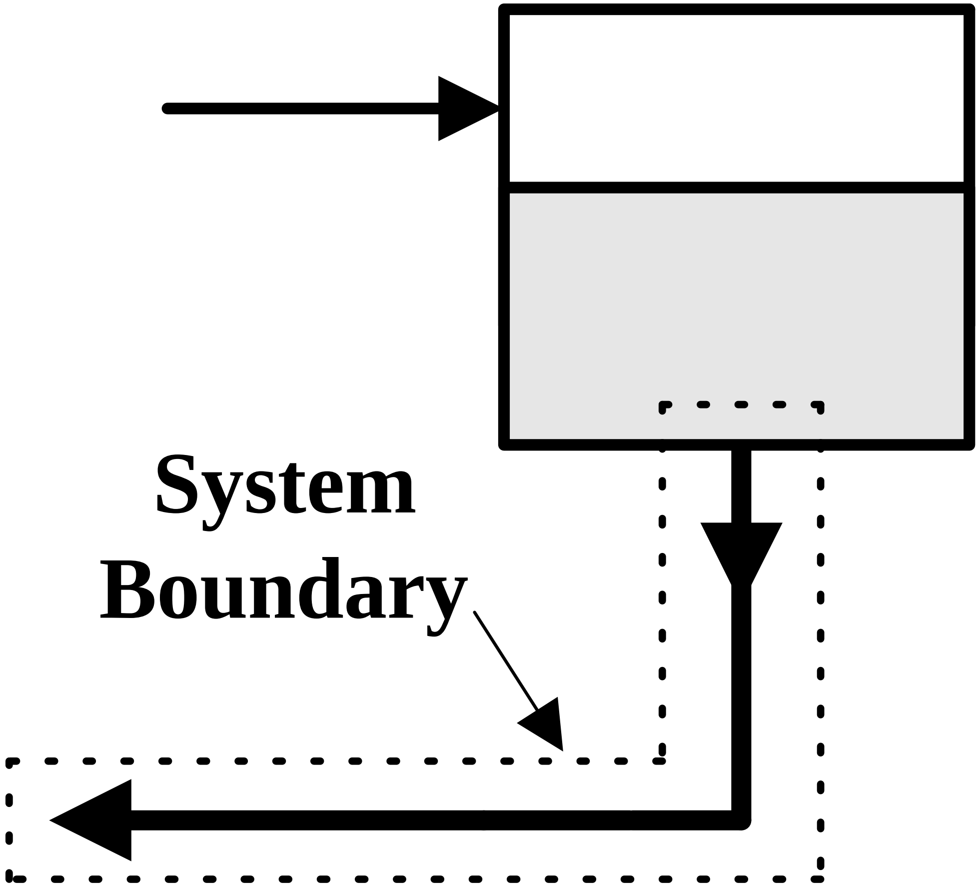
Different Types of Work

- **Shaft work** occurs by turning a shaft against mechanical resistance, e.g., a pump used to circulate a fluid.
- **Flow work** occurs when a fluid system moves as the result of forces placed on it by the surroundings, e.g., flow through a pipe because the pressure at the entrance to the pipe is greater than the pressure at the exit.

Example of Shaft Work

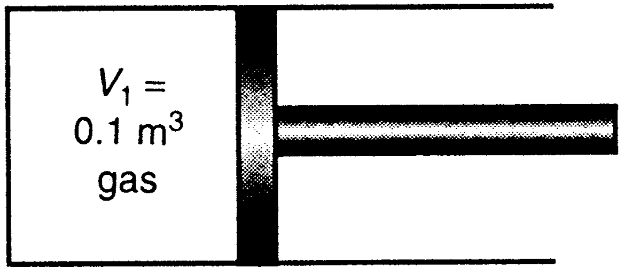


Example of Flow Work

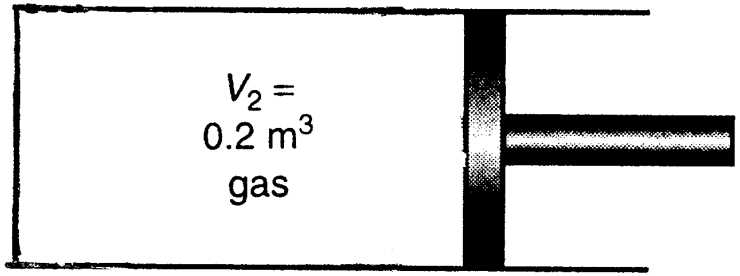


Work Example

- Consider an ideal gas at 300K and 200 kPa in a frictionless piston. The pressure in the piston causes the volume to slowly increase from 0.1 to 0.2 m^3. Calculate the work done by the gas on the piston if (a) the expansion occurs at constant pressure and (b) the expansion occurs at constant temperature.



State 1



State 2

Soln: Work Example

Using the initial conditions and the ideal gas law:

$$n = \frac{200\ \text{kPa}}{300\ \text{K}}\Bigg|\frac{0.1\ \text{m}^3}{}\Bigg|\frac{(\text{kg mol})(\text{K})}{8.314\ (\text{kPa})(\text{m}^3)} = 0.00802 \qquad \text{mol}$$

$$W = \int_{\text{state 1}}^{\text{state 2}} \frac{F}{A}\cdot A ds = \int_{V_1}^{V_2} p\, dV$$

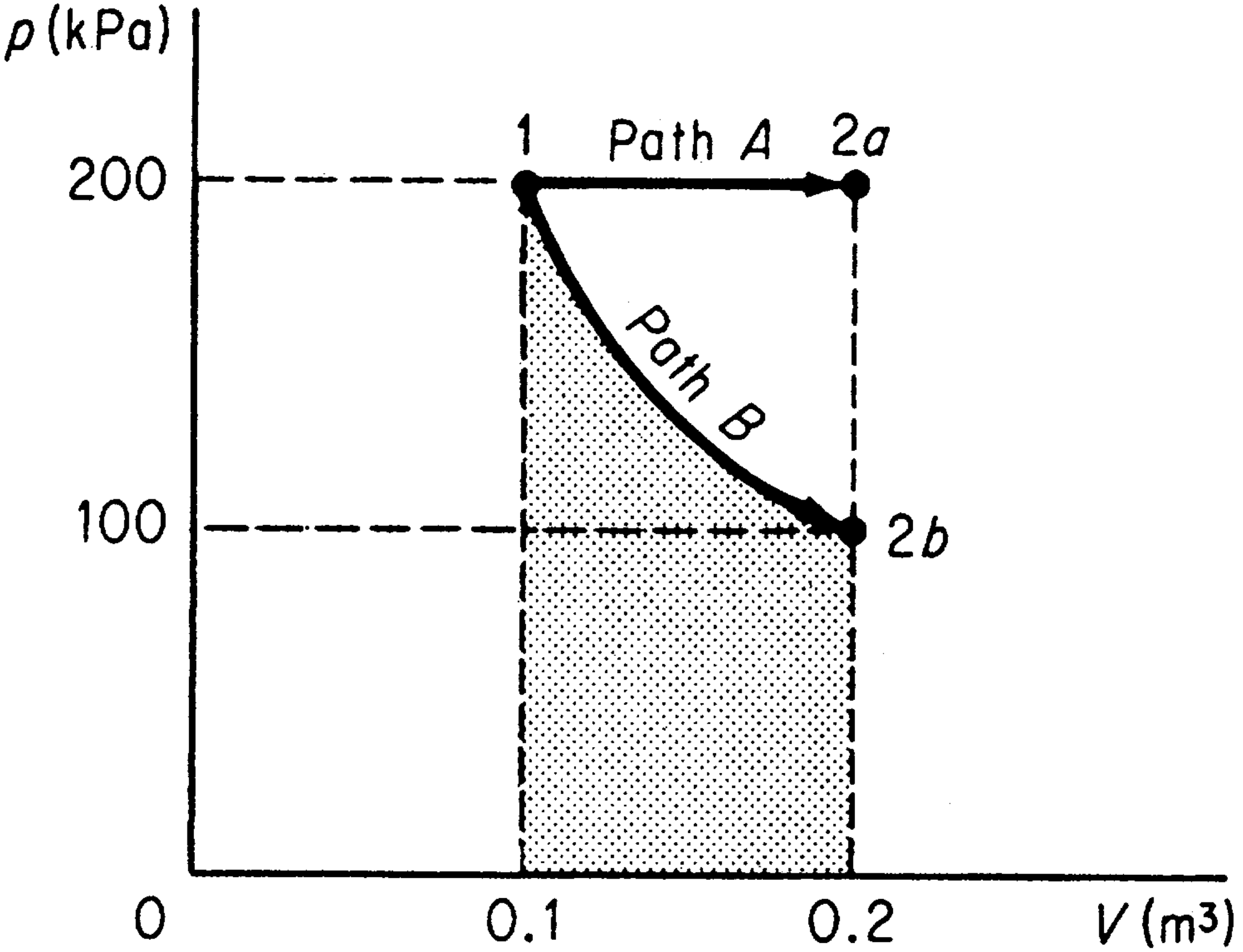
$$\text{(a)}\quad W = p\int_{V_1}^{V_2} dV = p(V_2 - V_1)$$

$$= \frac{200\times 10^3\ \text{Pa}}{}\Bigg|\frac{1\text{N}}{1\ (\text{m}^2)(\text{Pa})}\Bigg|\frac{0.1\ \text{m}^3}{}\Bigg|\frac{1\text{J}}{1(\text{N})(\text{m})} = 20\ \text{kJ}$$

$$\text{(b)}\quad W = \int_{V_1}^{V_2} \frac{nRT}{V}\, dV = -nRT\ln\left(\frac{V_2}{V_1}\right) =$$

$$\frac{0.00802\ \_\ \text{mol}}{}\Bigg|\frac{8.314\ \text{kJ}}{(\text{kg mol})(\text{K})}\Bigg|\frac{300\ \text{K}}{}\ \ln 2 = 13.86\ \text{kJ}$$

