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PHARMACEUTICAL ENGINEERING

UNIT 2

TOPIC :

- **Heat Transfer :** Objectives, applications & Heat transfer mechanisms. Fourier's law, Heat transfer by conduction, convection & radiation. Heat interchangers & heat exchangers.

Heat Transfer

Heat Transfer is the process of transfer of thermal energy from one body or system to another due to a temperature difference.

- Heat always flows from a region of higher temperature to a region of lower temperature.
- The process continues until thermal equilibrium is reached.

Objectives of Heat Transfer

1. Minimization of heat loss → to reduce energy wastage.
2. Maximizing heat recovery → reusing heat to improve efficiency.
3. Designing efficient heat exchangers → for controlled heat transfer in industry.
4. To maintain a desired temperature or temperature range → essential for pharmaceutical processes.
5. Material selection and development → choosing appropriate materials that can withstand and conduct heat effectively.

Applications of Heat Transfer in Pharmacy

- Sterilization → using steam or dry heat to destroy microorganisms.
- Drying → removal of moisture from drug powders, granules, or formulations.
- Evaporation → concentration of solutions by removing solvents.
- Crystallization → controlled cooling/evaporation for forming pure crystals of drugs.
- Distillation → separation and purification of volatile components using heat.

Mechanism of Heat Transfer

Heat can be transferred from one body to another by **three main mechanisms**:

1. **Conduction**
2. **Convection**
3. **Radiation**

1. Conduction

- Conduction is the process of heat transfer through a material by direct molecular contact without any actual movement of matter.
- **Mechanism:**
  - When a part of the material is heated, its particles gain energy and vibrate more rapidly.
  - These high-energy particles collide with adjacent lower-energy particles.
  - Energy is transferred from the hot region to the cold region until equilibrium is reached.
- **Example in Pharmacy:**
  - Heat transfer through the metal wall of an autoclave.
  - Sterilization by dry heat (hot air oven).

Thermal Conductivity (k)

- Thermal conductivity is the property of a material that defines its **ability to conduct heat**.
- **High k materials (e.g., metals)** → good conductors of heat.
- **Low k materials (e.g., wood, rubber, glass)** → poor conductors (insulators).

Rate of Heat Transfer by Conduction

It is governed by **Fourier's Law**:

$$Q = \frac{k\,A\,\Delta T}{d}$$

Where:

- Q = Rate of heat transfer (W or J/s)
- k = Thermal conductivity of the material (W/m·K)
- A = Cross-sectional area perpendicular to heat flow (m^2)
- ΔT = Temperature difference between hot and cold surfaces (K or °C)
- d = Thickness of material (m)

2. Convection

Convection is the process of heat transfer by the actual movement of fluid particles (liquids or gases) from one region to another.

- In this process, heat energy is carried along with the moving fluid.
- It occurs only in fluids (liquids and gases), because their molecules are free to move.

Types of Convection

1. **Natural (Free) Convection**
   - Occurs due to the difference in density of the fluid when heated.
   - Hot fluid becomes lighter (less dense) and rises, while cold fluid sinks, creating a circulation current.
   - **Example in Pharmacy:** Cooling of pharmaceutical solutions in containers, drying of granules in trays.
2. **Forced Convection**
   - Occurs when the fluid is forced to move by an external device such as a pump, fan, or stirrer.

- Heat transfer rate is much higher compared to natural convection.
- **Example in Pharmacy:** Forced air drying in fluidized bed dryer, circulation in heat exchangers.

Mechanism

- When a fluid near a hot surface is heated, it expands and its density decreases.
- The lighter (hot) portion rises, and the heavier (cold) portion comes down to replace it.
- This sets up a continuous **convection current**, transferring heat.
- In forced convection, this motion is enhanced by mechanical means.

Law of Heat Transfer by Convection

It is expressed by Newton's Law of Cooling:

$$Q = h\,A\,\Delta T$$

Where:

- Q = Rate of heat transfer (W or J/s)
- h = Heat transfer coefficient ($W/m^2\cdot K$)
- A = Surface area through which heat transfer occurs (m^2)
- ΔT = Temperature difference between the surface and surrounding fluid (K or °C)

Applications in Pharmacy

- Drying of powders, granules, and tablets.
- Sterilization by autoclaves (steam convection).
- Cooling of pharmaceutical solutions.
- Operation of fluidized bed dryers and spray dryers.

