Introduction to Chemical Engineering

Chapter 10

Heat Transfer
(*Cooling Down the Product*)

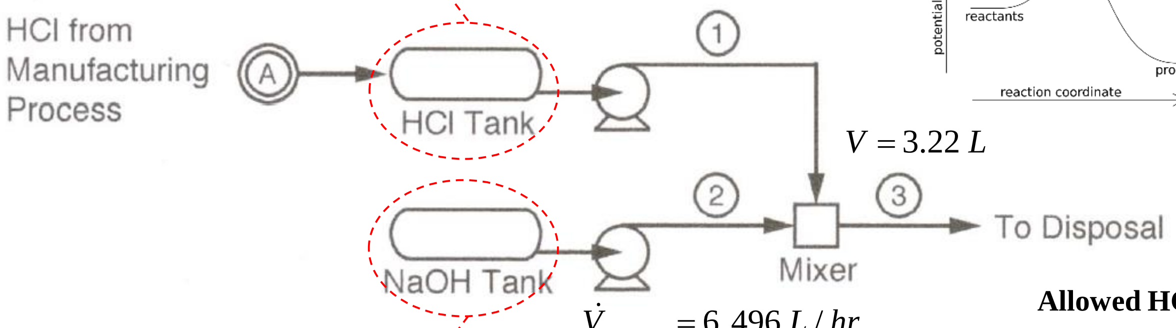
10.1 Energy balances for steady-state open systems

- **HCl neutralization process**

$c_{HCl_{in}} = 0.014\ gmol/L$

$T_{HCl_{in}} = 60\ ^{\circ}C$

$\dot{V}_{HCl_{in}} = 11,600\ L/hr$



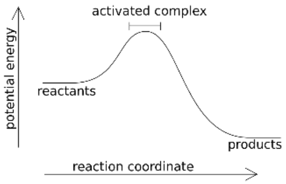
$V = 3.22\ L$

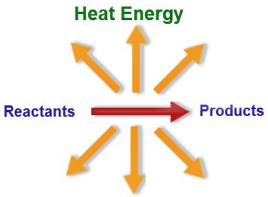
$\dot{V}_{out} = 18,096\ L/hr$

$\dot{V}_{NaOH_{in}} = 6,496\ L/hr$

$c_{NaOH_{in}} = 0.0254\ gmol/L$

$T_{NaOH_{in}} = 32\ ^{\circ}C$





Allowed HCl concentration

at final state by law (pH = 6.5)

$c_{HCl_{out}} = 10^{-6.5} = 3.16 \times 10^{-7}\ M$

$c_{NaOH_{out}} = c_{HCl_{out}} = 3.16 \times 10^{-7}\ M$

Allowed temperature of disposal

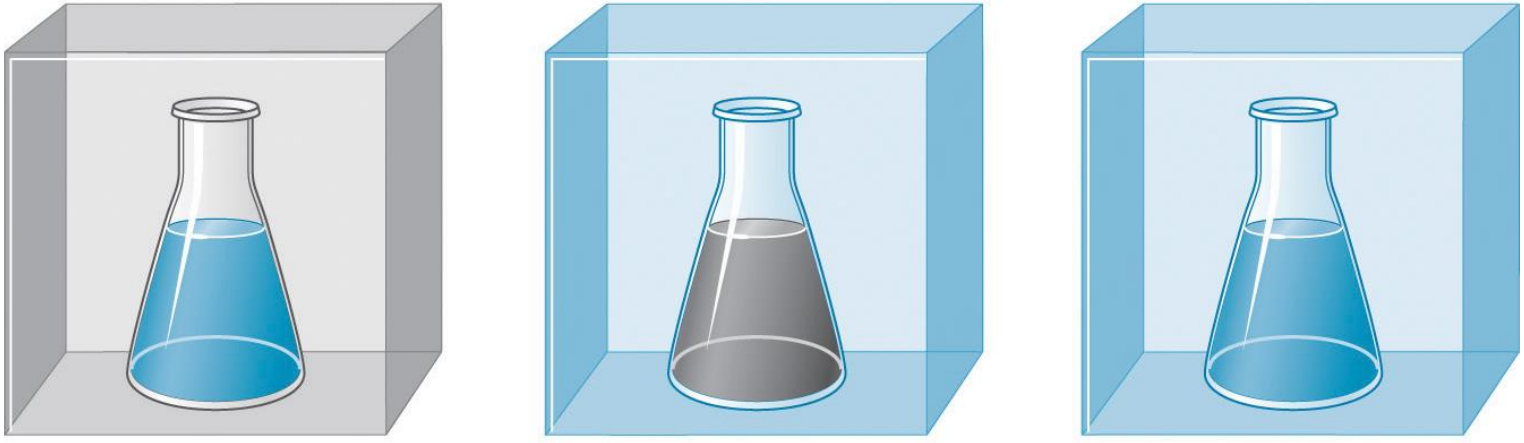
At final state by law ($T \leq 27^{\circ}$C)

10.1 Energy balances for steady-state open systems

- **Questions about temperature**
  1. **Will the temperature of the mixture still exceed the government's maximum temperature requirement even after the addition of the NaOH?**
  2. **If so,**
     - a. **How much heat would still need to be removed to bring the temperature down below the government's maximum temperature requirement?**
     - b. **What strategy should be used to remove the heat referred to in question 2a?**
     - c. **What other resources are needed to implement the strategy referred to in question 2b?**

10.1 Energy balances for steady-state open systems

- **First law of thermodynamics: conservation of energy**
- Although energy assumes many forms, the total quantity of energy is constant, and when energy disappears in one form it appears simultaneously in other forms.



System + **Surroundings** = **Universe**

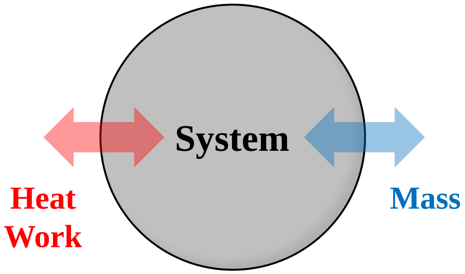
(process occurs) (everything except system)

$$\Delta(Energy\ of\ the\ system) + \Delta(Energy\ of\ the\ surroundings) = 0$$

10.1 Energy balances for steady-state open systems

- **Three types of system**

Open system

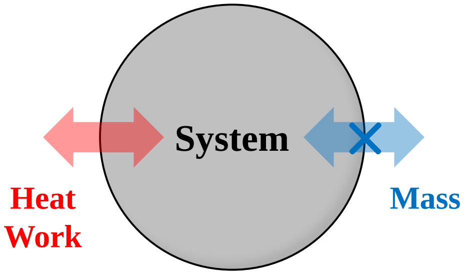


System

Heat
Work

Mass

Closed system

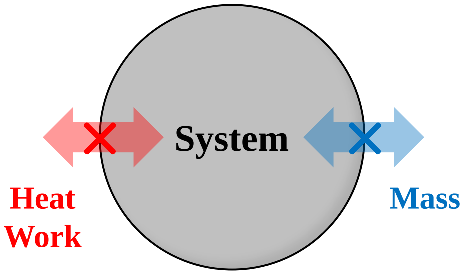


System

Heat
Work

Mass

Isolated system



System

Heat
Work

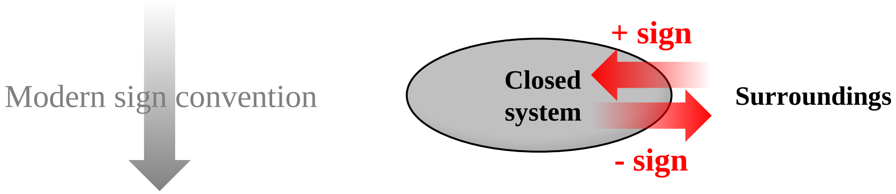
Mass

10.1 Energy balances for steady-state open systems

Modern sign convention

From the first law of thermodynamics,

$$\Delta(Energy\ of\ \ the\ surroundings)+\Delta(Energy\ of\ \ the\ system)=0$$



Heat: + $Q_{surr} = – Q$
Work: + $W_{surr} = – W$

$$\Delta(Energy\ of\ \ the\ surroundings)=Q_{surr}+W_{surr}=-Q-W$$

The equation now becomes:

$$\Delta(Energy\ of\ \ the\ system)=Q+W$$

10.1 Energy balances for steady-state open systems

- **First law of thermodynamics for closed system**

$$\Delta E = Q + W$$

$\Delta E = \text{total energy of the system (units of energy)}$

$Q = \text{heat transferred from the environment to the system through the boundaries of the volume (units of energy)}$

$W = \text{work done on the system by the environment (units of energy)}$

- **Energy balance for open system**

$$\sum_{\substack{\text{output}\\ \text{streams}}} \left\{\dot{m}\hat{E}\right\}_{out} - \sum_{\substack{\text{input}\\ \text{streams}}} \left\{\dot{m}\hat{E}\right\}_{in} = \dot{Q} + \dot{W}$$

