Modes of Heat Transfer – Part I

In this lecture...

- Heat Transfer Mechanisms
  - Conduction
    - Fourier’s law of heat conduction
    - Thermal Conductivity
    - Thermal Diffusivity
  - Convection
    - Newton’s law of cooling
    - Boundary layers: Internal and External flows
    - Boiling and Condensation
  - Radiation will be dealt separately in Part II later
1 Introduction

Heat transfer in refrigeration systems

Typical refrigerator heat exchangers

- For simple systems like window ACs or household fridges, the refrigerant flows in the tubes and air is passed over it (forced flow or natural convection)

Typical refrigerant evaporators

Typical refrigerant condenser (for a household refrigerator)
Typical refrigerator heat exchangers

- For large systems, two separate loops, i.e., primary and secondary refrigerant circuits are employed, with separate heat exchangers of their own.

Primary and secondary refrigeration loops (e.g. Ammonia and Carbon Dioxide)

Primary and secondary refrigeration loops (e.g. R134a + Water)

Basics: Heat Transfer

Heat transfer vs Thermodynamics
Heat transfer and thermodynamics

- **Heat**: The form of energy that can be transferred from one system to another as a result of temperature difference.
- **Thermodynamics** is concerned with the amount of heat transfer as a system undergoes a process from one equilibrium state to another.
- **Heat Transfer** deals with the determination of the rates of such energy transfers as well as variation of temperature.
- The transfer of energy as heat is always from the higher-temperature medium to the lower-temperature one. Heat transfer stops when the two mediums reach the same temperature.
- Heat can be transferred in three different modes: conduction, convection, and radiation.

Heat transfer vs thermodynamics

Thermodynamics

- Global accounting of momentum, energy and mass
- Feasibility of events under equilibrium conditions
- No consideration of the mechanisms of species transport
- Does not tell us how to compute the rate of species transport

\[ \eta = \frac{\text{output}}{\text{input}} \]

COP

!! Heat transfer is inherently a non-equilibrium process !!
Engineering heat transfer

- Heat transfer equipment such as heat exchangers, boilers, condensers, radiators, heaters, furnaces, refrigerators, and solar collectors are designed primarily on the basis of heat transfer analysis.

- The heat transfer problems encountered in practice can be considered in two groups: (1) rating and (2) sizing problems.

- The rating problems deal with the determination of the heat transfer rate for an existing system at a specified temperature difference.

- The sizing problems deal with the determination of the size of a system in order to transfer heat at a specified rate for a specified temperature difference.

Problem solving approach

- An engineering device or process can be studied either experimentally (testing and taking measurements) or analytically (by analysis or calculations).

- The experimental approach has the advantage that we deal with the actual physical system, and the desired quantity is determined by measurement, within the limits of experimental error. However, this approach is expensive, time consuming, and often impractical.

- The analytical approach (including the numerical approach) has the advantage that it is fast and inexpensive, but the results obtained are subject to the accuracy of the assumptions, approximations, and idealizations made in the analysis.
Conduction heat transfer

Fourier Law, thermal conductivity and its variation

Conduction:
The transfer of energy from the more energetic particles of a substance to the adjacent less energetic ones as a result of interactions between the particles.

In gases and liquids, conduction is due to the collisions and diffusion of the molecules during their random motion.

In solids, it is due to the combination of vibrations of the molecules in a lattice and the energy transport by free electrons.
Rate of conduction

The rate of heat conduction through a plane layer is proportional to the temperature difference across the layer and the heat transfer area, but is inversely proportional to the thickness of the layer.

\[
\dot{Q}_{\text{cond}} = kA \frac{T_1 - T_2}{\Delta x} = -kA \frac{\Delta T}{\Delta x} \quad \text{(W)}
\]

Fourier law of heat conduction

- **Thermal conductivity,** \(k\): A measure of the ability of a material to conduct heat.

- **Temperature gradient** \(dT/dx\): The slope of the temperature curve on a \(T-x\) diagram.

\[
\dot{Q}_{\text{cond}} = kA \frac{T_1 - T_2}{\Delta x} = -kA \frac{\Delta T}{\Delta x} \quad \text{(W)}
\]

When \(x \to 0\) \n\[
\dot{Q}_{\text{cond}} = -kA \frac{dT}{dx}
\]

The rate of heat conduction through a solid is directly proportional to its thermal conductivity.
Fourier law of heat conduction

- Heat is conducted in the direction of decreasing temperature, and the temperature gradient becomes negative when temperature decreases with increasing \( x \).
- The negative sign in the equation ensures that heat transfer in the positive \( x \) direction is a positive quantity.

\[
\dot{Q}_{\text{cond}} = k A \frac{T_1 - T_2}{\Delta x} = -k A \frac{\Delta T}{\Delta x} \quad (W)
\]

In heat conduction analysis, \( A \) represents the area normal to the direction of heat transfer.