3. Radiation

Radiation is the process of **heat transfer in the form of electromagnetic waves (infrared radiation)**, without the need of any medium (can occur in solids, liquids, gases, or even in a vacuum).

- Unlike conduction and convection, **no material particles** are required for the transfer of heat.
- Heat energy is emitted by a hot body and absorbed by a cooler body directly.

Mechanism

- All bodies above absolute zero temperature (0 K) emit thermal radiation due to the vibration of their atoms and molecules.
- This radiation travels at the speed of light and carries energy.
- When these waves strike another body, part of them is absorbed (causing heating), part is reflected, and part may be transmitted.
- The amount of heat absorbed depends on:
  - Temperature difference between bodies.
  - Surface properties (black body absorbs maximum, shiny/reflective surfaces absorb less).
  - Distance between the bodies.

Laws Governing Radiation

1. **Stefan-Boltzmann Law**
   - The total energy radiated is directly proportional to the fourth power of the absolute temperature of the body.

$$Q = \sigma A T^4$$

Where:

- Q = Radiant heat energy (W)
- σ = Stefan-Boltzmann constant (5.67×10^{-8} W/m²·K⁴)
- A = Surface area (m²)
- T = Absolute temperature (K)

2. **Kirchhoff's Law**
    - A good absorber of heat radiation is also a good emitter.
3. **Planck's Law**
    - Defines the spectral distribution of radiation at a given temperature.

Applications in Pharmacy

- **Infrared Dryers**: Drying of pharmaceutical powders and granules using IR lamps.
- **Sterilization**: Infrared sterilization of glassware, syringes, and instruments.
- **Radiant Heat Sterilizers**: Used in aseptic areas for sterilization of small equipment.
- **Freeze Drying**: Sublimation of water involves radiant heat input.
- **Analytical Instruments**: Infrared spectroscopy (IR) for structural determination of drugs.

Fourier's Law of Heat Transfer

Fourier's Law states that the rate of heat transfer (Q) through a material is directly proportional to:

1. The negative temperature gradient ($-dT/dx$) across the material.
2. The cross-sectional area **(A)** perpendicular to the direction of heat flow.

It explains heat conduction in solids.

Mathematical Expression

$$Q = -kA\frac{dT}{dx}$$

Where:

- Q = Rate of heat transfer (W or J/s)
- k = Thermal conductivity of the material (W/m·K)
- A = Cross-sectional area of the material (m^2)
- dT/dx = Temperature gradient across thickness (K/m)
- Negative sign (−) indicates that heat flows **from higher to lower temperature** (temperature drop).

Key Points

- Materials with high thermal conductivity (k), like metals, conduct heat quickly.
- Materials with low thermal conductivity, like wood or wool, act as insulators.
- The law is fundamental in the design of heat transfer equipment.

Applications in Pharmacy

- **Designing Heat Exchangers** → Used in distillation, evaporation, crystallization units.
- **Designing Insulation Systems** → To minimize heat loss during sterilization or drying.
- **Heat Transfer Analysis** → To optimize energy consumption in pharmaceutical processes.
- **Dryers** → Prediction of heat flow in tray dryers, fluidized bed dryers, etc.
- **Sterilization Units** → To calculate heat penetration in autoclaves and ovens.

Heat Interchanger vs Heat Exchanger

- In pharmaceutical and chemical industries, transfer of heat between two or more fluids is essential in many unit operations (drying, distillation, crystallization, sterilization, etc.).
  The terms heat exchanger and heat interchanger are often used interchangeably, but there is a slight difference in meaning.

Heat Interchanger

- A heat interchanger is a specific type of heat exchanger.
- It allows heat transfer between two or more fluids within the same system, often with the possibility of fluid mixing or interaction.
- It is less commonly used as a term in engineering, but refers to specialized devices where both energy transfer and partial fluid interaction may occur.
- Example: Certain reactor jackets or fluid-fluid contact equipment.

Heat Exchanger

- A heat exchanger is a device designed to transfer heat between two or more fluids (liquid, gas, or vapor) without mixing them.
- It is a broad term, widely used in engineering and pharmaceutical operations.
- Functions by transferring thermal energy from hot fluid to cold fluid while keeping them separate.
- Used in almost every industrial process involving heating or cooling.

