Thermal Unit Operation (ChEg3113)

Lecture 2- Introduction to Thermal Unit Operation

Instructor: Mr. Tedla Yeshitila (M.Sc.)
Today…

• Chemical Unit operations

• Heat transfer

• Different mode of heat transfer
  – Conduction
  – Convection
  – Radiation

• Multimode heat transfer
Chapter 1
Introduction to Thermal Unit Operation

What is a unit operation?

✓ A **unit operation** is any part of potentially multiple-step process which can be considered to have a single function.

✓ It is a basic step in a process because large processes can be broken into unit operations in order to make them easier to analyze.

✓ It can involve a physical change or chemical transformation.
Chemical engineering unit operations can be grouped into five general classes:

1. Fluid flow processes
2. Heat transfer processes
3. Mass transfer processes
4. Thermodynamic processes
5. Mechanical processes
1. Fluid Flow Process

- **Fluid flow processes:** deals about fluids transportation and its dynamics.
- It includes fluids transportation (pump, compressor, blowers, pipes and fittings,), gas-liquid two-phase flow, filtration, solids fluidization, mixing, etc.
2. Heat Transfer Processes

- **Heat transfer** is the exchange of thermal energy between physical systems, depending on the temperature and pressure, by dissipating heat.

- It includes heat exchange, evaporation, and condensation.
3. Mass Transfer Processes

- **Mass transfer** is the net movement of mass from one location to another.
- It occurs in many processes, such as absorption, distillation, extraction, adsorption, and drying.
4. Thermodynamics Process

✓ A thermodynamic process may be defined as the energetic development of a thermodynamic system proceeding from an initial state to a final state.

✓ It includes Refrigeration and Air Conditioning (AC), gas liquefaction
5. Mechanical Unit Operation

- Mechanical unit operation includes:
  - Solids transportation: different types of conveyors
  - Crushing and pulverization: reducing sizes
  - Screening and sieving: separation of different particles based on their size
• There are also some chemical engineering unit operations which involves more than one class such as distillation, and reaction crystallization.
• A "pure" unit operation is a physical transport process, while a mixed chemical/physical process requires modeling.
Heat transfer

• As you see from thermodynamic:
  – “Heat is defined as the energy-In-transit due to temperature difference.

• Heat transfer take place whenever there is a temperature gradient within a system.

• Heat transfer cannot be measured directly, but the effects produced by it can be observed and measured. E.g. temperature change
Heat transfer...

- All heat transfer process must obey the first and second laws of thermodynamics.
- In addition to the laws of thermodynamics it is essential to apply laws of heat transfer to estimate heat transfer rate.
- Estimating rate of heat transfer is a key requirement in the design and analysis heat exchanger, refrigeration and air conditioning.
Modes of Heat Transfer

• The basic modes are:
  – Conduction
  – Convection, and
  – Radiation

• In most of the engineering problems, heat transfer takes place by more than one mode simultaneously. Such kinds of heat transfer problems are called **multi-mode heat transfer**.
Conduction Heat Transfer

- Conduction heat transfer takes place whenever a temperature gradient exists in a stationary medium.

- On a microscopic level, conduction heat transfer is due to:
  - The elastic impact of molecules in fluids
  - Molecular vibration and rotation about their lattice positions in solids, and
  - Free electron migration in solids
Fourier`s Law of Heat Conduction

• It is empirical equation which relates the rate of heat transfer with temperature gradient and area of cross section.

\[ Q_x = -kA \frac{dT}{dx} \]

where \( Q_x \) = Rate of heat transfer by conduction in x-direction

\( \frac{dT}{dx} \) = Temperature gradient in x-direction

A = Area normal to x-direction

k = Thermal conductivity of the medium

• The negative sign is the consequence of thermodynamics as it says heat transfer takes place spontaneously from system of high temperature to system of lower temperature. So \( \frac{dT}{dx} \) is always negative.
Typical thermal conductivity values at 300k:

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal conductivity (W/m K)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diamond</td>
<td>1000</td>
</tr>
<tr>
<td>Silver</td>
<td>406</td>
</tr>
<tr>
<td>Copper</td>
<td>399</td>
</tr>
<tr>
<td>Gold</td>
<td>317</td>
</tr>
<tr>
<td>Aluminum</td>
<td>237</td>
</tr>
<tr>
<td>Iron</td>
<td>80</td>
</tr>
<tr>
<td>carbon steel</td>
<td>43</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>15.1</td>
</tr>
<tr>
<td>Glass, ordinary</td>
<td>0.8</td>
</tr>
<tr>
<td>Plastic</td>
<td>0.2-0.3</td>
</tr>
<tr>
<td>Wood</td>
<td>0.087</td>
</tr>
<tr>
<td>Cork</td>
<td>0.039</td>
</tr>
<tr>
<td>Water at 20°C</td>
<td>0.6</td>
</tr>
<tr>
<td>Ethylene glycol (20°C)</td>
<td>0.26</td>
</tr>
<tr>
<td>Hydrogen(20°C)</td>
<td>0.18</td>
</tr>
<tr>
<td>Benezene (Liquids)(20°C)</td>
<td>0.159</td>
</tr>
<tr>
<td>Oxygen(20°C)</td>
<td>0.0238</td>
</tr>
<tr>
<td>Air</td>
<td>0.026</td>
</tr>
</tbody>
</table>