Thermal conductivity, \( k \)

- The rate of heat transfer through a unit thickness of the material per unit area per unit temperature difference.
- The thermal conductivity of a material is a measure of the ability of the material to conduct heat.
- A high value for thermal conductivity indicates that the material is a good heat conductor, and a low value indicates that the material is a poor heat conductor or insulator.

\[
k = \frac{L}{A(T_1 - T_2)} \dot{Q}
\]
Thermal conductivity

The thermal conductivities of some materials at room temperature.

<table>
<thead>
<tr>
<th>Material</th>
<th>$k$, W/m $\cdot$ °C$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diamond</td>
<td>2300</td>
</tr>
<tr>
<td>Silver</td>
<td>429</td>
</tr>
<tr>
<td>Copper</td>
<td>401</td>
</tr>
<tr>
<td>Gold</td>
<td>317</td>
</tr>
<tr>
<td>Aluminum</td>
<td>237</td>
</tr>
<tr>
<td>Iron</td>
<td>80.2</td>
</tr>
<tr>
<td>Mercury (l)</td>
<td>8.54</td>
</tr>
<tr>
<td>Glass</td>
<td>0.78</td>
</tr>
<tr>
<td>Brick</td>
<td>0.72</td>
</tr>
<tr>
<td>Water (l)</td>
<td>0.607</td>
</tr>
<tr>
<td>Human skin</td>
<td>0.37</td>
</tr>
<tr>
<td>Wood (oak)</td>
<td>0.17</td>
</tr>
<tr>
<td>Helium (g)</td>
<td>0.152</td>
</tr>
<tr>
<td>Soft rubber</td>
<td>0.13</td>
</tr>
<tr>
<td>Glass fiber</td>
<td>0.043</td>
</tr>
<tr>
<td>Air (g)</td>
<td>0.025</td>
</tr>
<tr>
<td>Urethane, rigid foam</td>
<td>0.026</td>
</tr>
</tbody>
</table>

The range of thermal conductivity of various materials at room temperature.

Thermal insulation in refrigeration industry

- Thermal insulation plays a pivotal role in the refrigeration industry.
- Several different types of insulating materials are available.
- Chosen as per economy, operating temperature, humidity conditions, volatile discharges, flammability, ease of application, availability, environmental degradation, etc.
Thermal insulation in refrigeration industry

Common insulating materials
- Nitrile
- Polyurethane foam
- Rubber foam
- Fibre glass
- Mineral Wool (Slag/rock/ Basalt)
- Cellulose
- Polystyrene
- Aerogel/ Pyrogel

Hot and Cold insulation materials

- Materials used in hot insulation covers does not require a water vapor barrier that a cold insulation system needs to properly function. The water vapor barrier helps prevent metal degradation that can occur overtime.

- Closed cell structure is needed in cold insulation to help avoid wicking. The material in high temperature insulations allows water to enter because the heat will cause the moisture to evaporate. However, in a cold insulation system the water will not evaporate. Closed cell structure of the cold insulation material helps prevent this problem.
Heat conduction mechanism

◉ The thermal conductivities of gases such as air vary by a factor of $10^4$ from those of pure metals such as copper.

◉ Pure crystals and metals have the highest thermal conductivities, and gases and insulating materials the lowest.

Thermal conductivity = fn(T)

The thermal conductivity of an alloy is usually much lower than the thermal conductivity of either metal of which it is composed.

<table>
<thead>
<tr>
<th>Pure metal or alloy</th>
<th>$k$, W/m-K at 300 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>401</td>
</tr>
<tr>
<td>Nickel</td>
<td>91</td>
</tr>
<tr>
<td>Constantan (55% Cu, 45% Ni)</td>
<td>23</td>
</tr>
<tr>
<td>Copper</td>
<td>401</td>
</tr>
<tr>
<td>Aluminum</td>
<td>237</td>
</tr>
<tr>
<td>Commercial bronze (90% Cu, 10% Al)</td>
<td>52</td>
</tr>
</tbody>
</table>

Variation of the thermal conductivity of various solids, liquids, and gases with temperature.
Examples: Conduction heat transfer

Heat conduction through cylinder wall and fins

Heat conduction through electronic chips

Convection heat transfer

Boundary layers, Newton's law of cooling, Nusselt number
The convection problem

Convective heat transfer

- **Convection**: The mode of energy transfer between a solid surface and the adjacent liquid or gas that is in motion, and it involves the combined effects of conduction and fluid motion.

- The faster the fluid motion, the greater the convection heat transfer.

- In the absence of any bulk fluid motion, heat transfer between a solid surface and the adjacent fluid is by pure conduction.
Types of convection

- **Forced convection**: If the fluid is forced to flow over the surface by external means such as a fan, pump, or the wind.