Soln: Mechanical Work Example



7.4b Enthalpy

- The term $U+pV$ appears in energy balance applied to open systems. The term pV represents the contribution of flow work.
- Enthalpy is defined as:

$$\hat{H} = \hat{U} + P\hat{V}$$

$\hat{U}$ **Specific internal energy (J/kg)**

U **internal energy (J) = m(kg)x** $\hat{U}$ **(J/kg)**

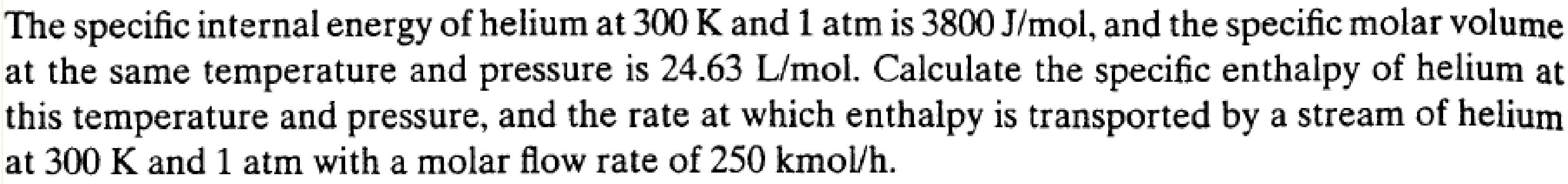
$\dot{U}$ **internal energy (J/s) =** $\dot{m}$ **(kg/s)x** $\hat{U}$ **(J/kg)**

Similarly $\longrightarrow$ $\hat{H}$ **&** $\hat{V}$

Enthalpy

- Enthalpy is a state variable.
- Enthalpy has no absolute value, but is always a difference from a reference value (that may be 0).
- Because enthalpy includes the flow work, it is used for open systems.
- If a system undergoes a phase change, the enthalpy term in the energy balance must include the enthalpy of the phase change (e.g., heat of vaporization).

Example 7.4.1



The specific internal energy of helium at 300 K and 1 atm is 3800 J/mol, and the specific molar volume at the same temperature and pressure is 24.63 L/mol. Calculate the specific enthalpy of helium at this temperature and pressure, and the rate at which enthalpy is transported by a stream of helium at 300 K and 1 atm with a molar flow rate of 250 kmol/h.

Solution of Example 7.4.1

$$\hat{H} = \hat{U} + P\hat{V} = 3800 \text{ J/mol} + (1 \text{ atm})(24.63 \text{ L/mol})$$

To convert the second term to joules we need the factor J/(L·atm). From the gas constant table on the inside back cover,

$$0.08206 \text{ L}\cdot\text{atm/(mol}\cdot\text{K)} = 8.314 \text{ J/(mol}\cdot\text{K)}$$

Dividing the right side by the left side yields the desired factor:

$$\frac{8.314 \text{ J/mol}\cdot\text{K}}{0.08206 \text{ L}\cdot\text{atm/(mol}\cdot\text{K)}} = 101.3 \text{ J/(L}\cdot\text{atm)}$$

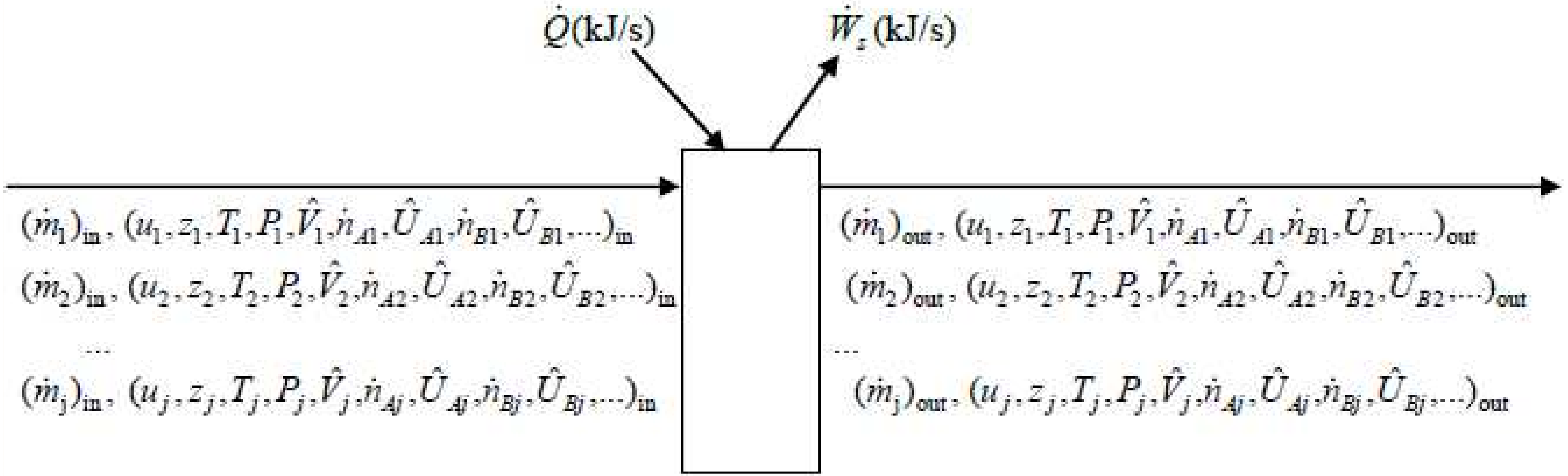
$$\hat{H} = 3800 \text{ J/mol} + \frac{24.63 \text{ L}\cdot\text{atm}}{\text{mol}}\bigg|\frac{101.3 \text{ J}}{1 \text{ L}\cdot\text{atm}} = \boxed{6295 \text{ J/mol}}$$

$$\dot{H} = \dot{n}\hat{H} = \frac{250 \text{ kmol}}{\text{h}}\bigg|\frac{10^3 \text{ mol}}{\text{kmol}}\bigg|\frac{6295 \text{ J}}{\text{mol}} = \boxed{1.57 \times 10^9 \text{ J/h}}$$

Accumulation = In – Out

EB: Continuous (Open) System at Steady-State

Accumulation = 0 !!



$\dot{Q}$(kJ/s)

$\dot{W}_s$ (kJ/s)

$(\dot{m}_1)_{in}, (u_1, z_1, T_1, P_1, \hat{V}_1, \dot{n}_{A1}, \hat{U}_{A1}, \dot{n}_{B1}, \hat{U}_{B1}, \ldots)_{in}$

$(\dot{m}_2)_{in}, (u_2, z_2, T_2, P_2, \hat{V}_2, \dot{n}_{A2}, \hat{U}_{A2}, \dot{n}_{B2}, \hat{U}_{B2}, \ldots)_{in}$

…

$(\dot{m}_j)_{in}, (u_j, z_j, T_j, P_j, \hat{V}_j, \dot{n}_{Aj}, \hat{U}_{Aj}, \dot{n}_{Bj}, \hat{U}_{Bj}, \ldots)_{in}$

$(\dot{m}_1)_{out}, (u_1, z_1, T_1, P_1, \hat{V}_1, \dot{n}_{A1}, \hat{U}_{A1}, \dot{n}_{B1}, \hat{U}_{B1}, \ldots)_{out}$

$(\dot{m}_2)_{out}, (u_2, z_2, T_2, P_2, \hat{V}_2, \dot{n}_{A2}, \hat{U}_{A2}, \dot{n}_{B2}, \hat{U}_{B2}, \ldots)_{out}$

…

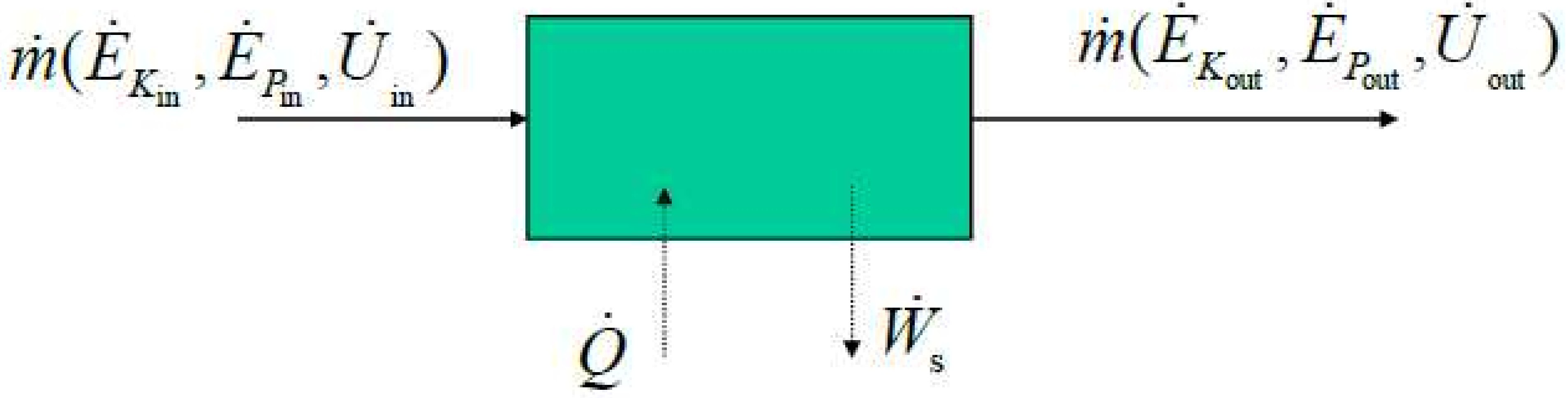
$(\dot{m}_j)_{out}, (u_j, z_j, T_j, P_j, \hat{V}_j, \dot{n}_{Aj}, \hat{U}_{Aj}, \dot{n}_{Bj}, \hat{U}_{Bj}, \ldots)_{out}$

$\dot{Q}$ (kJ/s) = rate of heat transfer to the system

$\dot{W}_s$ (kJ/s) = rate of *shaft work* done by the system on its surroundings, which includes energy transmitted by moving parts (pistons, propellers, turbines,...) or electric currents that cross the system boundary.

$\dot{m}_j$(kg/s or mol/s) = flow rate of the jth stream, and the variables that follow it are the velocity, elevation (relative to a reference height at which E_p = 0), temperature, pressure, and specific volume of that stream, and the molar flow rates and specific internal energies of the stream components.

