Chapter 1

General Introduction to Heat Transfer

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Lecture 1: Fundamentals of Heat Transfer

Learning Objectives

By the end of this lecture, students should be able to:

1. Explain the role of heat transfer in engineering systems ;
2. Define key terms: heat, temperature, thermal gradient, and heat flux ;
3. Describe the three modes of heat transfer: conduction, convection, and radiation ;
4. Identify real-world applications of heat transfer in various engineering disciplines ;
5. Use the electrical analogy to conceptualize thermal systems.

1) Role of Heat Transfer in Engineering Systems

Ask? (Socratic Questioning)

"Let's pause for a moment. We always say ***heat transfers***... but does it *really* transfer? What is heat? Is it a substance? Does it flow like water?"

Imagine:

- A hot cup of tea left on a table.
- The room is cooler than the tea.

"Over time, the tea cools. Where did the 'heat' go? Did something *move* from the cup to the air?"

Ans.: No physical substance moved, but **thermal energy was transferred** from the hot tea molecules to the slower-moving air molecules.

Figure 1: A hot cup of tea

Let's take another example,

"If you hold a metal rod with one end heated and the other end cold, the cold end eventually warms up. What is transferred through the rod to cause this?"

Ans.: "A difference in temperature over a distance creates a **temperature gradient**, which **drives the transfer of thermal energy** from the hotter region to the colder one."

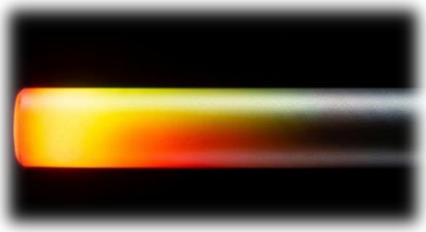

Figure 2: a metal rod

Discipline-Specific Applications

Heat transfer is a universal phenomenon with tailored applications across every engineering field. **Table 1** below gives the most important application filed.

Table 1: Discipline-specific applications

Discipline	System	Heat Transfer Role
Mechanical Eng.	Internal combustion engines	Cooling of cylinders to prevent overheating
	HVAC systems	Heat exchange for climate control
Chemical Eng.	Reactors	Removal of heat from exothermic reactions
	Distillation columns	Reboilers and condensers for phase change
Electrical Eng.	Power electronics	Heat sinks and fans to dissipate Joule heating
Civil Eng.	Buildings	Insulation to minimize heating/cooling load
Energy Systems	Solar panels, turbines	Heat to electricity conversion; heat loss mitigation
Biomedical Eng.	Hyperthermia therapy	Controlled heat delivery to tissues

2) Recap of Thermodynamics, Fluid mechanics, and Mathematics

○ Recap of Thermodynamics Fundamentals

❖ First Law of Thermodynamics (Law of Energy Conservation)

Statement: Energy cannot be created or destroyed; it can only change forms. The change in internal energy of a system is equal to the heat added to the system minus the work done by the system on its surroundings.

Equation:

$$\Delta \boldsymbol{U} = \boldsymbol{Q} - \boldsymbol{W}$$

Where

ΔU : change in internal energy of the system ;
Q: heat added to the system ;
W: work done by the system.

- ✓ Internal energy (U) includes kinetic, potential, and microscopic energies.
- ✓ Work done by the system is often pressure-volume work, $W = P.\Delta V$ for constant external pressure.
- ✓ Heat transfer and work change the system's energy but do not create or destroy it.

❖ Second Law of Thermodynamics (Law of Entropy and Irreversibility)

Statement: Natural processes tend to increase the total entropy ($\boldsymbol{S}$) of an isolated system. Heat spontaneously flows from hotter to colder bodies, not the reverse.

$$\Delta \boldsymbol{S} > \boldsymbol{0}$$

Recap of Fluid Mechanics Basics

A fluid is a substance that can flow and take the shape of its container, encompassing both liquids (incompressible) and gases (compressible).

Fluids deform continuously **under shear stress**, unlike solids.

❖ Flow Properties

Velocity (v): Fluid flow speed and direction, a vector quantity depending on position and time.

Pressure (p): Force exerted per unit area within the fluid.

Density (ρ): Mass per unit volume of the fluid.

Viscosity (μ): Measure of the fluid's internal resistance to flow (shear resistance).

Temperature (T): Thermodynamic property affecting fluid behavior.

❖ Flow Regimes

Laminar flow: Smooth, orderly fluid motion in parallel layers with minimal mixing.

Turbulent flow: Chaotic fluid motion with eddies and vortices causing mixing.

Transitional flow: Intermediate state between laminar and turbulent.

Using **Reynold's Number**, we can determine the flow regime of the fluid

$$\boldsymbol{Re = \frac{\rho v L}{\mu}}$$

Where:

- ρ : fluid density,
- v : characteristic velocity,
- L : characteristic length (e.g., pipe diameter),
- μ : dynamic viscosity.

For **internal flow** (e.g. flow inside a pipe):

$Re < 2\ 000$: Laminar flow

$2000 < Re < 4\ 000$: Transitional flow

$Re > 4\ 000$: Turbulent flow

For **external flow** (e.g. flow on a flat plate):

$Re_x < 5 \times 10^5$: Laminar flow

$Re_x \geq 5 \times 10^5$: Turbulent flow

Mathematic Tools

❖ Derivative Concept

The derivative of a function measures the rate at which the function value changes with respect to a change in its independent variable.