- **Natural (or free) convection**: If the fluid motion is caused by buoyancy forces that are induced by density differences due to the variation of temperature in the fluid.

![ Forced and natural convection images ]

The cooling of a boiled egg by forced and natural convection.

Types of forced convection

- **Internal forced convection**: If the fluid flow is bounded inside a pipe, duct, channel, tube, capillary etc, it is categorized as an internal flow situation.

- **External forced convection**: If the fluid flows on a solid wall, object, bluff body, etc. externally, then the situation is categorized as an external flow.

![ Internal and external flow situations ]

Internal and external flow situations
The boundary layer concept

Boundary layer refers to the layer of fluid in the immediate vicinity of a bounding surface where the effects of viscosity are significant.

The velocity boundary layer (external flow)

The development of a velocity profile due to the no-slip condition as a fluid flows over a blunt nose.

"Hunter Rowe: Laminar and Turbulent Flow Film." Copyright 1988, Hydroscience & Engineering, The University of Iowa. Used by permission.

External flow over a blunt nose, showing the turbulent wake region behind.

The flow of an originally uniform fluid stream over a flat plate, and the regions of viscous flow (next to the plate on both sides) and inviscid flow (away from the plate).
Implications of the boundary layers

Velocity boundary layer  ► velocity gradients  ► shear stress
Thermal boundary layer  ► temperature gradients  ► heat flux
Concentration boundary layer  ► concentration gradients  ► molar flux

For practical engineering design and applications the direct implications are:

Momentum transfer  ►  Friction Factor (non-dimensional shear stress)

Energy transfer  ►  Nusselt Number (heat transfer coefficient)

Mass Transfer  ►  Sherwood Number (mass transfer coefficient)

Laminar Transitional and turbulent flows

Dye injection
(a) Laminar flow

Dye injection
(b) Turbulent flow
**Turbulent flow characteristics**

- The velocity gradients at the wall, and thus the wall shear stress, are much larger for turbulent flow than they are for laminar flow, even though the turbulent layer is thicker than the laminar one for the same value of free stream velocity.

**Development of BL in internal flows (pipe)**

- The development of velocity profile in a circular pipe, $V = V(r, z)$ and thus the flow is two-dimensional in the entrance region, and becomes one-dimensional downstream when the velocity profile fully develops and remains unchanged in the flow direction $V = V(r)$.
Newton’s law of cooling

- The convection heat transfer coefficient $h$ is not a property of the fluid.
- It is an experimentally determined parameter whose value depends on all the variables influencing convection such as:
  - the surface geometry
  - the nature of fluid motion
  - the properties of the fluid
  - the bulk fluid velocity

\[ \dot{Q}_{\text{conv}} = h A_s (T_s - T_\infty) \] (W)

$h$ : convection heat transfer coefficient, W/m$^2$·°C
$A_s$ : the surface area through which convection takes place
$T_s$ : the surface temperature
$T_\infty$ : temperature of the fluid sufficiently far from the surface.

Boiling and condensation

- Heat transfer processes that involve change of phase of a fluid are also considered to be convection because of the fluid motion induced during the process, such as the rise of the vapor bubbles during boiling or the fall of the liquid droplets during condensation.
### Typical values of HTC

**Typical values of convection heat transfer coefficient**

<table>
<thead>
<tr>
<th>Type of convection</th>
<th>$h$, W/m² K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free convection of gases</td>
<td>2–25</td>
</tr>
<tr>
<td>Free convection of liquids</td>
<td>10–1000</td>
</tr>
<tr>
<td>Forced convection of gases</td>
<td>25–250</td>
</tr>
<tr>
<td>Forced convection of liquids</td>
<td>50–20,000</td>
</tr>
<tr>
<td>Boiling and condensation</td>
<td>2500–100,000</td>
</tr>
</tbody>
</table>

### Engine/Automobile cooling

- **IC engines in automobiles are cooled by circulating water.**
- **The water cools the engine and the atmospheric air cools the water.**

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Microprocessor/PC cooling

Phase-change technology is most effective, which is usually coupled with air cooling.

Air cooling is frequently employed in PCs and instruments.

The nuclear power plant (BWR)
Summary (Conduction and Convection)

- Conduction and Convection are important processes for heat exchanger design.
- Estimation of convective heat transfer coefficient is one of the main tasks in designing a refrigeration system (external as well as internal flow situations; single-phase as well as phase-change situations).
- Convective heat transfer coefficients can vary in a wide range depending on the type of flow processes used.
- Improvement in convective heat transfer is also generally associated with enhanced penalty in terms of frictional head.

Thanks!

Any questions? (End of Part-I of the lecture)

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