$\dot{m} = \text{mass flow rate of a stream (units of mass per time)}$

$\hat{E} = \text{energy per mass of a stream of flowing material}$

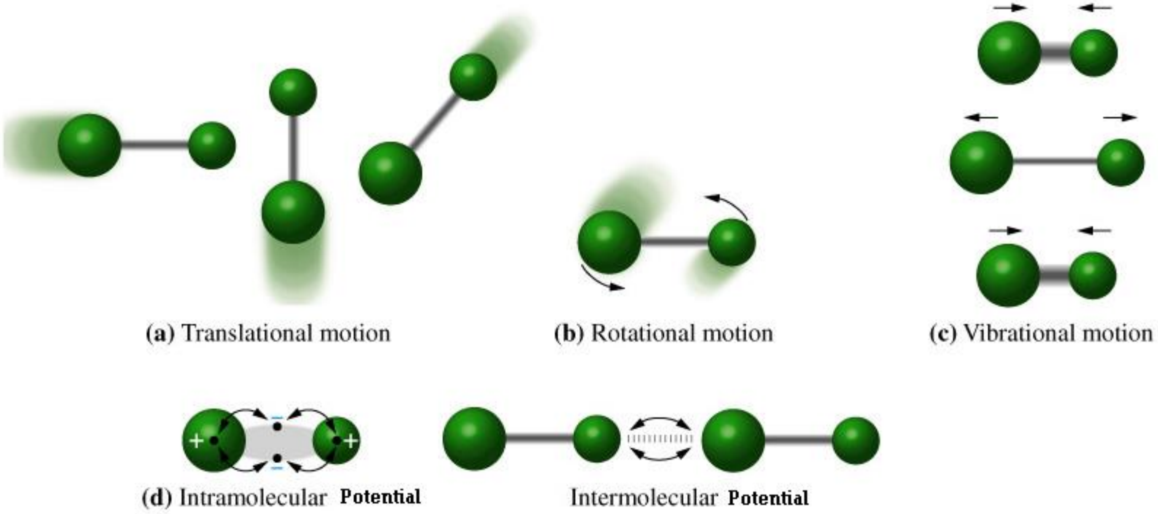
$\dot{Q} = \text{rate of transfer of energy across the boundaries of a system into that system (units of energy per time)}$

$\dot{W} = \text{rate that work is done on a system (units of energy per time)}$

10.1 Energy balances for steady-state open systems

10.1.1 Energy (*E*)

- **Internal energy:** an energy contained within the system, excluding the kinetic energy of motion of the system as a whole and the potential energy of the system as a whole due to external force fields.



(a) Translational motion (b) Rotational motion (c) Vibrational motion

(d) Intramolecular Potential Intermolecular Potential

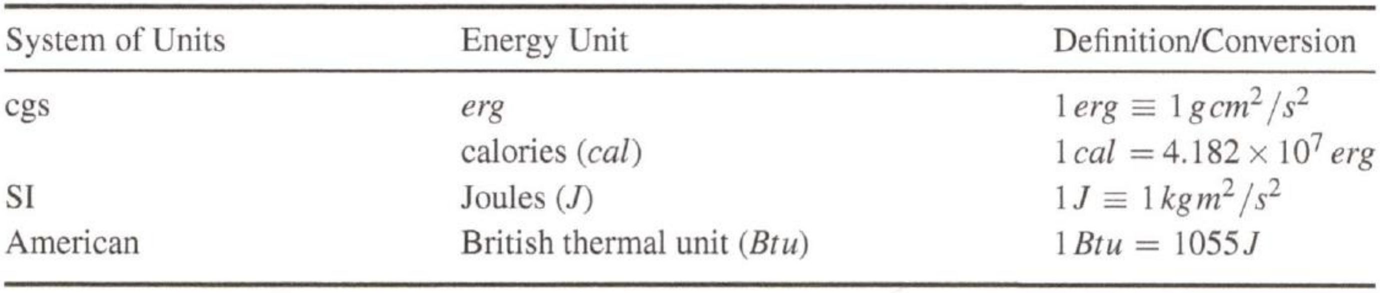
10.1 Energy balances for steady-state open systems

10.1.1 Energy (*E*)

- **Total energy per mass of material**

$$\hat{E}_{total} = \hat{E}_{internal} + \hat{E}_{kinetic} + \hat{E}_{potential} = \hat{U} + \frac{1}{2}\alpha v^2 + gz$$

- **Units of energy**



System of Units	Energy Unit	Definition/Conversion
cgs	*erg*	$1\,erg \equiv 1\,g\,cm^2/s^2$
	calories (*cal*)	$1\,cal = 4.182 \times 10^7\,erg$
SI	Joules (*J*)	$1\,J \equiv 1\,kg\,m^2/s^2$
American	British thermal unit (*Btu*)	$1\,Btu = 1055\,J$

10.1 Energy balances for steady-state open systems

10.1.1 Energy (*E*)

- **Energy balance for open system**

$$\sum_{\substack{output\\ streams}} \left\{\dot{m}\hat{E}\right\}_{out} - \sum_{\substack{input\\ streams}} \left\{\dot{m}\hat{E}\right\}_{in} = \dot{Q} + \dot{W}$$

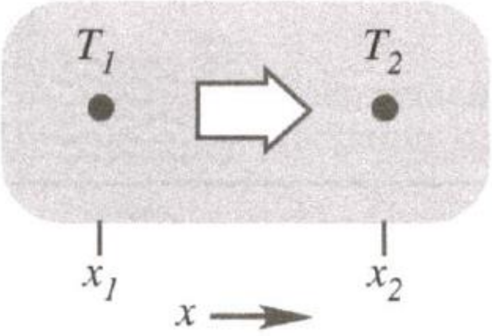
$$\hat{E} = \hat{U} + \frac{1}{2}\alpha v^2 + gz$$

$$\sum_{\substack{output\\ streams}} \dot{m}\left[\hat{U} + \frac{1}{2}\alpha v^2 + gz\right]_{out} - \sum_{\substack{input\\ streams}} \dot{m}\left[\hat{U} + \frac{1}{2}\alpha v^2 + gz\right]_{in} = \dot{Q} + \dot{W}$$

10.1 Energy balances for steady-state open systems

10.1.2 Rate of heat transfer ($\dot{Q}$)

- **Conduction:** heat transfer through a stationary medium when one location in the medium is at a higher temperature than another location.



Fourier's Law of Heat Conduction

$$\dot{Q}_{cond,x} = -kA\frac{T_2 - T_1}{x_2 - x_1} = -kA\frac{\Delta T}{\Delta x}$$

$\dot{Q}_{cond,x}$ = conduction heat transfer rate (energy transferred per time) through area A in the x direction between location 1 and 2

A = cross-sectional area through which conduction occurs

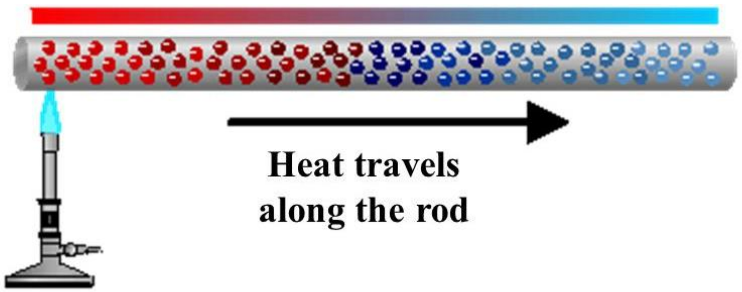
k = the thermal conductivity of the material, with units of energy per time per length per temperature (e.g., W/mK)

T = temperature

10.1 Energy balances for steady-state open systems

10.1.2 Rate of heat transfer ($\dot{Q}$)

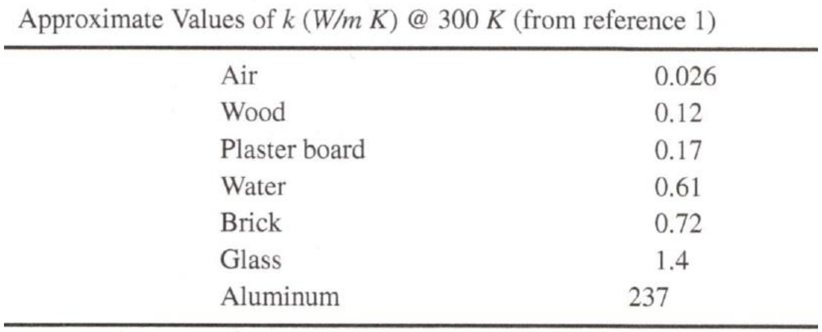
- **Conduction**



Hot
(lots of vibration)

Cold
(not much vibration)

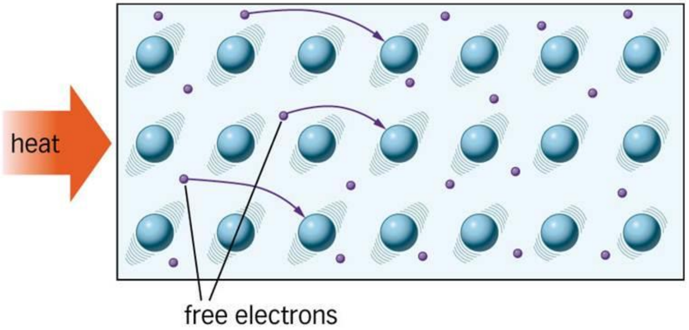
- **Thermal conductivity**



Approximate Values of k ($W/m\ K$) @ 300 K (from reference 1)