- All pure metals have very high thermal conductivity. So they are good conductor of heat.
- Compare to pure metals, alloy have lower thermal conductivity.
- Compare to metals, non-metals e.g. glass, plastics... have lower thermal conductivity.
- Cork has lower thermal conductivity so used as insulation material.
- Thermal conductivity: Solids>Liquids>Gases.
General Heat Conduction Equation

• For Cartesian coordinates with constant thermal physical properties (thermal conductivity, specific heat...), by combining first law of thermodynamics along Fourier law, we will get:

\[
\frac{1}{\alpha} \frac{\partial T}{\partial \tau} = \left[ \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right] + \frac{q_g}{k}
\]

Where \( \alpha \) is thermal diffusivity given by: \( \alpha = \frac{k}{\rho c_p} \)

\( q_g \) is the heat generation per unit volume

\( \tau \) is time rate (thaw)

• Similarly, you can drive for other coordinate system.
General Heat Conduction Equation...

- The above equation is partial differential equation, in order to solve you need initial and boundary condition.

- In a compact form using Laplacian operator ($\nabla^2$)

$$\frac{1}{\alpha} \frac{\partial T}{\partial \tau} = \nabla^2 T + \frac{q_g}{k}$$

- When there is no heat generation ($q_g = 0$), then you will have transient heat equation:

$$\frac{1}{\alpha} \frac{\partial T}{\partial \tau} = \nabla^2 T$$

- When heat transfer is not depending on time, you will have steady state heat transfer equation:

$$\nabla^2 T = 0$$
General Heat Conduction Equation…

• Assuming thin wall whose dimension is very small in x-direction compared to y and z direction.

• And we have 2 boundary conditions when x=0 and x=L where L is thickness of the plate.

• The solution is:

\[ T = T_1 + (T_2 - T_1) \frac{x}{L} ; \]

=> This is linear relationship

• Heat transfer rate is:

\[ Q_x = -kA \frac{dT}{dx} = kA \left( \frac{T_1 - T_2}{L} \right) = \frac{\Delta T}{R_{cond}} \]

=> This equation is analogous to ohms law: I=E/R
General Heat Conduction Equation...

- $R_{cond}$ is resistivity to conduction. $R_{cond} = \left( \frac{L}{kA} \right)$. So it is function of both geometry of a system and property of system that is thermal conductivity.

- For 1-dimensionlal steady state conduction through a cylinder, by applying energy balance you will get the basic heat transfer equation, then by applying suitable boundary equation you will get:

\[
T = T_1 + (T_1 - T_2) \frac{\ln (r/r_1)}{\ln (r_2/r_1)} ;
\]

=> This is logarithmic relationship

- Heat transfer rate is:

\[
Q_x = -kA \frac{dT}{dx} = 2\pi kL \left( \frac{T_1-T_2}{\ln (r_2/r_1)} \right) = \frac{\Delta T}{R_{cyl}}
\]
General Heat Conduction Equation...

- $R_{cyl} = \left( \frac{\ln \left( \frac{r_2}{r_1} \right)}{2\pi kL} \right)$

Where $r_2$ is outer radius of cylinder

$r_1$ is inner radius of cylinder,

$L$ is length of a cylinder
Convective Heat Transfer

- Convection heat transfer takes place between a surface and a moving fluid, when they are at different temperature. It is the transfer of energy between an object and its environment, due to fluid motion.

- All convective processes also move heat partly by diffusion/conduction, as well.

- Convective heat transfer consists of two mechanisms operating simultaneously:
Convective Heat Transfer…

1. Energy transfer due to conduction through a fluid layer adjacent to the surface

- **Hydrodynamic boundary layer**: when fluid flow on the surface, fluid layer adjacent to surface attain velocity of surface. If surface is stationary, then fluid layer is stationary. i.e. no slip condition.

- Similarly, when a fluid flow on surface whose temperature different from fluid surface, then the fluid layer adjacent to the surface attain temperature of surface. This is also no slip condition. This is called **thermal boundary layer**.

- And the heat transfer is initially from surface to fluid stationary layer by conduction. Then the heat transfer will be by motion of the bulk fluid.

- This show similarity between momentum transfer and convective heat transfer.
Convective Heat Transfer…

2. Energy transfer by macroscopic motion of fluid particles by using of an external force (due to a fan/pump or buoyancy).

• If you are using external force e.g. due to a fan/pump/ stirrers or other mechanical means, this is called forced convection.