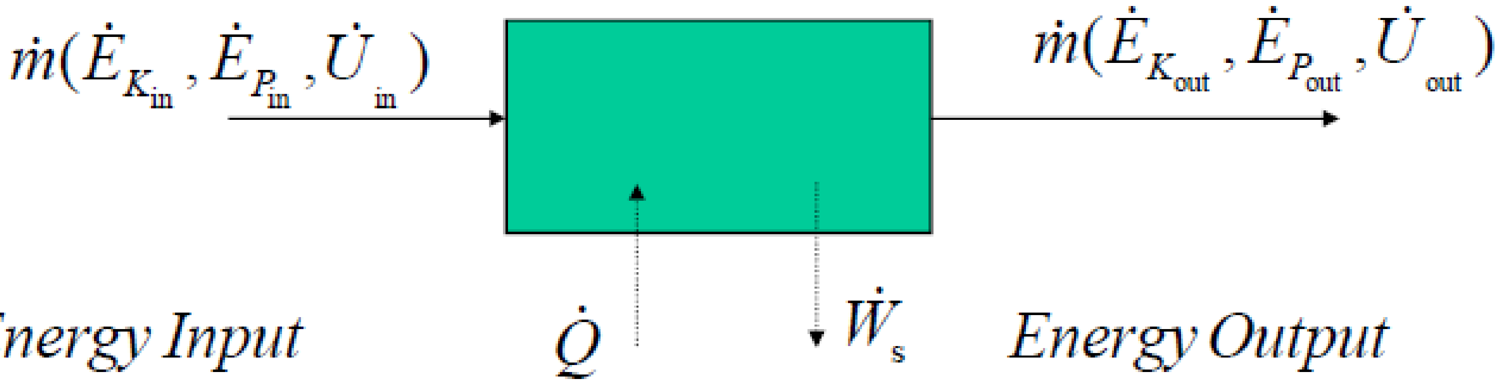
For only one stream



$$Energy\ Input = \dot{E}_{K_{in}} + \dot{E}_{P_{in}} + \dot{U}_{in}$$

$$Energy\ Output = \dot{E}_{K_{out}} + \dot{E}_{P_{out}} + \dot{U}_{out}$$

$$Energy\ Transferred = \dot{Q} - (\dot{W}_s + \dot{W}_{fl})$$



$$\text{Energy Input} = \sum_{\substack{input\\streams}} (\dot E_{K_j} + \dot E_{P_j} + \dot U_j) = \sum_{\substack{input\\streams}} \dot m_j \left(\hat E_{K_j} + \hat E_{P_j} + \hat H_j - P_j \hat V_j\right)$$

$$\text{Energy Output} = \sum_{\substack{output\\streams}} (\dot E_{K_j} + \dot E_{P_j} + \dot U_j) = \sum_{\substack{output\\streams}} \dot m_j \left(\hat E_{K_j} + \hat E_{P_j} + \hat H_j - P_j \hat V_j\right)$$

$$\text{Energy Transferred} = \dot Q - (\dot W_s + \dot W_{fl})$$

$$\dot W_{fl} = \sum_{\substack{output\\streams}} P_j \dot V_j - \sum_{\substack{input\\streams}} P_j \dot V_j$$

Shaft Work ($\dot W_s$): rate of work done by the process on a moving part (piston, turbine)

Flow Work ($\dot W_{fl}$): rate of work done by the fluid at outlet – rate of work done by the fluid at the inlet

EB: Continuous (Open) System at Steady-State

In = Out

$$\dot{Q} + \sum_{\substack{\text{input}\\\text{streams}}} \dot{m}_j\left(\hat{E}_{K_j} + \hat{E}_{P_j} + \hat{H}_j - P_j\hat{V}_j\right) = \left(\dot{W}_s + \sum_{\substack{\text{output}\\\text{streams}}} P_j\dot{V}_j - \sum_{\substack{\text{input}\\\text{streams}}} P_j\dot{V}_j\right)$$

$$+ \sum_{\substack{\text{output}\\\text{streams}}} \dot{m}_j\left(\hat{E}_{K_j} + \hat{E}_{P_j} + \hat{H}_j - P_j\hat{V}_j\right)$$

PV terms cancel

$$\Downarrow$$

$$\boxed{\Delta\dot{E}_K + \Delta\dot{E}_P + \Delta\dot{H} = \dot{Q} - \dot{W}_s}$$

First law of thermodynamics for an open system at steady state

Δ signifies (outputs – inputs). For example:

$$\Delta\dot{H} = \sum_{\substack{\text{output}\\\text{streams}}} \dot{m}_j\hat{H}_j - \sum_{\substack{\text{input}\\\text{streams}}} \dot{m}_j\hat{H}_j$$

$$\boxed{\dot{Q} - \dot{W}_s = \Delta\dot{H} + \Delta\dot{E}_k + \Delta\dot{E}_p}$$ (Each term has units of kJ/s)

where

$$\left.\begin{array}{l}\Delta\dot{H} = \sum\limits_{\substack{\text{outlet}\\\text{streams}}} \dot{m}_j\hat{H}_j - \sum\limits_{\substack{\text{inlet}\\\text{streams}}} \dot{m}_j\hat{H}_j \quad \left[= \sum\limits_{\substack{\text{outlet}\\\text{streams}}} \dot{m}_j(\hat{U}_j + P\hat{V}_j) - \sum\limits_{\substack{\text{inlet}\\\text{streams}}} \dot{m}_j(\hat{U}_j + P\hat{V}_j)\right] \\ \Delta\dot{E}_k = \left[\sum\limits_{\substack{\text{outlet}\\\text{streams}}} \frac{1}{2}\dot{m}_j u_j^2 - \sum\limits_{\substack{\text{inlet}\\\text{streams}}} \frac{1}{2}\dot{m}_j u_j^2\right], \quad \Delta\dot{E}_p = \left[\sum\limits_{\substack{\text{outlet}\\\text{streams}}} \dot{m}_j g z_j - \sum\limits_{\substack{\text{inlet}\\\text{streams}}} \dot{m}_j g z_j\right]\end{array}\right\}$$

Notes on Energy Balances for an Open System

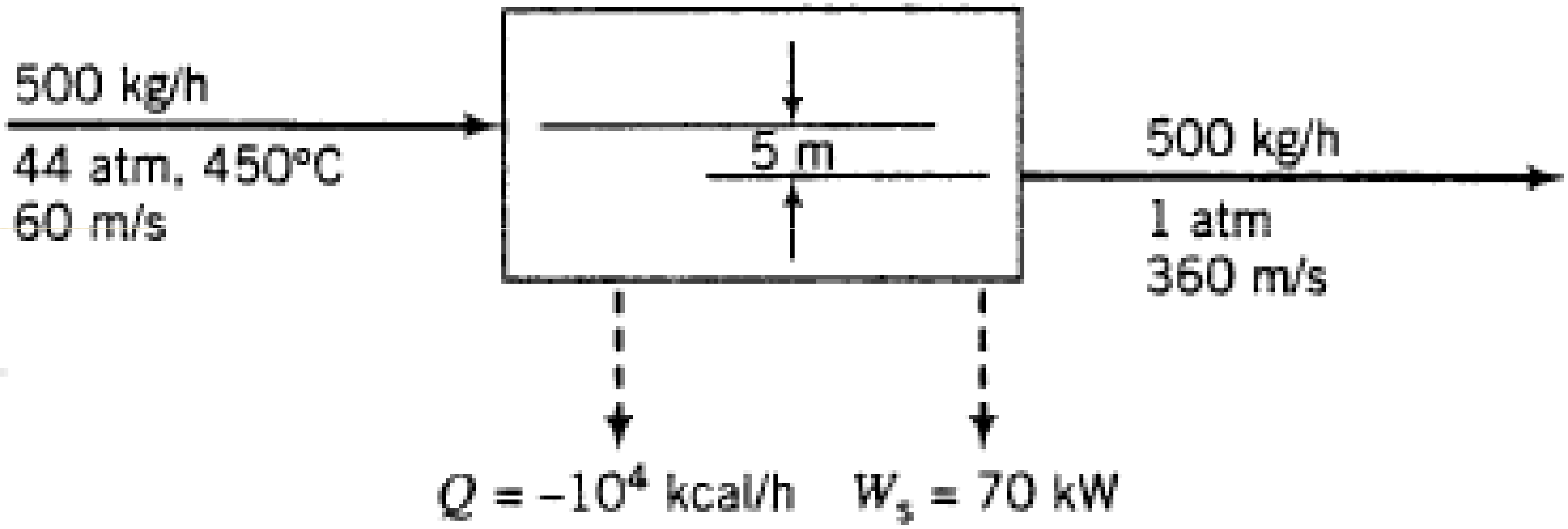
$$\boxed{\Delta\dot{H} + \Delta\dot{E}_k + \Delta\dot{E}_p = \dot{Q} - \dot{W}_s}$$

Possible Simplifications:

- if $T_{system} = T_{surroundings}$, then $Q = 0$ since no heat is being transferred due to temperature difference
- if the system is perfectly insulated, then $Q = 0$ (system is adiabatic) since no heat is being transferred between the system and the surroundings
- if energy is not transferred across the boundary by a moving part (e.g., piston, impeller, rotor), then $\dot{W}_s = 0$
- if inflow and outflow streams are of the same velocity, then $\Delta\dot{E}_k = 0$
- if there is no large vertical distance between the inlets and outlets of a system, then $\Delta\dot{E}_p = 0$
- if system is at constant temperature (system is isothermal), no phase changes or chemical reactions are taking place, and only minimal pressure changes, then $\Delta\dot{H} = 0$

Solution of Example 7.4.2

Five hundred kilograms per hour of steam drives a turbine. The steam enters the turbine at 44 atm and 450°C at a linear velocity of 60 m/s and leaves at a point 5 m below the turbine inlet at atmospheric pressure and a velocity of 360 m/s. The turbine delivers shaft work at a rate of 70 kW, and the heat loss from the turbine is estimated to be 10^4 kcal/h. Calculate the specific enthalpy change associated with the process.