Air	0.026
Wood	0.12
Plaster board	0.17
Water	0.61
Brick	0.72
Glass	1.4
Aluminum	237

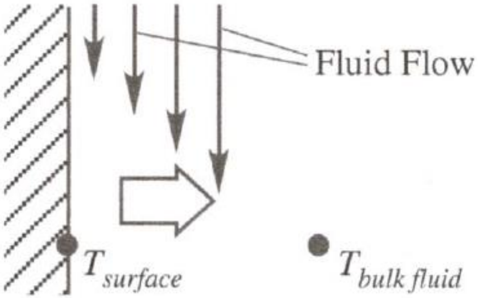
Conduction in metals



10.1 Energy balances for steady-state open systems

10.1.2 Rate of heat transfer ($\dot{Q}$)

- **Convection:** if a fluid flows along a surface and is at a temperature different from the temperature of that surface, heat will transfer to or away from that surface.



$$\dot{Q}_{conv} = hA\left(T_{surface} - T_{bulk\ \ fluid}\right)$$

$\dot{Q}_{conv}$ = convection heat transfer rate (energy transferred per time) through area A from the surface to the bulk fluid

h = heat transfer coefficient

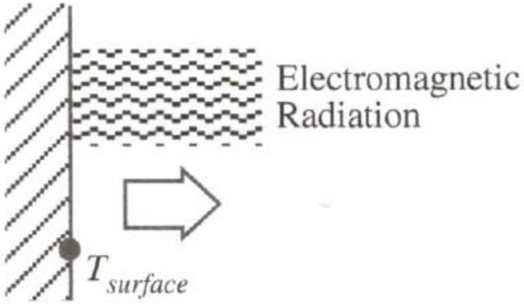
A = cross-sectional area through which convection occurs

T = temperature

10.1 Energy balances for steady-state open systems

10.1.2 Rate of heat transfer ($\dot{Q}$)

- **Radiation:** All surface radiate heat as electromagnetic waves.



$$\dot{Q}_{rad} = \varepsilon\sigma A T_{surface}^{4}$$

$\dot{Q}_{rad}$ = radiation heat transfer rate (energy transferred per time) through area A from location 1 to location 2

ε = emissivity, which indicates how well the surface emits radiation compared with a "perfect" radiator (unitless)

σ = Stefan – Boltzmann constant (equals 5.67×10^{-8} $W/m^2\ K^4$)

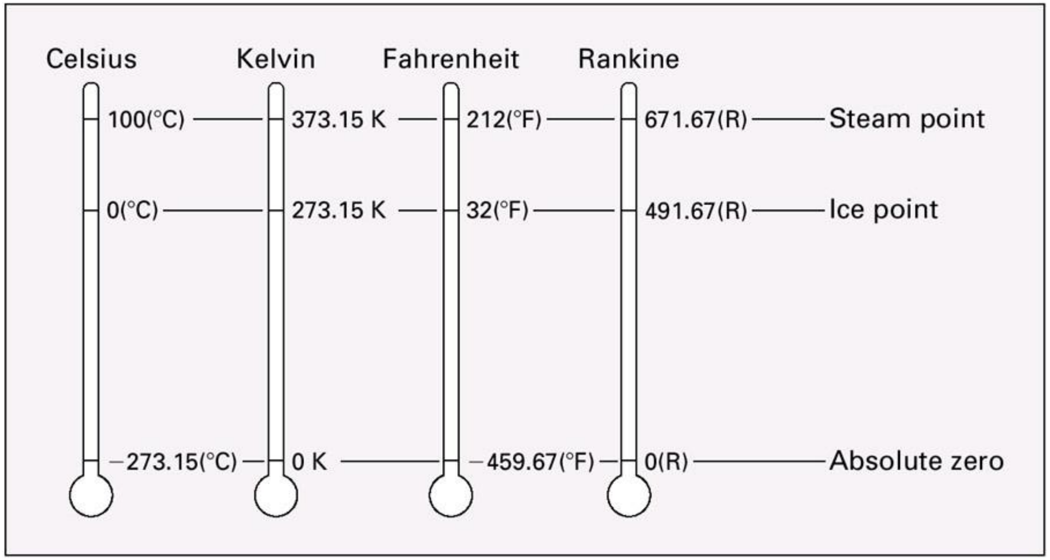
A = cross – sectional area from which radiation occurs

T = absolute surface temperature

10.1 Energy balances for steady-state open systems

10.1.2 Rate of heat transfer ($\dot{Q}$)

- **Temperature scales**



$t(^\circ C) = T(K) - 273.15$

$t(^\circ F) = T(R) - 459.67$

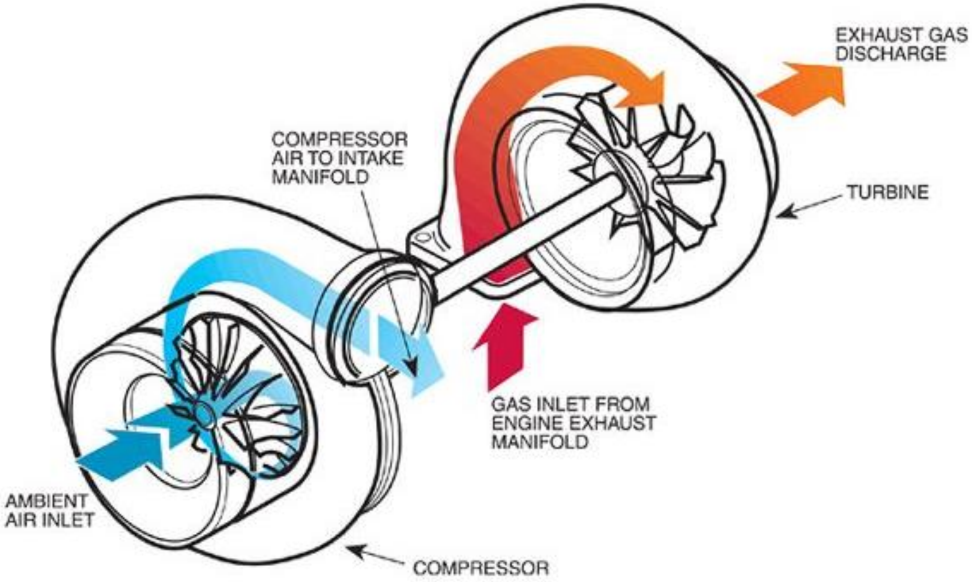
$t(^\circ F) = 1.8\, t(^\circ C) + 32$

$T(R) = 1.8\, T(K)$

10.1 Energy balances for steady-state open systems

10.1.3 Rate of work ($\dot{W}$)

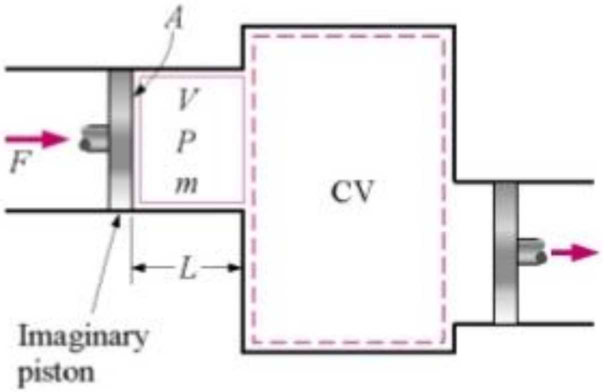
- Rate of shaft work ($\dot{W}_s$)



10.1 Energy balances for steady-state open systems

10.1.3 Rate of work ($\dot{W}$)

- **Rate of flow work ($\dot{W}_{PV}$)**



$$F = PA$$

$$W_{PV} = FL = PAL = PV$$

$$\dot{W}_{PV} = P\dot{V}$$

$$\dot{W}_{PV} = \sum_{\substack{input\\stream}} \left(P\dot{V}\right)_{in} - \sum_{\substack{output\\stream}} \left(P\dot{V}\right)_{out} = \sum_{\substack{input\\stream}} \left(\dot{m}P\hat{V}\right)_{in} - \sum_{\substack{output\\stream}} \left(\dot{m}P\hat{V}\right)_{out}$$

$$\hat{V} = volume\ per\ unit\ mass\ of\ the\ stream \left(=1/\rho\right)$$

10.1 Energy balances for steady-state open systems

10.1.3 Rate of work ($\dot{W}$)

- **Energy balance for open system**

$$\sum_{\substack{output\\streams}} \dot{m}\left[\hat{U}+\frac{1}{2}\alpha v^2+gz\right]_{out} - \sum_{\substack{input\\streams}} \dot{m}\left[\hat{U}+\frac{1}{2}\alpha v^2+gz\right]_{in} = \dot{Q}+\dot{W}$$

$$\dot{W}=\dot{W}_s+\dot{W}_{PV}$$

$$\sum_{\substack{output\\streams}} \dot{m}\left[\hat{U}+\frac{1}{2}\alpha v^2+gz\right]_{out} - \sum_{\substack{input\\streams}} \dot{m}\left[\hat{U}+\frac{1}{2}\alpha v^2+gz\right]_{in} = \dot{Q}+\dot{W}_s+\dot{W}_{PV}$$

$$\dot{W}_{PV}=\sum_{\substack{input\\stream}}\left(\dot{m}P\hat{V}\right)_{in}-\sum_{\substack{output\\stream}}\left(\dot{m}P\hat{V}\right)_{out}$$

$$\sum_{\substack{output\\streams}} \dot{m}\left[\hat{U}+P\hat{V}+\frac{1}{2}\alpha v^2+gz\right]_{out} - \sum_{\substack{input\\streams}} \dot{m}\left[\hat{U}+P\hat{V}+\frac{1}{2}\alpha v^2+gz\right]_{in} = \dot{Q}+\dot{W}_s$$

10.1 Energy balances for steady-state open systems

10.1.3 Rate of work ($\dot{W}$)

- **Enthalpy** $\hat{H} = \hat{U} + P\hat{V}$
  - Enthalpy has actually no meaning, it's an abstract concept which is impossible to calculate absolute value.
  - SI unit of enthalpy is *J/mol* which express the change of enthalpy.
  - Enthalpy is a state function.