• If it is without using any external force, it is called free/natural convection.

• Free, or natural, convection occurs when bulk fluid motions (streams and currents) are caused by buoyancy forces that result from density variations due to variations of temperature in the fluid.
Convective Heat Transfer…

- Convective heat transfer, or convection, is the transfer of heat from one place to another by the movement of fluids, a process that is essentially the transfer of heat via mass transfer.
- Convection is usually the dominant form of heat transfer in liquids and gases.
Convective Heat Transfer…

• Heat transfer rate by convection is written as:

\[ Q = h_c A(T_w - T_\infty) \ldots \]

=> This is called Newton’s law of cooling (basic equation for convective heat transfer/Convective cooling).

Where \( h_c \) = the convective heat transfer coefficient,

\( T_w \) is surface temperature, and

\( T_\infty \) is temperature of fluid in the free stream

• Newton’s law of cooling states “The rate of heat loss of a body is proportional to the temperature difference between the body and its surroundings.”
Convective Heat Transfer...

• However, by definition, the validity of Newton's law of cooling requires that the rate of heat loss from convection be a linear function of ("proportional to") the temperature difference that drives heat transfer, and in convective cooling this is sometimes not the case.

• In general, convection is not linearly dependent on temperature gradients, and in some cases is strongly nonlinear. In these cases, Newton's law does not apply.
Convective Heat Transfer...

• Since near the surface, the heat transfer is by conduction, it can be shown that:

\[
h_c = \frac{-k_f \left( \frac{dT}{dy} \right)_{y=0}}{(T_w - T_\infty)}
\]

\( \Rightarrow \) This obtained by writing heat transfer rate in terms of conduction for stationary layer and equating Newton’s law of cooling.

• Convective heat transfer coefficient depends on:
  – Thermal conductivity of the fluid, \( k_f \)
  – Temperature difference \( (T_w - T_\infty) \), and
  – Temperature gradient \( \left( \frac{dT}{dy} \right)_{y=0} \)
Convective Heat Transfer...

- \( \left( \frac{dT}{dy} \right)_{y=0} \) depends on the rate at which the fluid near the wall can transport energy into the mainstream.
- Fluid flow has to be considered along with heat transfer.
- Convective heat transfer resistance:
  \[
  Q = h_c A (T_w - T_\infty) = \frac{(T_w - T_\infty)}{R_{conv}}
  \]
  Where \( R_{conv} = \frac{1}{h_c A} \)
- Evaluation of \( h_c \) is the main problem and objective of convective heat transfer analysis.
## Typical convective heat transfer coefficients:

<table>
<thead>
<tr>
<th>Typical Fluid</th>
<th>Convective heat transfer coefficient (W/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air, free convection</td>
<td>6-30</td>
</tr>
<tr>
<td>Water, free convection</td>
<td>20-100</td>
</tr>
<tr>
<td>Air or superheated steam, forced convection</td>
<td>30-300</td>
</tr>
<tr>
<td>Oil, forced convection</td>
<td>60-1,800</td>
</tr>
<tr>
<td>Water, forced convection</td>
<td>300-18,000</td>
</tr>
<tr>
<td>Synthetic refrigerants, boiling</td>
<td>500-3,000</td>
</tr>
<tr>
<td>Water, boiling</td>
<td>3,000-60,000</td>
</tr>
<tr>
<td>Synthetic refrigerants, condensing</td>
<td>1,500-5,000</td>
</tr>
<tr>
<td>Steam, condensing</td>
<td>6,000-120,000</td>
</tr>
</tbody>
</table>
Radiation Heat Transfer

• **Radiation** heat transfer does not require a medium for transmission. And it is more effective in vacuum. It is the transfer of energy from the movement of charged particles within atoms is converted to electromagnetic radiation.

• Energy transfer occurs due to the propagation of **electromagnetic waves** such as microwave and light wave. A body due to its temperature emits electromagnetic radiation.

• It is propagated with the speed of light in a straight line in vacuum. Its speed decreases in a medium but it travels in a straight line in homogenous medium.
Radiation Heat Transfer ...

- The basic law or radiation energy emitted by surface is given by Stefan-Boltzmann law which obtained by integrating Planck’s equation.

- This equation can be derived from thermodynamics unlike conduction and convection which are only from observation.

\[ Q_r = \varepsilon \cdot \sigma \cdot A \cdot (T_s^4 - T_{sur}^4) \]

Where \( Q_r \) = Rate of thermal energy emission (W)

\( \varepsilon \) = Emissivity of the surface. So it is surface property

\( \sigma = \text{Stefan-Boltzmann`s constant} = 5.669 \times 10^{-8} \text{W/m}^2\cdot\text{K}^4 \)
At the end of this class:

• What are the different types of chemical unit operations?

• What is heat transfer?

• What are the different mode of heat transfer?

• What are the basic governing equation for each types of heat transfer modes?
End of lecture -2