Solution of Example 7.4.2

$$\Delta\dot{H} = \dot{Q} - \dot{W}_s - \Delta\dot{E}_k - \Delta\dot{E}_p$$

$$\Delta\dot{E}_k = \frac{\dot{m}}{2}(u_2^2 - u_1^2) = \begin{array}{c|c|c|c|r} 0.139\ \text{kg/s} & 1\ \text{N} & (360^2 - 60^2)\ \text{m}^2 & 1\ \text{W} & 1\ \text{kW} \\ \hline 2 & 1\ \text{kg}\cdot\text{m/s}^2 & \text{s}^2 & 1\ \text{N}\cdot\text{m/s} & 10^3\ \text{W} \end{array}$$

$$= 8.75\ \text{kW}$$

$$\Delta\dot{E}_p = \dot{m}g(z_2 - z_1) = \begin{array}{c|c|c|c} 0.139\ \text{kg/s} & 9.81\ \text{N} & (-5)\ \text{m} & 1\ \text{kW} \\ \hline & \text{kg} & & 10^3\ \text{N}\cdot\text{m/s} \end{array} = -6.81 \times 10^{-3}\ \text{kW}$$

$$\dot{Q} = \begin{array}{r|r|r|c} -10^4\ \text{kcal} & 1\ \text{J} & 1\ \text{h} & 1\ \text{kW} \\ \hline \text{h} & 0.239 \times 10^{-3}\ \text{kcal} & 3600\ \text{s} & 10^3\ \text{J/s} \end{array} = -11.6\ \text{kW}$$

$$\dot{W}_s = 70\ \text{kW}$$

$$\Downarrow$$

$$\Delta\dot{H} = \dot{Q} - \dot{W}_s - \Delta\dot{E}_k - \Delta\dot{E}_p = -90.3\ \text{kW}$$

But

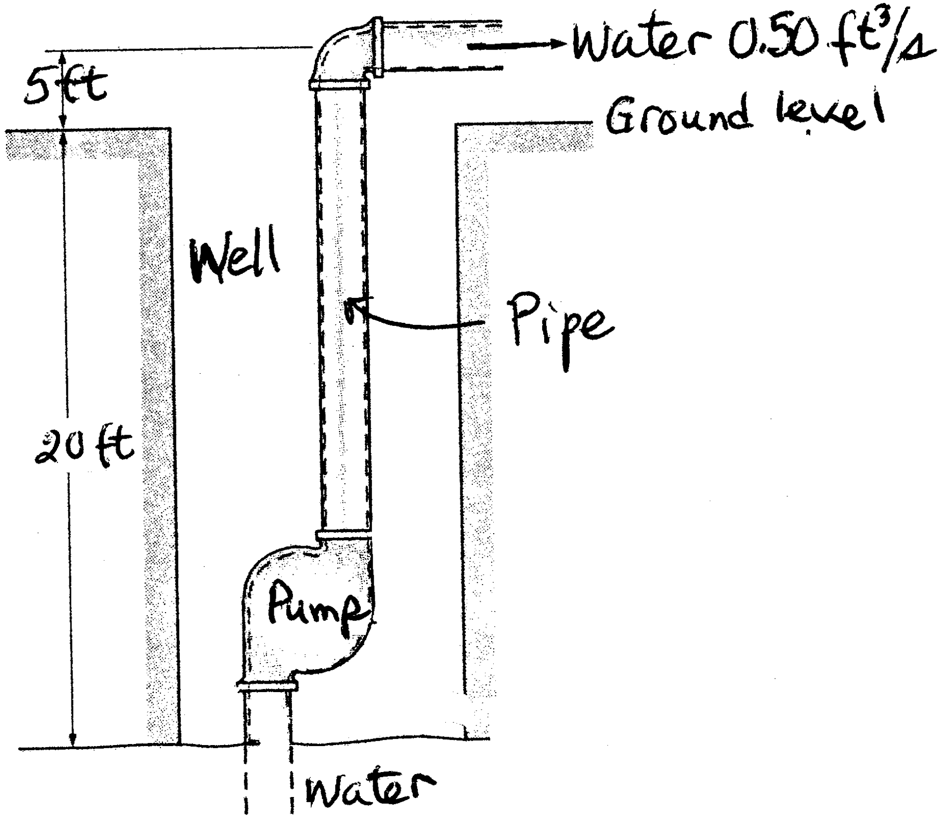
$$\Delta\dot{H} = \dot{m}(\hat{H}_2 - \hat{H}_1) \quad \text{(from Equation 7.4-16)}$$

$$\Downarrow$$

$$\hat{H}_2 - \hat{H}_1 = \Delta\dot{H}/\dot{m}$$

$$= \frac{-90.3\ \text{kJ/s}}{0.139\ \text{kg/s}} = \boxed{-650\ \text{kJ/kg}}$$

In-Class Exercise



- Calculate the electric power in hp. required by a pump if it is 100% efficient and you can neglect friction in the pipe and pump and assume that no heat transfer takes place.

Solution to In-Class Exercise

Energy Balance Eqr

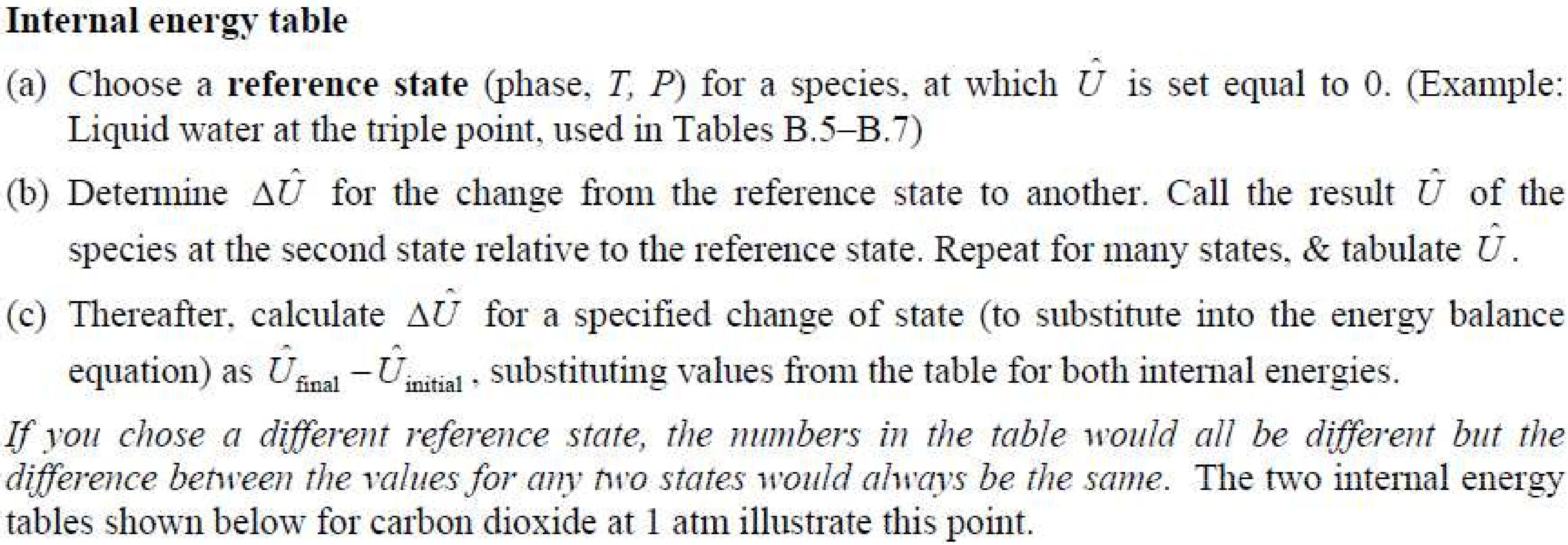
$$Q = 0;\ \Delta H = 0;\ \Delta KE = 0$$

After the simplifications: $W = \Delta PE = mg\Delta h$

$$W = \frac{0.5\ \text{ft}^3}{\text{s}}\,\Bigg|\,\frac{62.4\ \text{lb}_\text{m}}{\text{ft}^3}\,\Bigg|\,\frac{25\ \text{ft}}{}\,\Bigg|\,\frac{32.2\ \text{ft}}{\text{s}^2}\,\Bigg|\,\frac{(\text{s}^2)(\text{lb}_\text{f})}{32.2\ (\text{ft})(\text{lb}_\text{m})}$$

$$\frac{(\text{hp})(\text{s})}{550\ (\text{ft})(\text{lb}_\text{f})} = 1.42\ \text{hp}$$

7.5 Table of thermodynamic data: Reference state



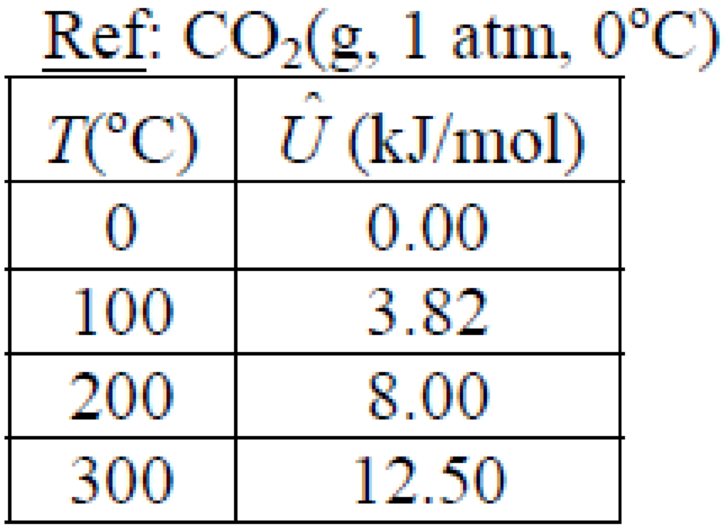
Internal energy table

(a) Choose a **reference state** (phase, T, P) for a species, at which $\hat{U}$ is set equal to 0. (Example: Liquid water at the triple point, used in Tables B.5–B.7)

(b) Determine $\Delta\hat{U}$ for the change from the reference state to another. Call the result $\hat{U}$ of the species at the second state relative to the reference state. Repeat for many states, & tabulate $\hat{U}$.