- **Energy balance for open system**

$$\sum_{\substack{output\\streams}} \dot{m}\left[\hat{U} + P\hat{V} + \frac{1}{2}\alpha v^2 + gz\right]_{out} - \sum_{\substack{input\\streams}} \dot{m}\left[\hat{U} + P\hat{V} + \frac{1}{2}\alpha v^2 + gz\right]_{in} = \dot{Q} + \dot{W}_s$$

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

$$\sum_{\substack{output\\streams}} \dot{m}\left[\hat{H} + \frac{1}{2}\alpha v^2 + gz\right]_{out} - \sum_{\substack{input\\streams}} \dot{m}\left[\hat{H} + \frac{1}{2}\alpha v^2 + gz\right]_{in} = \dot{Q} + \dot{W}_s$$

10.2 Applications of the steady-state energy balance

Steady-state energy balance

with negligible change in kinetic and potential energies

with no shaft work

$$\sum_{\substack{output\\streams}} \dot{m}\left[\hat{H} + \cancelto{0}{\frac{1}{2}\alpha v^2} + \cancelto{0}{gz}\right]_{out} - \sum_{\substack{input\\streams}} \dot{m}\left[\hat{H} + \cancelto{0}{\frac{1}{2}\alpha v^2} + \cancelto{0}{gz}\right]_{in} = \dot{Q} + \cancelto{0}{\dot{W}_s} \quad \Longrightarrow \quad \sum_{\substack{output\\streams}} \left(\dot{m}\hat{H}\right)_{out} - \sum_{\substack{input\\streams}} \left(\dot{m}\hat{H}\right)_{in} = \dot{Q}$$

Example

Water flows over a waterfall 100 m in height. Take 1 kg of the water as the system, and assume that it does not exchange energy with its surroundings.

(a) What is the potential energy of the water at the top of the falls with respect to the base of the falls?
(b) What is the kinetic energy of the water just before it strikes bottom?
(c) After the 1 kg of water enters the stream below the falls, what change has occurred in its state?

The 1 kg of water exchanges no energy with the surroundings. Thus, for each part of the process Eq. (2.1) reduces to:

$$\Delta(Energy\ of\ \ the\ system) = \Delta U + \Delta E_K + \Delta E_P = 0$$

10.2 Applications of the steady-state energy balance

(a) From Eq. (1.7), with *g* equal to its standard value,

$$\Delta E_P = mzg = 1\,kg \times 100\,m \times 9.8066\,m\,s^{-2} = 980.66\,\frac{kg\,m^2}{s^2} = 980.66\,N\,m = 980.66\,J$$

(b) During the free fall of the water no mechanism exists for conversion of potential or kinetic energy into internal energy. Thus ΔU must be zero:

$$\Delta E_K + \Delta E_P = E_{K_2} - E_{K_1} + E_{P_2} - E_{P_1} = 0$$

As an excellent approximation, let $E_{K_1} = E_{P_2} = 0$

Then, $E_{K_2} = E_{P_1} = 980.66\,J$

(c) As the 1 kg of water strikes bottom and mixes with other falling water to form a stream, the resulting turbulence has the effect of converting kinetic energy into internal energy. During this process, E_P is essentially zero, and Eq. (2.1) becomes:

$$\Delta U + \Delta E_K = 0 \quad or \quad \Delta U = E_{K_2} - E_{K_3}$$

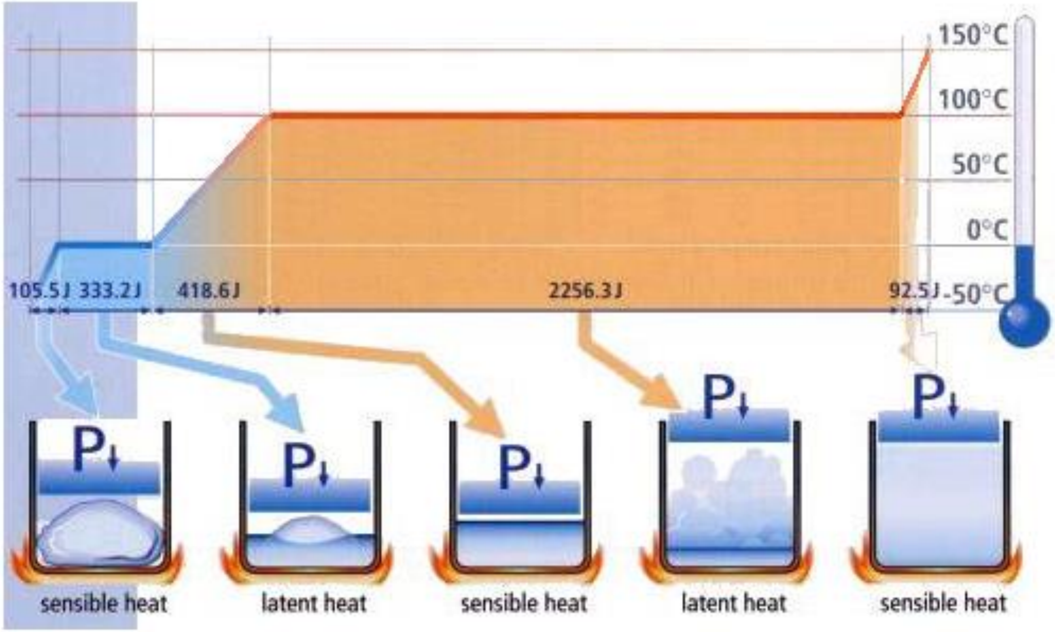
However, the stream velocity is assumed small, making E_{K_3} negligible. Thus,

$$\Delta U = E_{K_2} = 980.66\,J$$

The overall result of the process is the conversion of potential energy of the water into internal energy of the water. This change in internal energy is manifested by a temperature rise of the water. Because energy in the amount of 4184 J kg^{-1} is required for a temperature rise of 1 °C in water, the temperature increase is 980.66/4184 = 0.234 °C, assuming no heat transfer with the surroundings.

10.2 Applications of the steady-state energy balance

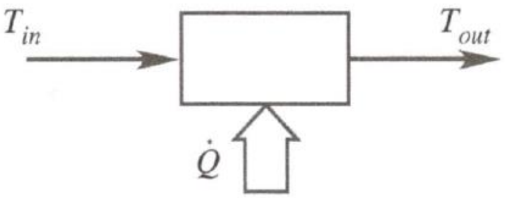
Sensible heat vs. Latent heat



- ➢ Sensible heat: when an object is heated, its temperature rises as heat is added. The increase in heat is called sensible heat (no phase transitions, no chemical reaction and no changes in composition).
- ➢ Latent heat: All pure substances in nature are able to change their state. The heat that causes these changes is called latent heat.

10.2 Applications of the steady-state energy balance

10.2.1 Scenario #1: sensible heating or cooling



$T_{out} > T_{in}$

No phase change

Specific enthalpy

$$\hat{H} \approx \bar{C}_P \left(T - T_{ref}\right)$$

- **Steady-state energy balance for sensible heating or cooling**

$$\sum_{\substack{\text{output}\\ \text{streams}}} \left(\dot{m}\hat{H}\right)_{out} - \sum_{\substack{\text{input}\\ \text{streams}}} \left(\dot{m}\hat{H}\right)_{in} = \dot{Q}$$

$$\hat{H} \approx \bar{C}_P \left(T - T_{ref}\right)$$

$$\sum_{\substack{\text{output}\\ \text{streams}}} \dot{m}\bar{C}_P \left(T - T_{ref}\right) - \sum_{\substack{\text{input}\\ \text{streams}}} \dot{m}\bar{C}_P \left(T - T_{ref}\right) = \dot{Q}$$

10.2 Applications of the steady-state energy balance

10.2.1 Scenario #1: sensible heating or cooling

Example 10.2

Motor oil is being blended in a steady-state process where the feed streams to the process are two oil stocks and an additive. The properties of the feed streams are

	Mass flow rate (kg/min)	Heat capacity ($kJ/kg\ K$)	Temperature ($^\circ C$)
Oil #1	18.3	2.11	105
Oil #2	13.9	2.32	112
Additive	1.4	1.87	93

a. If no heat is added to or removed from the process, what is the temperature of the product stream?
b. If the temperature of the product stream must be 78$^\circ C$, how much heat must be added or removed from the process?