Types of Heat Exchangers

1. **Shell and Tube Heat Exchanger**
    - Consists of a series of tubes inside a cylindrical shell.
    - One fluid flows through tubes, another flows around them in the shell.
    - Widely used in distillation, evaporation, and cooling pharmaceutical fluids.
2. **Double Pipe Heat Exchanger**
    - Simplest type: One fluid flows inside the inner pipe, the other in the annular space between pipes.
    - Suitable for small-scale operations in laboratories or pilot plants.
3. **Plate Heat Exchanger**
    - Made of thin, corrugated plates stacked together.
    - Fluids flow in alternate channels, exchanging heat efficiently.
    - Provides high heat transfer efficiency in compact size.

Applications in Pharmacy

- **Sterilization processes** → To transfer heat efficiently in autoclaves and sterilizers.
- **Distillation units** → For condensation and reflux heating.
- **Evaporation and Crystallization** → Maintaining energy efficiency.
- **Fermentation processes** → Controlling temperature of fermenters.
- **Drying operations** → Pre-heating air in dryers.

Shell & Tube Heat Exchanger

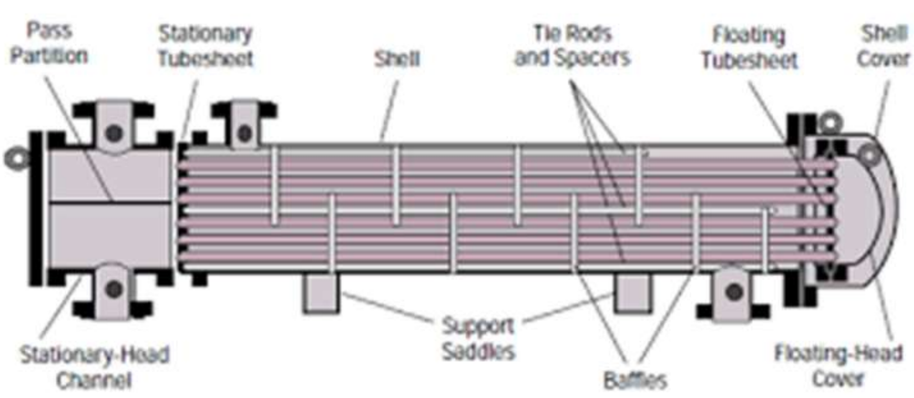
- A Shell & Tube Heat Exchanger is the most commonly used type of heat exchanger in chemical, pharmaceutical, and power industries.
- It is designed to transfer heat between two immiscible fluids (liquid or gas) without mixing them.

Principle

- Operates on conduction and convection heat transfer.
- Heat is transferred from the hot fluid to the cold fluid through the tube walls.
- One fluid flows inside the tubes, while the other flows over the tubes, inside the shell.
- The temperature difference between fluids drives the heat exchange process.

Construction

1. Shell → A cylindrical vessel that holds the tube bundle.
2. Tubes → A set of small diameter tubes placed inside the shell through which one fluid flows.
3. Tube Sheets → Plates that fix and seal the tubes at both ends.
4. Baffles → Plates placed inside the shell to direct the fluid flow, increase turbulence, and improve heat transfer efficiency.
5. Heads (Channel & Bonnet) → Provide inlet and outlet connections for both shell-side and tube-side fluids.



Working

- Step 1: One fluid flows through the tubes.
- Step 2: Another fluid flows over the tubes, inside the shell.
- Step 3: Heat is exchanged across the tube walls due to the temperature difference.
- Step 4: Baffles inside the shell create turbulence, enhancing heat transfer efficiency.

Applications

- Power plants → For steam condensation and feed water heating.
- Pharmaceutical industry → For sterilization, distillation, evaporation, and cooling processes.
- Chemical industry → For heating/cooling chemical solutions.
- HVAC systems → For heating, ventilation, and air-conditioning.

Advantages

- High thermal efficiency.
- Durable and long-lasting design.
- Easy to clean (tube side).
- Can handle high pressure and temperature.

Disadvantages

- High initial cost.
- Requires large space for installation.
- Design and maintenance can be complex.