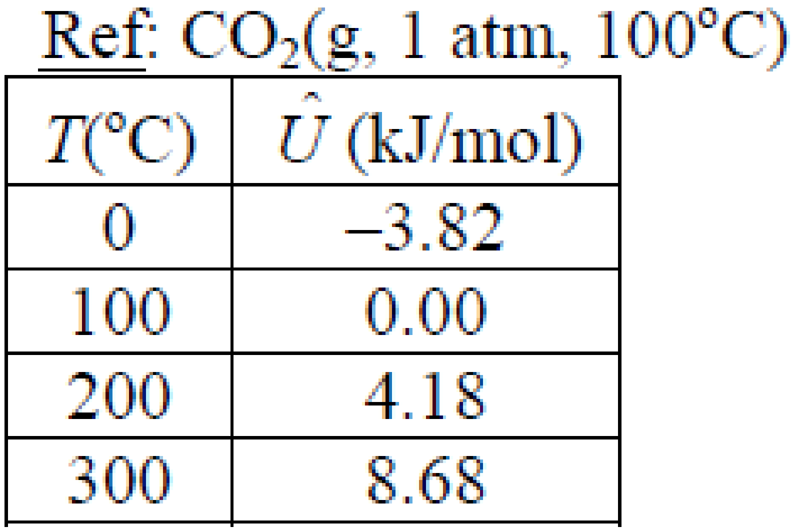
(c) Thereafter, calculate $\Delta\hat{U}$ for a specified change of state (to substitute into the energy balance equation) as $\hat{U}_{\text{final}} - \hat{U}_{\text{initial}}$, substituting values from the table for both internal energies.

If you chose a different reference state, the numbers in the table would all be different but the difference between the values for any two states would always be the same. The two internal energy tables shown below for carbon dioxide at 1 atm illustrate this point.



Ref: CO_2(g, 1 atm, 0°C)

T(°C)	$\hat{U}$ (kJ/mol)
0	0.00
100	3.82
200	8.00
300	12.50



Ref: CO_2(g, 1 atm, 100°C)

T(°C)	$\hat{U}$ (kJ/mol)
0	–3.82
100	0.00
200	4.18
300	8.68

Example 7.5.1 Tabulated Enthalpy

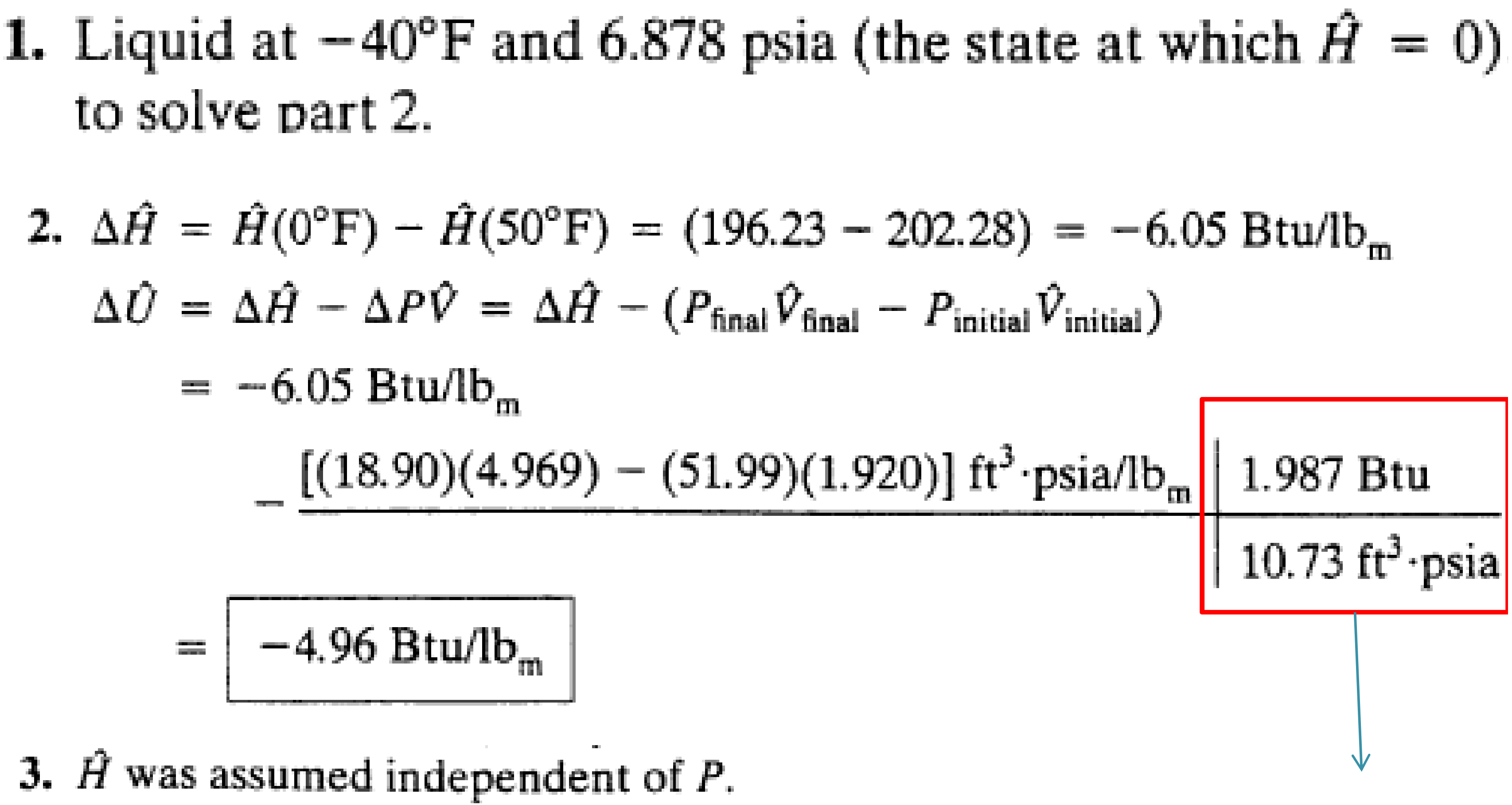
Use of Tabulated Enthalpy Data

The following entries are taken from a data table for saturated methyl chloride:

State	T(°F)	P(psia)	$\hat{V}$(ft^3/lb$_m$)	$\hat{H}$(Btu/lb$_m$)
Liquid	−40	6.878	0.01553	0.000
Vapor	0	18.90	4.969	196.23
Vapor	50	51.99	1.920	202.28

1. What reference state was used to generate the given enthalpies?
2. Calculate $\Delta\hat{H}$ and $\Delta\hat{U}$ for the transition of saturated methyl chloride vapor from 50°F to 0°F.
3. What assumption did you make in solving question 2 regarding the effect of pressure on specific enthalpy?

Solution



1. Liquid at −40°F and 6.878 psia (the state at which $\hat{H} = 0$) to solve part 2.

2. $$\Delta\hat{H} = \hat{H}(0°\text{F}) - \hat{H}(50°\text{F}) = (196.23 - 202.28) = -6.05\ \text{Btu/lb}_m$$

$$\Delta\hat{U} = \Delta\hat{H} - \Delta P\hat{V} = \Delta\hat{H} - (P_{\text{final}}\hat{V}_{\text{final}} - P_{\text{initial}}\hat{V}_{\text{initial}})$$

$$= -6.05\ \text{Btu/lb}_m - \begin{array}{l|l} [(18.90)(4.969) - (51.99)(1.920)]\ \text{ft}^3\cdot\text{psia/lb}_m & 1.987\ \text{Btu} \\ \hline & 10.73\ \text{ft}^3\cdot\text{psia} \end{array}$$

$$= \boxed{-4.96\ \text{Btu/lb}_m}$$

3. $\hat{H}$ was assumed independent of P.

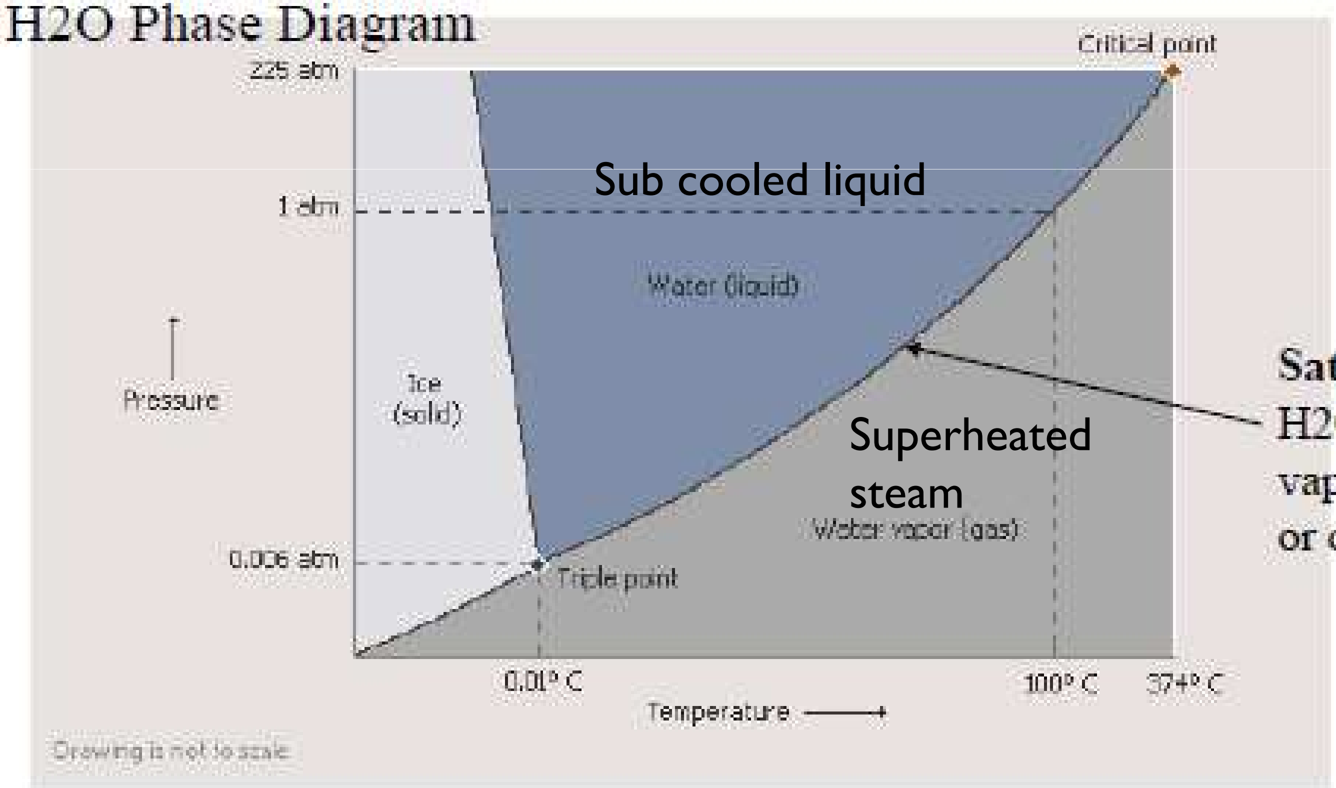
Verify this?