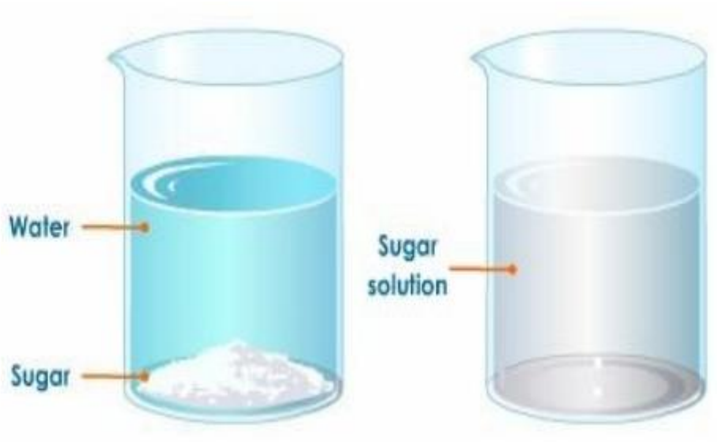
The heat capacity of the resulting product stream equals 2.19 $kJ/kg\ K$, and the reference temperature for all streams is 25$^\circ C$.

10.2 Applications of the steady-state energy balance

10.2.2 Scenario #2: phase changes

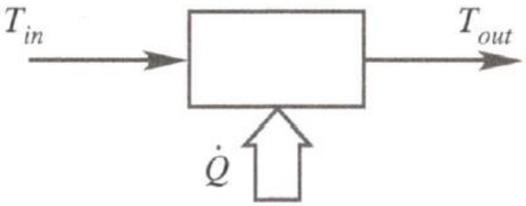
Phase

- A phase is a region of space (a thermodynamic system), throughout which all physical properties of a material are essentially uniform.



1. Liquid to vapor (vaporization) or vapor to liquid (condensation)
2. Solid to liquid (melting) or liquid to solid (freezing)
3. Solid to vapor (sublimation) or vapor to solid (solid condensation)

10.2.2 Scenario #2: phase changes



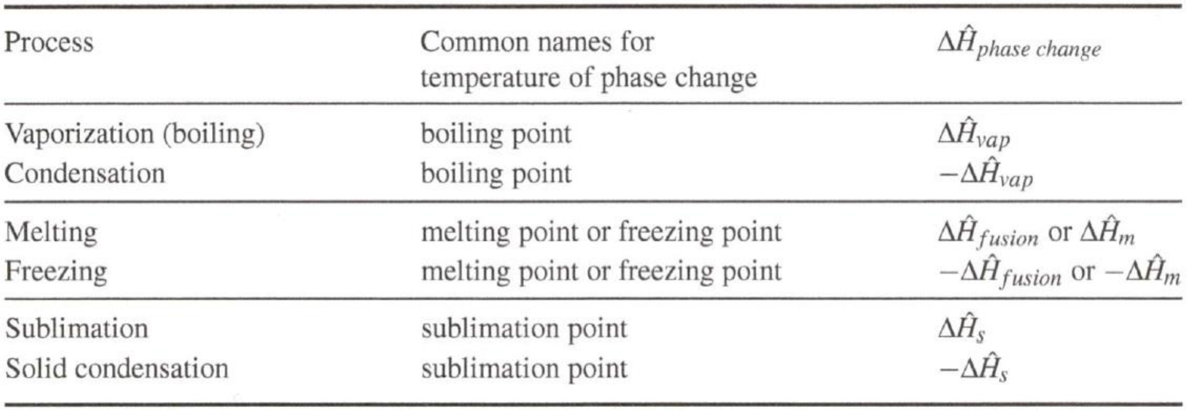
$T_{out} = T_{in}$

Phase change

Phase change with one inlet and one outlet

$$\hat{H}_{out} - \hat{H}_{out} = \Delta\hat{H}_{phase\ change}$$

$$\sum_{\substack{output\\streams}} \left(\dot{m}\hat{H}\right)_{out} - \sum_{\substack{input\\streams}} \left(\dot{m}\hat{H}\right)_{in} = \dot{Q} \xrightarrow[\hat{H}_{out} - \hat{H}_{out} = \Delta\hat{H}_{phase\ change}]{} \dot{m}_{phase\ change}\Delta\hat{H}_{phase\ change} = \dot{Q}$$



Process	Common names for temperature of phase change	$\Delta\hat{H}_{phase\ change}$
Vaporization (boiling)	boiling point	$\Delta\hat{H}_{vap}$
Condensation	boiling point	$-\Delta\hat{H}_{vap}$
Melting	melting point or freezing point	$\Delta\hat{H}_{fusion}$ or $\Delta\hat{H}_m$
Freezing	melting point or freezing point	$-\Delta\hat{H}_{fusion}$ or $-\Delta\hat{H}_m$
Sublimation	sublimation point	$\Delta\hat{H}_s$
Solid condensation	sublimation point	$-\Delta\hat{H}_s$

10.2 Applications of the steady-state energy balance

10.2.2 Scenario #2: phase changes

Example 10.3

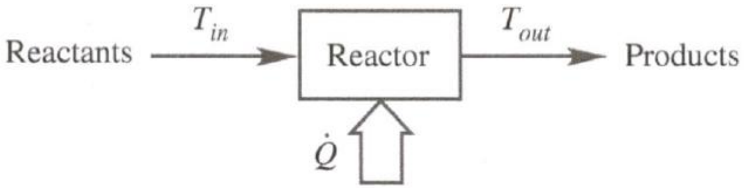
A steady-state boiler produces steam from a waste-water stream. The water enters the boiler as saturated water at 5.7 *atm* and 430 *K* (the boiling point of water at 5.7 *atm*), and the steam exits the boiler as saturated steam at that same temperature and pressure. The properties of importance are

Mass flow rate: 8150 *kg*/*hr*
Heat of vaporization at 5.7 *atm* and 430 *K*: 2091 *kJ*/*kg*

How much heat must be added to the process? (Notice that the boiling point and heat of vaporization are dependent on pressure, so it was necessary to know their value for the operating pressure of the process. These were provided for this problem and will be provided in similar problems in his book.)

10.2 Applications of the steady-state energy balance

10.2.3 Scenario #3: chemical reaction

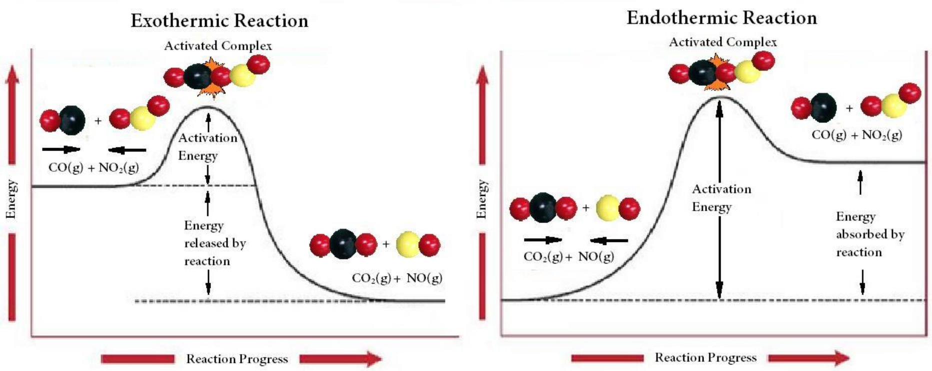


$T_{out} = T_{in}$

Reaction enthalpy change

$\Delta\tilde{H}_{reaction,A}$

$$\sum_{\substack{output\\streams}} \left(\dot{m}\hat{H}\right)_{out} - \sum_{\substack{input\\streams}} \left(\dot{m}\hat{H}\right)_{in} = \left(\frac{moles\ A\ reacted}{time}\right)\Delta\tilde{H}_{reaction,A} = r_{consumption,A}\Delta\tilde{H}_{reaction,A} = \dot{Q}$$



10.2 Applications of the steady-state energy balance

10.2.3 Scenario #3: chemical reaction

Example 10.4

Toluene at 1200˚*F* is fed to a reactor at 373 *lbmol*/*hr* where 75% of it reacts with hydrogen form benzene by the following reaction:

$$\text{Toluene} + H_2 \rightarrow \text{Benzene} + CH_4$$

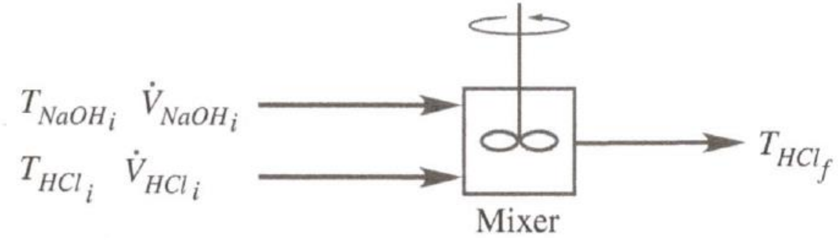
The H_2 enters the reactor as a separate feed stream (also at 1200˚*F*) at three times the rate required to react with all of the toluene. The reactor is maintained at 1200˚*F* and 500 *psia*, and the heat of reaction is -21,540 *Btu*/*lbmol* of toluene reacted.

a. In which direction (addition or removal) would heat need to be transferred relative to the reactor to keep the temperature constant in the reactor?
b. How much heat (expressed as *Btu*/*hr*) would need to be added or removed?