7.5 Tables of thermodynamic data

Give you values of $\hat{H}, \hat{U}$ and $\hat{V}$ for pure water

- Table B.5: As saturated liquid and vapour (as function of T)
- Table B.6: As saturated liquid and vapour (as function of P)
- Table B.7: Of superheated steam (at various T and P)

H2O Phase Diagram



Saturation Line: H2O may exist as vapour or liquid or coexist as both

F&R 7.5

Steam Tables

<u>Saturated Steam Tables</u>: data taken along the VLE curve or saturation line

- Table B.5 – properties of saturated water and saturated steam as a function of temperature from 0.01°C (triple point) to 102°C
- Table B.6 – properties of saturated water and saturated steam as a function of pressure (same data as Table B.5 but over a much larger range of temperatures and pressures)

<u>Superheated Steam Table</u>: data taken from points above or below the VLE curve or saturation line (especially vapour heated above its saturation temperature)

- Table B.7: properties of superheated steam table at any temperature and pressure – includes data for liquid water (data in the enclosed region), and saturated water and saturated steam

Steam Tables

- The reference state for the steam tables is liquid water at triple point conditions (0.01 °C, 0.00611 bar) [The triple point is where all three phases of water can coexist.]
  - – Absolute values of H and U for a species are never known. Values are always reported relative to a defined reference state.
    - At the reference state, H and U = 0.
  - – In your work, you are always calculating *changes* in energy or enthalpy
- Units are on mass basis (not moles): $\hat{V}\,[=]\,\dfrac{\text{m}^3}{\text{kg}}\quad \hat{H},\hat{U}\,[=]\,\dfrac{\text{kJ}}{\text{kg}}$
- Know how to use these!!!

– Volumetric properties of steam are tabulated. Do not use ideal gas law

– Properties of liquid water are not a strong function of pressure (at constant T)

– Heat of vaporization is the difference between vapour and liquid enthalpy

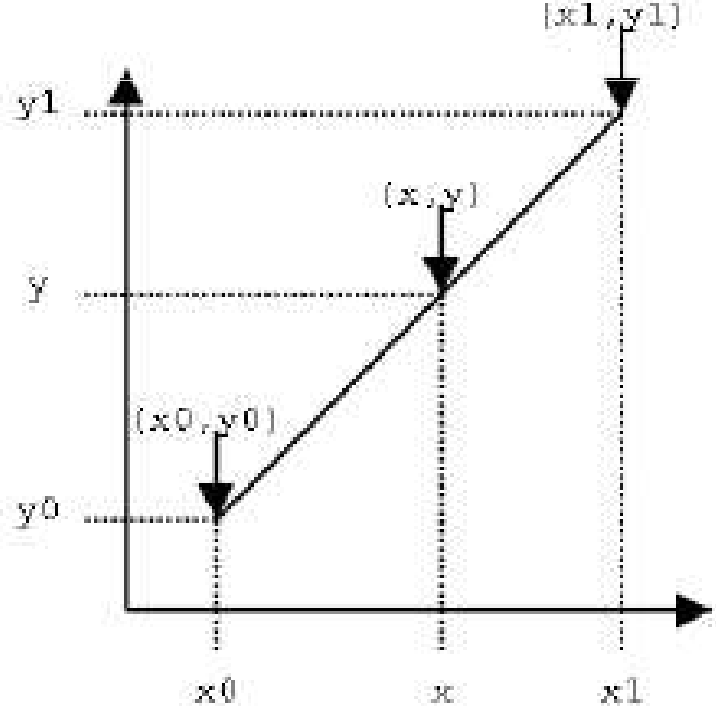
– Remember that $\hat{H} = \hat{U} + P\hat{V}$

Steam Tables- interpolation

- Sometimes you need to estimate a condition that is between tabulated quantities (usually Table B.7)
  - E.g.; superheated steam at 20 bar, with enthalpy of 3065 kJ/kg. What T is the steam at?
  - Steam at 400 °C and 25 bar. What is the specific enthalpy?
- Use linear interpolation:

(x_0, y_0) and (x_1, y_1) are known;
given $x_0 < x < x_0$, find y

$$\frac{y - y_0}{y_1 - y_0} = \frac{x - x_0}{x_1 - x_0}.$$



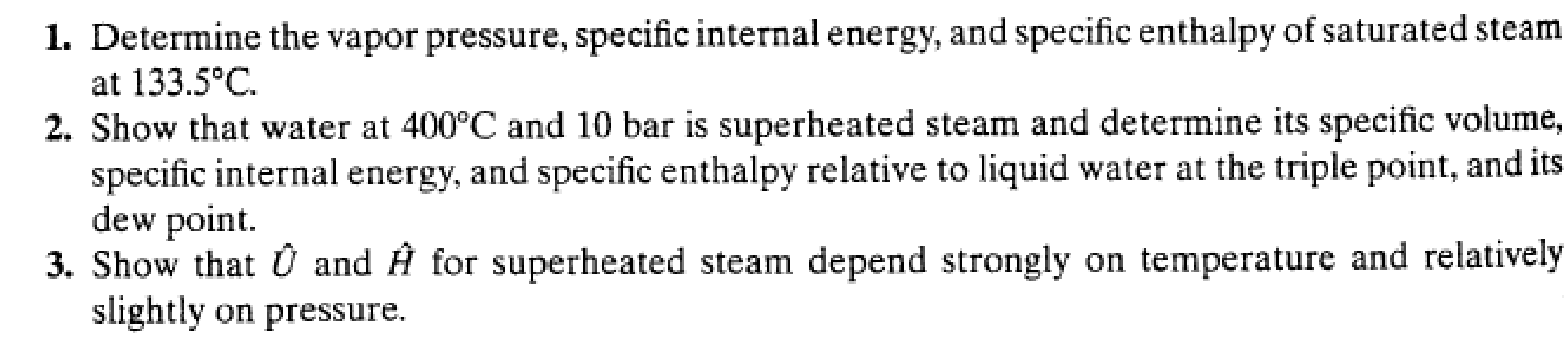
In class example

One pound of liquid water is at its boiling point of 575°F. It is then heated at constant pressure to 650°F, and then compressed at constant temperature to one-half of its volume (at 650°F), and finally returns to its original state of the boiling point at 575°F. Calculate ΔH and ΔU for the overall process.

Solution

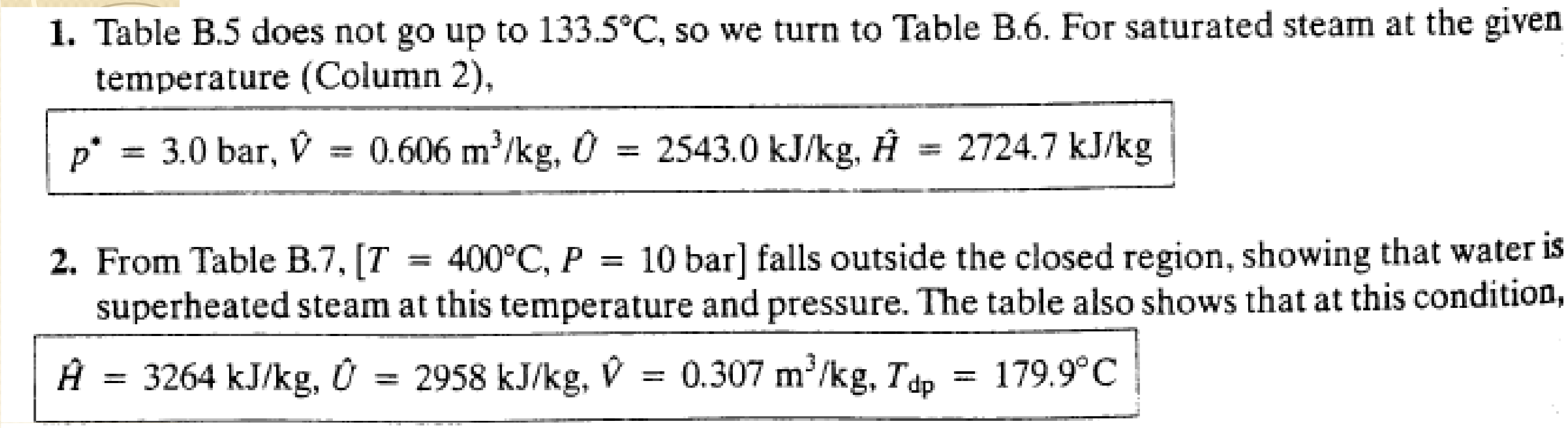
ΔH and ΔU are zero because ΔH and ΔU are point (state) functions (variables).

Example 7.5.2 The Steam Table



1. Determine the vapor pressure, specific internal energy, and specific enthalpy of saturated steam at 133.5°C.
2. Show that water at 400°C and 10 bar is superheated steam and determine its specific volume, specific internal energy, and specific enthalpy relative to liquid water at the triple point, and its dew point.
3. Show that $\hat{U}$ and $\hat{H}$ for superheated steam depend strongly on temperature and relatively slightly on pressure.

Solution



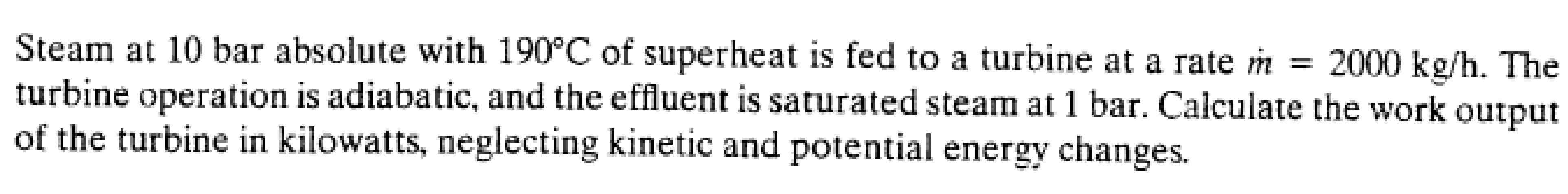
1. Table B.5 does not go up to 133.5°C, so we turn to Table B.6. For saturated steam at the given temperature (Column 2),

$$\boxed{p^* = 3.0\text{ bar},\ \hat{V} = 0.606\text{ m}^3/\text{kg},\ \hat{U} = 2543.0\text{ kJ/kg},\ \hat{H} = 2724.7\text{ kJ/kg}}$$

2. From Table B.7, [$T = 400°\text{C}$, $P = 10$ bar] falls outside the closed region, showing that water is superheated steam at this temperature and pressure. The table also shows that at this condition,

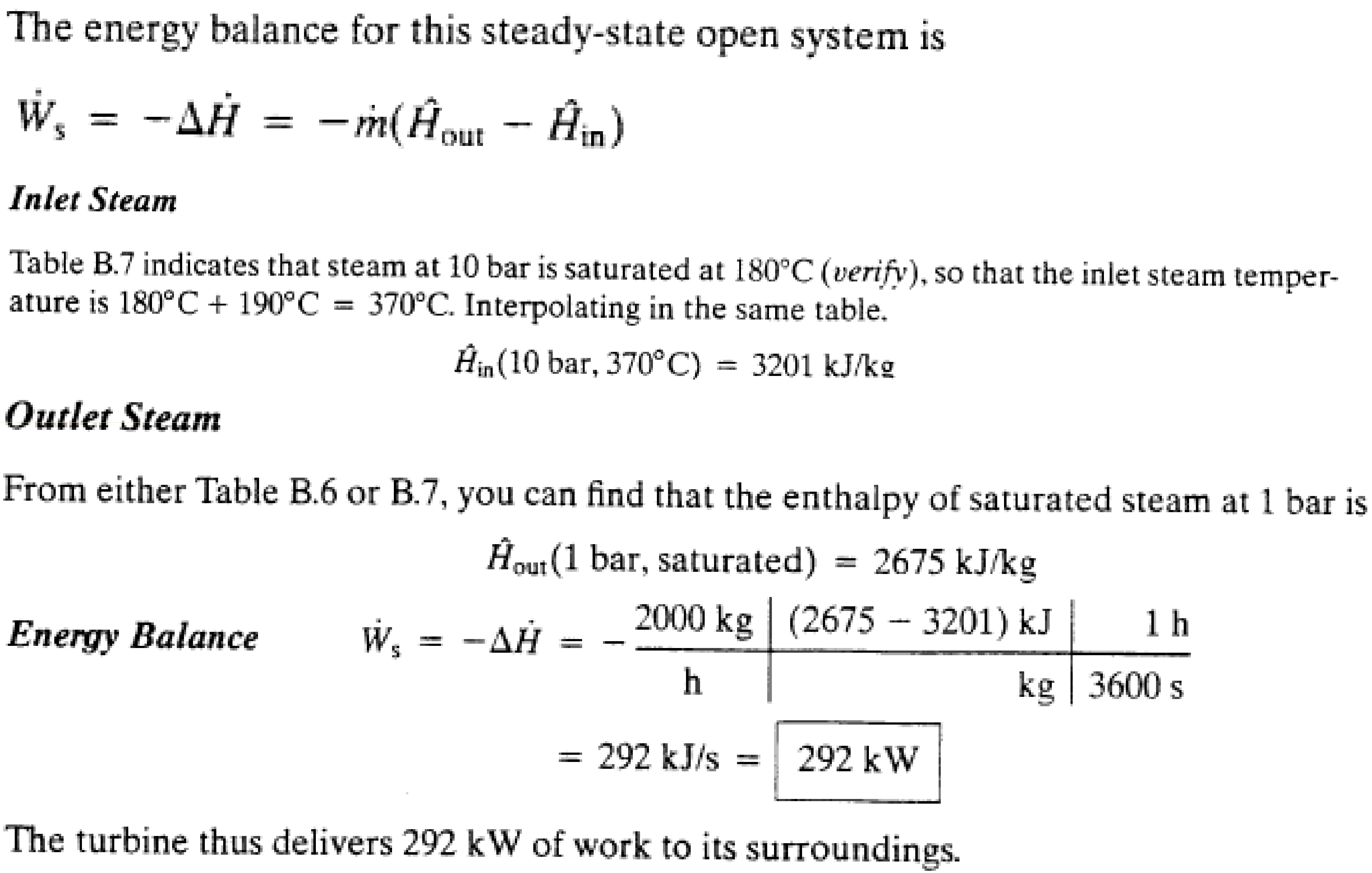
$$\boxed{\hat{H} = 3264\text{ kJ/kg},\ \hat{U} = 2958\text{ kJ/kg},\ \hat{V} = 0.307\text{ m}^3/\text{kg},\ T_{\text{dp}} = 179.9°\text{C}}$$

Example 7.5.3 EB on Turbine



Steam at 10 bar absolute with 190°C of superheat is fed to a turbine at a rate $\dot{m} = 2000$ kg/h. The turbine operation is adiabatic, and the effluent is saturated steam at 1 bar. Calculate the work output of the turbine in kilowatts, neglecting kinetic and potential energy changes.

Solution



The energy balance for this steady-state open system is

$$\dot{W}_s = -\Delta\dot{H} = -\dot{m}(\hat{H}_{\text{out}} - \hat{H}_{\text{in}})$$

Inlet Steam

Table B.7 indicates that steam at 10 bar is saturated at 180°C (*verify*), so that the inlet steam temperature is 180°C + 190°C = 370°C. Interpolating in the same table.

$$\hat{H}_{\text{in}}(10 \text{ bar}, 370°\text{C}) = 3201 \text{ kJ/kg}$$

Outlet Steam

From either Table B.6 or B.7, you can find that the enthalpy of saturated steam at 1 bar is

$$\hat{H}_{\text{out}}(1 \text{ bar, saturated}) = 2675 \text{ kJ/kg}$$

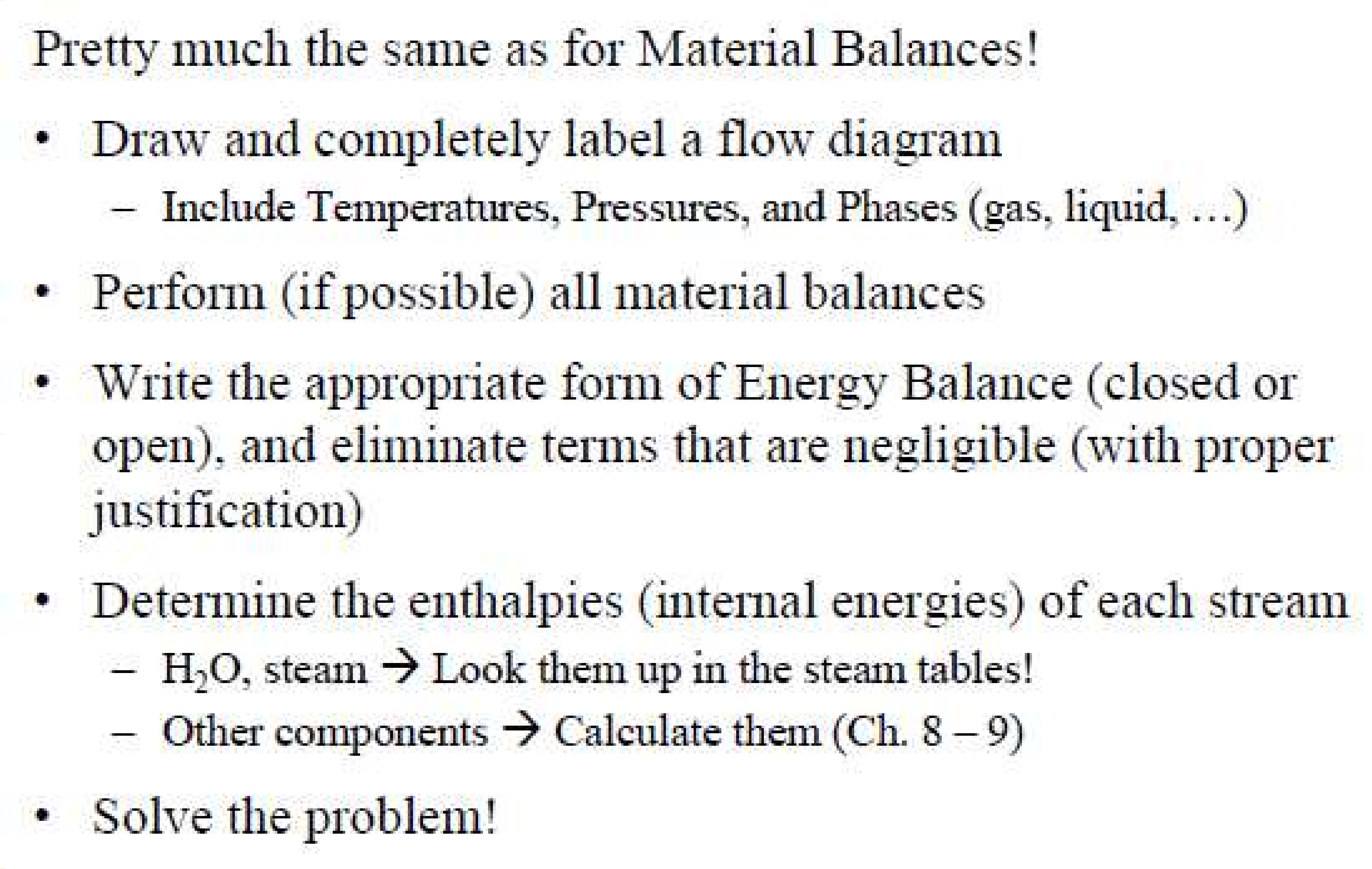
Energy Balance

$$\dot{W}_s = -\Delta\dot{H} = -\frac{2000 \text{ kg}}{\text{h}}\,\bigg|\,\frac{(2675 - 3201) \text{ kJ}}{\text{kg}}\,\bigg|\,\frac{1 \text{ h}}{3600 \text{ s}}$$

$$= 292 \text{ kJ/s} = \boxed{292 \text{ kW}}$$

The turbine thus delivers 292 kW of work to its surroundings.