Hint: You may not need all of the above information to solve this problem.

10.2 Applications of the steady-state energy balance

10.2.4 Application to the acid-neutralization problem



Assumptions

1. Neglecting the heat effects from the reaction
2. Ignoring heat transfer by walls of pipes and mixer
3. Negligible kinetic and potential energies
4. No significant shaft work
5. $\rho_{water} = \rho_{HCl} = \rho_{NaOH}$, $C_{P,water} = C_{P,HCl} = C_{P,NaOH}$

$$\sum_{\substack{output\\streams}} \dot m\left[\hat H + \cancelto{0}{\frac{1}{2}\alpha v^2} + \cancelto{0}{gz}\right]_{out} - \sum_{\substack{input\\streams}} \dot m\left[\hat H + \cancelto{0}{\frac{1}{2}\alpha v^2} + \cancelto{0}{gz}\right]_{in} = \cancelto{0}{\dot Q} + \cancelto{0}{\dot W_s}$$

$$\hat H \approx \bar C_P\left(T - T_{ref}\right)$$

$$\dot m = \dot V \rho$$

$$\sum_{\substack{output\\streams}} \dot m \bar C_P\left(T - T_{ref}\right) - \sum_{\substack{input\\streams}} \dot m \bar C_P\left(T - T_{ref}\right) = \left\{\dot V \rho C_P\left(T - T_{ref}\right)\right\}_f - \left\{\dot V \rho C_P\left(T - T_{ref}\right)\right\}_{HCl} - \left\{\dot V \rho C_P\left(T - T_{ref}\right)\right\}_{NaOH} = 0$$

$$\rho_{water} = \rho_{HCl} = \rho_{NaOH}\,,\ C_{P,water} = C_{P,HCl} = C_{P,NaOH}$$

$$\dot V_f = \dot V_{HCl_i} + \dot V_{NaOH_i}$$

$$T_f = \frac{\dot V_{HCl_i} T_{HCl_i} + \dot V_{NaOH_i} T_{NaOH_i}}{\dot V_{HCl_i} + \dot V_{NaOH_i}}$$

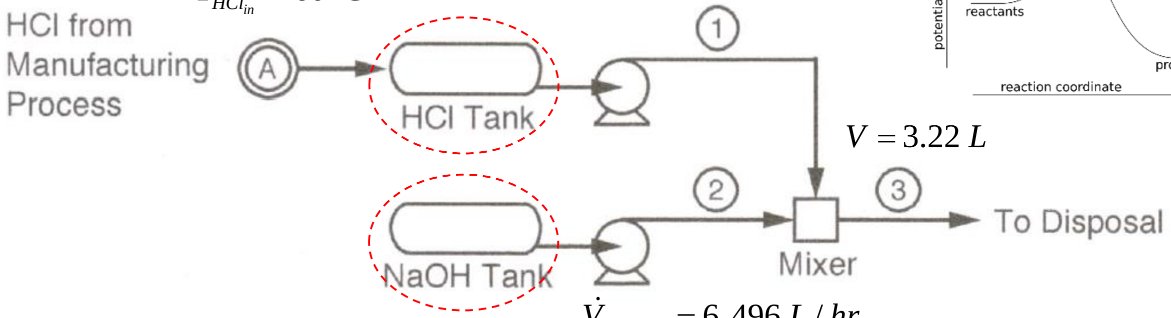
10.2 Applications of the steady-state energy balance

10.2.4 Application to the acid-neutralization problem

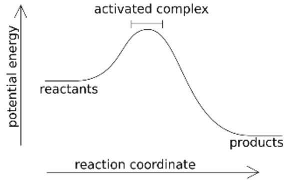
$$c_{HCl_{in}} = 0.014\ gmol/L$$

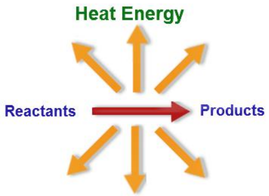
$$T_{HCl_{in}} = 60\ ^{\circ}C$$

$$\dot{V}_{HCl_{in}} = 11{,}600\ L/hr$$



$$V = 3.22\ L$$





$$\dot{V}_{out} = 18{,}096\ L/hr$$

$$\dot{V}_{NaOH_{in}} = 6{,}496\ L/hr$$

$$c_{NaOH_{in}} = 0.0254\ gmol/L$$

$$T_{NaOH_{in}} = 32\ ^{\circ}C$$

Allowed HCl concentration at final state by law (pH = 6.5)

$$c_{HCl_{out}} = 10^{-6.5} = 3.16\times10^{-7}\ M$$

$$c_{NaOH_{out}} = c_{HCl_{out}} = 3.16\times10^{-7}\ M$$

$$T_f = \frac{\dot{V}_{HCl_i}T_{HCl_i} + \dot{V}_{NaOH_i}T_{NaOH_i}}{\dot{V}_{HCl_i} + \dot{V}_{NaOH_i}} = \frac{(11600\ L/hr)(60^{\circ}C) + (6496\ L/hr)(32^{\circ}C)}{11600\ L/hr + 6496\ L/hr} = 49.9^{\circ}C$$

Allowed temperature of disposal At final state by law ($T \leq 27$°C)

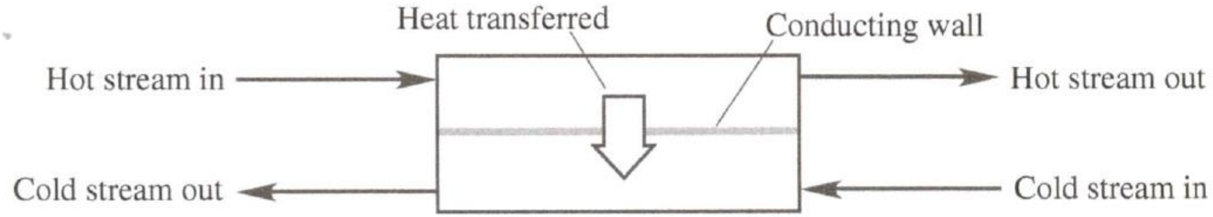
10.2 Applications of the steady-state energy balance

10.2.5 Summarizing the procedure for using the energy balance

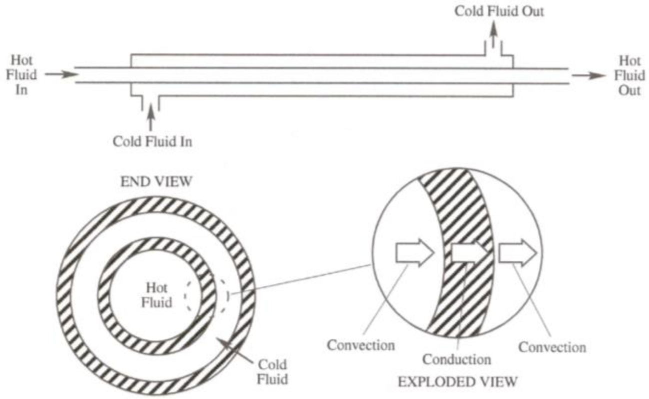
1. Draw a diagram
2. Write all known quantities
3. Identify and assign symbols
4. Write the appropriate simplified energy balance
5. Construct appropriate material balance equations
6. Solve the equations

10.3 Heat exchange devices

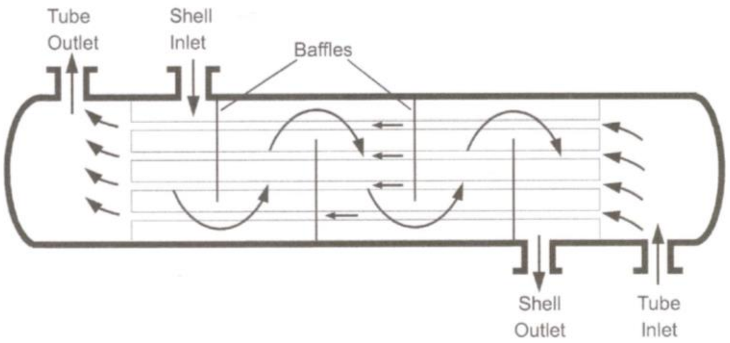
Heat exchanger: a device designed to exchange heat between two flowing streams