7.6 Energy Balance Procedure

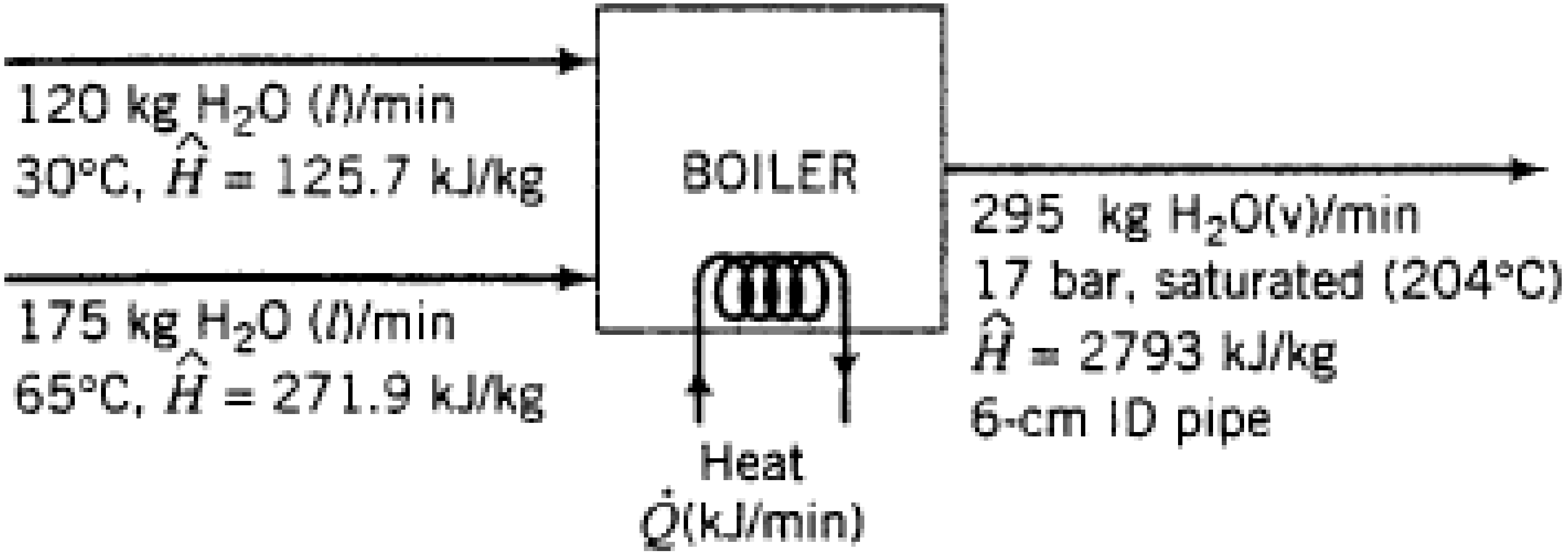


Pretty much the same as for Material Balances!

- Draw and completely label a flow diagram
  - Include Temperatures, Pressures, and Phases (gas, liquid, …)
- Perform (if possible) all material balances
- Write the appropriate form of Energy Balance (closed or open), and eliminate terms that are negligible (with proper justification)
- Determine the enthalpies (internal energies) of each stream
  - H_2O, steam → Look them up in the steam tables!
  - Other components → Calculate them (Ch. 8 – 9)
- Solve the problem!

Example 7.6.1 EB on a one-component process

Feed stream 1	120 kg/min @ 30°C
Feed stream 2	175 kg/min @ 65°C
Boiler pressure	17 bar (absolute)



solution

$$\dot{Q} - \dot{W}_s = \Delta\dot{H} + \Delta\dot{E}_k + \Delta\dot{E}_p$$

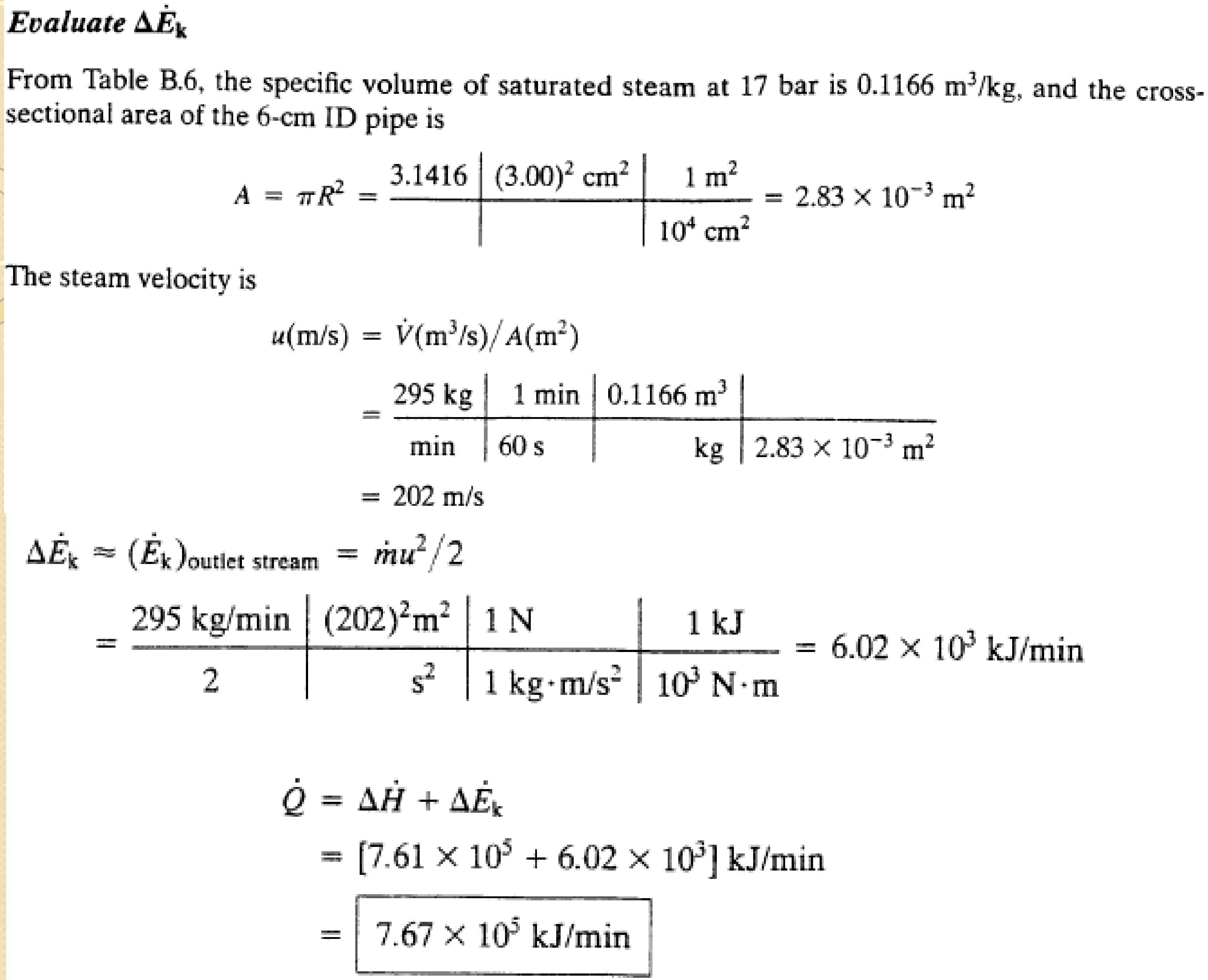
$$\Bigg\Downarrow \quad \begin{aligned} \dot{W}_s &= 0 \quad \text{(no moving parts)} \\ \Delta\dot{E}_p &= 0 \quad \text{(generally assumed unless displacements through large heights are involved)} \end{aligned}$$

$$\dot{Q} = \Delta\dot{H} + \Delta\dot{E}_k$$

$$\Delta\dot{H} = \sum_{\text{outlet}} \dot{m}_i\hat{H}_i - \sum_{\text{inlet}} \dot{m}_i\hat{H}_i$$

$$= \begin{array}{c|c} 295\text{ kg} & 2793\text{ kJ} \\ \hline \text{min} & \text{kg} \end{array} - \begin{array}{c|c} 120\text{ kg} & 125.7\text{ kJ} \\ \hline \text{min} & \text{kg} \end{array} - \begin{array}{c|c} 175\text{ kg} & 271.9\text{ kJ} \\ \hline \text{min} & \text{kg} \end{array}$$

$$= 7.61 \times 10^5\ \text{kJ/min}$$



Evaluate $\Delta\dot{E}_k$

From Table B.6, the specific volume of saturated steam at 17 bar is 0.1166 m³/kg, and the cross-sectional area of the 6-cm ID pipe is

$$A = \pi R^2 = \begin{array}{c|c|c} 3.1416 & (3.00)^2\ \text{cm}^2 & 1\ \text{m}^2 \\ \hline & & 10^4\ \text{cm}^2 \end{array} = 2.83 \times 10^{-3}\ \text{m}^2$$

The steam velocity is

$$\begin{aligned} u(\text{m/s}) &= \dot{V}(\text{m}^3/\text{s})/A(\text{m}^2) \\ &= \begin{array}{c|c|c|c} 295\ \text{kg} & 1\ \text{min} & 0.1166\ \text{m}^3 & \\ \hline \text{min} & 60\ \text{s} & \text{kg} & 2.83 \times 10^{-3}\ \text{m}^2 \end{array} \\ &= 202\ \text{m/s} \end{aligned}$$

$$\Delta\dot{E}_k \approx (\dot{E}_k)_{\text{outlet stream}} = \dot{m}u^2/2$$

$$= \begin{array}{c|c|c|c} 295\ \text{kg/min} & (202)^2\text{m}^2 & 1\ \text{N} & 1\ \text{kJ} \\ \hline 2 & \text{s}^2 & 1\ \text{kg}\cdot\text{m/s}^2 & 10^3\ \text{N}\cdot\text{m} \end{array} = 6.02 \times 10^3\ \text{kJ/min}$$

$$\begin{aligned} \dot{Q} &= \Delta\dot{H} + \Delta\dot{E}_k \\ &= [7.61 \times 10^5 + 6.02 \times 10^3]\ \text{kJ/min} \\ &= \boxed{7.67 \times 10^5\ \text{kJ/min}} \end{aligned}$$