A concentric-cylinder heat exchanger



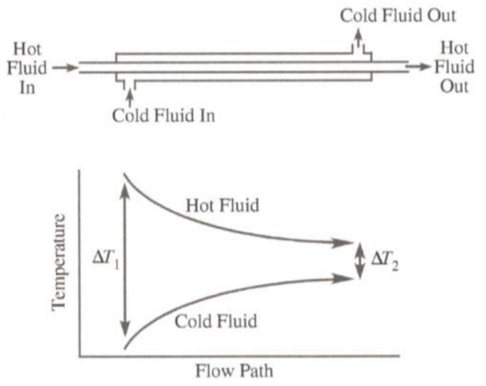
Shell-and-tube heat exchanger



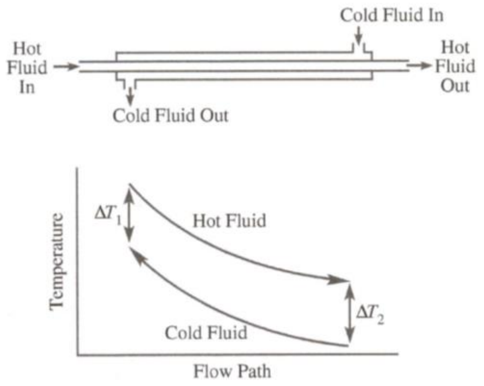
10.3 Heat exchange devices

A concentric-cylinder heat exchanger

Co-current flow

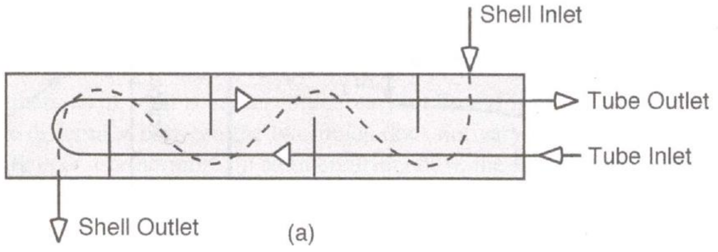


Countercurrent flow

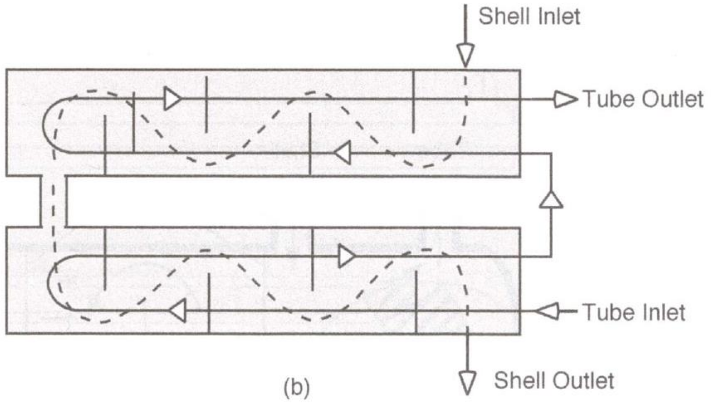


Shell-and-tube heat exchanger

One shell pass and two tube passes



Two shell pass and four tube passes



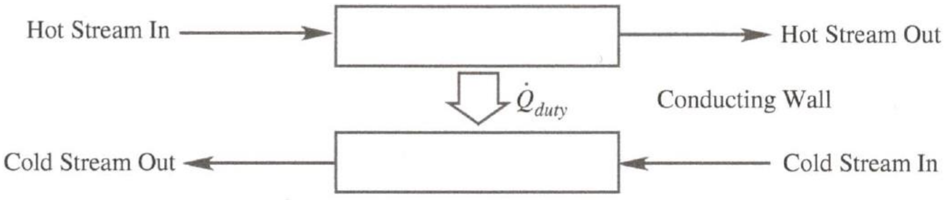
10.3 Heat exchange devices

10.3.1 Applying the energy balance equations to heat exchanger

$$\text{Sensible cooling}: \left[\dot{m}\bar{C}_P\left(T_{out}-T_{in}\right)\right]_{hot} = -\dot{Q}_{duty}$$

$$\text{Phase change}: \left[\dot{m}\Delta\hat{H}_{phase\ change}\right]_{hot} = -\dot{Q}_{duty}$$

$$\text{Chemical reaction}: \left[r_{consumption,A}\Delta\tilde{H}_{reaction,A}\right]_{hot} = -\dot{Q}_{duty}$$



$$\text{Sensible heating}: \left[\dot{m}\bar{C}_P\left(T_{out}-T_{in}\right)\right]_{cold} = \dot{Q}_{duty}$$

$$\text{Phase change}: \left[\dot{m}\Delta\hat{H}_{phase\ change}\right]_{cold} = \dot{Q}_{duty}$$

$$\text{Chemical reaction}: \left[r_{consumption,A}\Delta\tilde{H}_{reaction,A}\right]_{cold} = \dot{Q}_{duty}$$

10.3 Heat exchange devices

10.3.1 Applying the energy balance equations to heat exchanger

Example 10.5

A heavy oil stream must be heated to a higher temperature, so the decision is made to use a heat exchanger with saturated steam being condensed to saturated water as the heating source on the other side of the exchanger. The characteristics of the oil are:

Oil mass flow rate: 960 lb_m/min
Oil mean heat capacity: 0.74 $Btu/lbm\ ^{\circ}F$
Oil inlet temperature: 35$^{\circ}F$
Desired oil outlet temperature: 110$^{\circ}F$

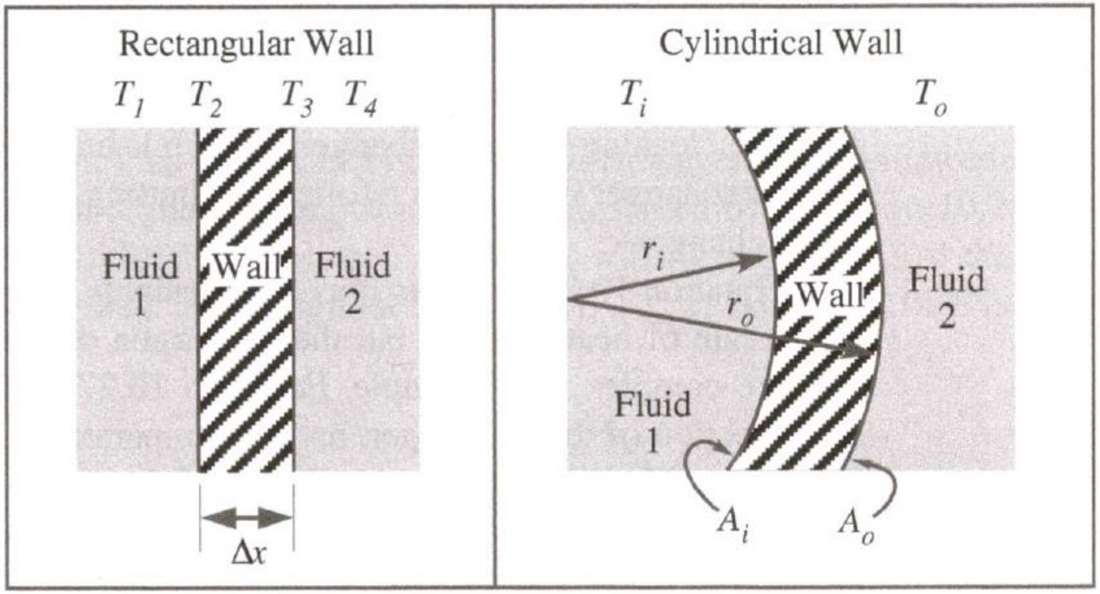
The saturated steam has the following properties:

Steam temperature: 280$^{\circ}F$
Heat of vaporization (@280$^{\circ}F$): 925 Btu/lb_m

What steam flow rate is needed for this exchanger?

10.3 Heat exchange devices

10.3.2 Determining the size (heat-transfer area) of the exchanger



$$\dot{Q} = \frac{T_1 - T_4}{\frac{1}{h_1 A} + \frac{\Delta x}{kA} + \frac{1}{h_2 A}} = \frac{overall\ driving\ \ force}{\sum resistance}$$

$$\dot{Q} = \frac{T_i - T_o}{\frac{1}{h_i A_i} + \frac{\ln\left(r_o / r_i\right)}{2\pi kL} + \frac{1}{h_o A_o}} = \frac{overall\ driving\ \ force}{\sum resistance}$$

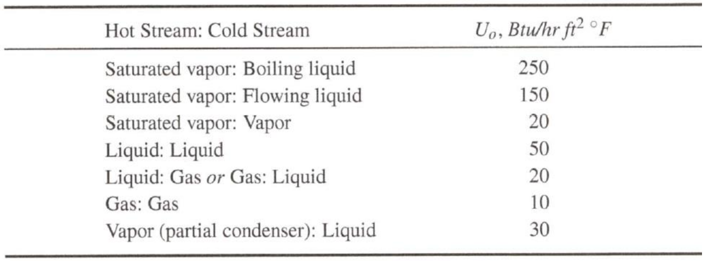
10.3 Heat exchange devices

10.3.2 Determining the size (heat-transfer area) of the exchanger

Overall heat-transfer coefficient

$$\dot{Q}_{duty} = U_0 A \Delta T_{avg}$$

Approximate values of U_0



Hot Stream: Cold Stream	U_o, Btu/hr ft^2 °F
Saturated vapor: Boiling liquid	250
Saturated vapor: Flowing liquid	150
Saturated vapor: Vapor	20
Liquid: Liquid	50
Liquid: Gas *or* Gas: Liquid	20
Gas: Gas	10
Vapor (partial condenser): Liquid	30

Log mean temperature difference

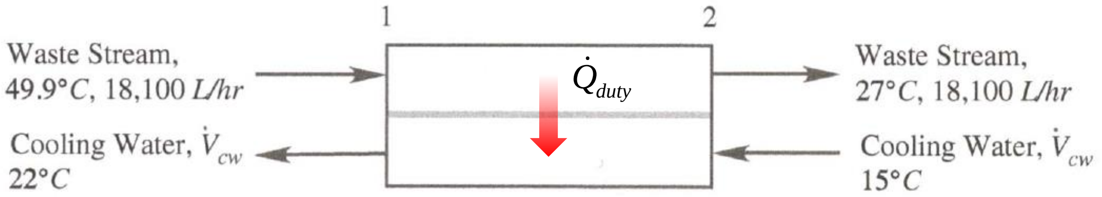
$$\Delta T_{log\ mean} = \frac{\Delta T_1 - \Delta T_2}{\ln \dfrac{\Delta T_1}{\Delta T_2}}$$

Heat exchanger area: $$A = \frac{\dot{Q}_{duty}}{U_0 \Delta T_{log\ mean}}$$

10.3.3 Heat exchanger for the acid-neutralization problem

Calculated value

5°C <



Limited by law

Maximum value (summer)

$$\bar{C}_P = 4.17\ kJ/kg\ ^\circ C,\ \rho = 992\ kg/m^3$$

1. Determining $\dot{Q}_{duty}$

$$\begin{aligned}
\dot{Q}_{duty} &= -\left[\dot{m}\bar{C}_P\left(T_{out}-T_{in}\right)\right]_{hot} \\
&= \left[\dot{m}\bar{C}_P\left(T_{in}-T_{out}\right)\right]_{hot} \\
&= \left[\dot{V}\rho\bar{C}_P\left(T_{in}-T_{out}\right)\right]_{hot} \\
&= \left(18{,}100\frac{L}{hr}\right)\left(992\frac{kg}{m^3}\right)\left(4.17\frac{kJ}{kg\ ^\circ C}\right)\left(49.9-27^\circ C\right) \\
&= 477{,}000\ W
\end{aligned}$$

2. Finding $\dot{V}_{cold}$

$$\begin{aligned}
\dot{V}_{cold} &= \frac{\dot{Q}_{duty}}{\left[\rho\bar{C}_P\left(T_{out}-T_{in}\right)\right]_{cold}} \\
&= \frac{477{,}000\ W}{\left(992\dfrac{kg}{m^3}\right)\left(4.17\dfrac{kJ}{kg\ ^\circ C}\right)\left(22-15^\circ C\right)} \\
&= 59{,}200\frac{L}{hr}
\end{aligned}$$

10.3 Heat exchange devices

10.3.3 Heat exchanger for the acid-neutralization problem

3. Calculating U_0

$$U_0 = 50\frac{Btu}{hr\ ft^2\ {}^\circ F}\left(\frac{1055\,W}{Btu\ s}\right)\left(\frac{1\,hr}{3600\,s}\right)\left(\frac{10.764\ ft^2}{m^2}\right)\left(\frac{1.8^\circ F}{{}^\circ C}\right) = 284\frac{W}{m^{2\circ}C}$$

4. Calculating $\Delta T_{log\ mean}$

$$\Delta T_1 = 49.9 - 22 = 27.9^\circ C$$

$$\Delta T_2 = 27 - 15 = 12^\circ C$$

$$\Delta T_{log\ mean} = \frac{\Delta T_1 - \Delta T_2}{\ln\dfrac{\Delta T_1}{\Delta T_2}} = \frac{27.9 - 12}{\ln\dfrac{27.9}{12}} = 18.8^\circ C$$

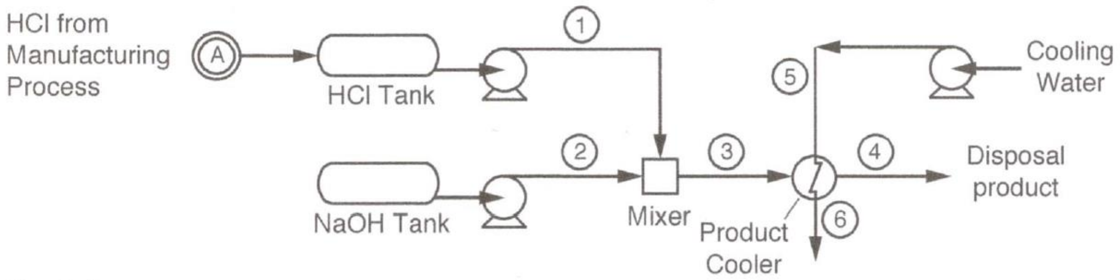
5. Determining A

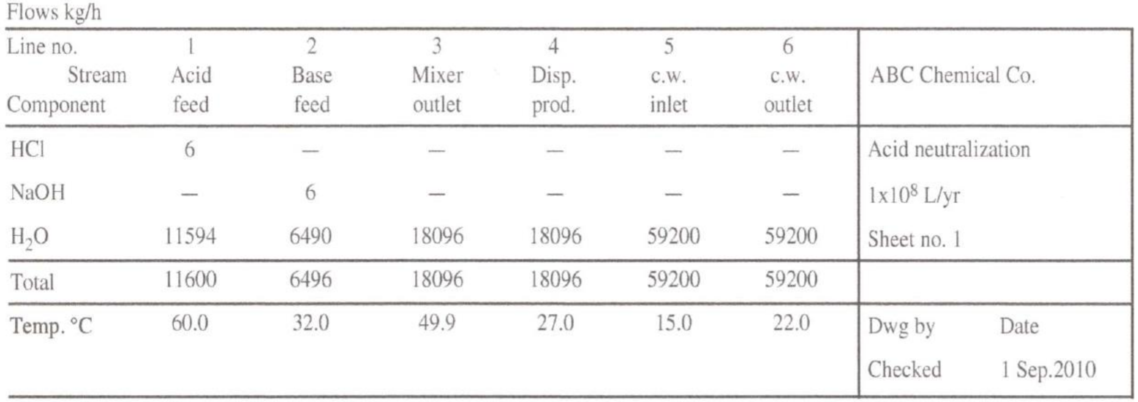
$$A = \frac{\dot{Q}_{duty}}{U_0 \Delta T_{log\ mean}} = \frac{477,000\,W}{\left(284\dfrac{W}{m^2\ {}^\circ C}\right)\left(18.8^\circ C\right)} = 89.3\,m^3$$

10.3 Heat exchange devices

10.3.3 Heat exchanger for the acid-neutralization problem

- **Process flow diagram (PFD) for the acid-neutralization process with heat exchanger**





Flows kg/h

Line no. Stream Component	1 Acid feed	2 Base feed	3 Mixer outlet	4 Disp. prod.	5 c.w. inlet	6 c.w. outlet	ABC Chemical Co.
HCl	6	—	—	—	—	—	Acid neutralization
NaOH	—	6	—	—	—	—	1x10^8 L/yr
H_2O	11594	6490	18096	18096	59200	59200	Sheet no. 1
Total	11600	6496	18096	18096	59200	59200	
Temp. °C	60.0	32.0	49.9	27.0	15.0	22.0	Dwg by Date
							Checked 1 Sep.2010

Homework problems

Homework problem 3.

A stream of bread dough is fed steadily through an oven in a large bread-baking operation. The dough enters the oven at a rate of 110 ft^3/hr and at a temperature of 70˚F. It exits the oven at 400˚F. Other properties of the dough include

density = 58.7 lb_m/ft^3
heat capacity = 0.9 $Btu/lb_m\ ^\circ F$

At what rate is heat being added to the dough by the heating coils the oven (in *Watts*)?

Homework problems

Homework problem 6.

A liquid stream contains 27 mole% species A dissolved in a solvent. In a steady-state process, the stream enters a reactor where 2/3 of the species A is converted to species B. The heat of reaction at the reactor temperature equals -918 *kJ*/*kgmol* of A reacted. How much heat (per *kgmol* of entering stream) must be transferred from the reactor to maintain a steady temperature in the reactor? (As indicated in the chapter, kinetic and potential energy effects can be neglected.) While there is some shaft work from the stirrer in the reactor, such work is usually negligible and can be considered so in this case. Hint: You will need to choose a basis.

Homework problems

Homework problem 8.

You have been assigned to design a heat exchanger to cool a gaseous process stream in a chemical plant. The stream (20 kg/s) enters at 431 K, has a heat capacity of 3.45 $J/g\ ^\circ C$, and needs to be cooled to 402 K. Cooling water is available at 85$^\circ F$ and has a specified maximum temperature of 120$^\circ F$. The overall heat-transfer coefficient is approximately 570 $W/m^2\ K$. How much area must the heat exchanger have?