For a single-variable function $f(x)$, the derivative is:

$$\boldsymbol{\frac{df}{dx} = \lim_{\Delta x \to 0} \frac{f(x + \Delta x) - f(x)}{\Delta x}}$$

It represents instantaneous rate of change or slope of the function at a point.

3) Fundamentals Definitions

Table 2: Key definitions

Term	Symbol	Units (SI)	Definition
Heat transfer (Quantity of heat)	Q	J	The **total amount of thermal energy** transferred between two systems due to a temperature difference.
Temperature	T	K	Temperature is **a measure of the average kinetic energy** of the molecules in a substance.
Thermal gradient	∇T	K/m	The **rate of temperature change over distance**.
Heat rate	q	W or (J/s)	The **time rate of heat transfer**, i.e., how much heat is transferred per unit time.
Heat flux	q''	W/m²	The **rate of heat transfer per unit area**. It measures how much thermal energy flows through a surface.

4) Modes of Heat Transfer

4.1. Conduction

Conduction is the mode of heat transfer that occurs within a solid, or between bodies in direct physical contact, due to a temperature gradient, **without any macroscopic motion of the material**.

It results from microscopic interactions:

- **In solids:** through vibrations of molecules (lattice vibrations) and free electron transport (important in metals).
- **In stationary liquids and gases:** through molecular collisions and diffusion.

The **driving force** of conduction is the **temperature difference (ΔT)** within the medium.

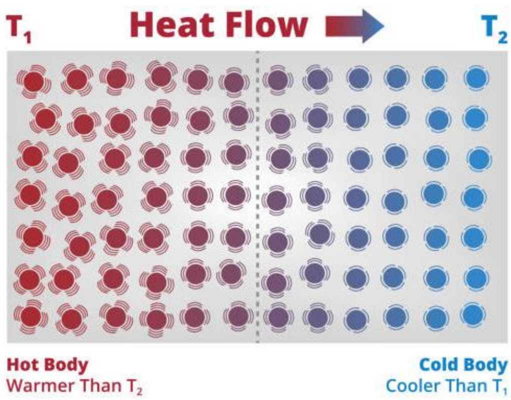

Figure 3: Transfer of thermal energy by vibration of molecules in solids.

The fundamental law describing conduction is **Fourier's Law**:

$$q'' = -k\frac{dT}{dx}$$

Where

q'': Heat flux (W/m²)

k : Thermal conductivity of the material (**W/m·K**), a property that measures the ability of a material to conduct heat

$\frac{dT}{dx}$: Temperature gradient in the direction of heat flow (K/m)

The **negative sign** indicates that heat flows from higher to lower temperature (down the gradient).

Then, the **Total Heat Transfer Rate** For a plane wall of area A and thickness L is:

$$q = kA\frac{T_{hot} - T_{cold}}{L}$$

4.2. Convection

Convection is the mode of heat transfer between a solid surface and an adjacent fluid (liquid or gas), or within the fluid itself, caused by the combined action of conduction and fluid motion.

- **At the solid–fluid interface**, heat is transferred by **conduction**.
- The **bulk motion** of the fluid then transports this energy away, enhancing the overall heat transfer.

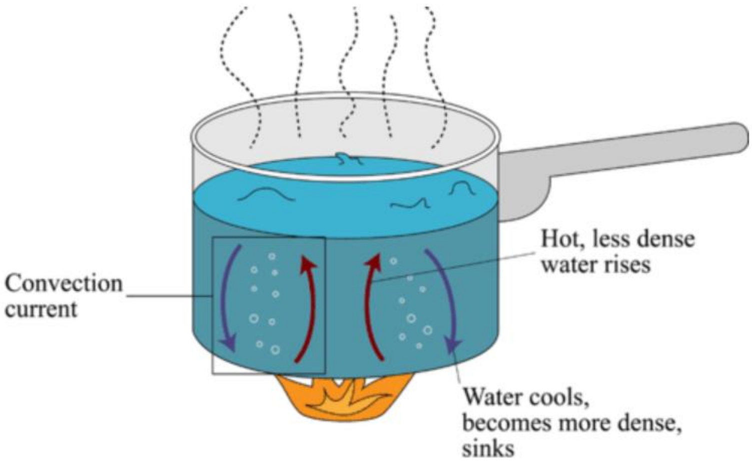

Figure 4: Transfer of thermal energy by convection.

The heat flux by convection is expressed by the **Newton's law of cooling** as:

$$q'' = h(T_s - T_\infty)$$

and the total heat transfer rate:

$$q = hA(T_s - T_\infty)$$

Where:

q''**:** Convective heat flux (**W/m²**)

q : Total heat transfer rate (**W**)

$\boldsymbol{h}$: Convection heat transfer coefficient (**W/m²·K**) – depends on fluid properties, velocity, geometry, and flow regime

$\boldsymbol{T_s}$: Surface temperature (**K** or **°C**)

$\boldsymbol{T_\infty}$: Fluid temperature far from the surface (**K** or **°C**).

4.3. Thermal radiation

Thermal radiation is the mode of heat transfer that occurs through the emission of **electromagnetic waves**, as a result of the **thermal motion of charged particles** within matter. Unlike conduction and convection, thermal radiation **does not require a material medium** and can propagate through a vacuum. Everybody at a temperature above absolute zero (**0 K**) continuously emits radiant energy.

Figure 5: Example of radiation heat transfer.

Real materials ($\boldsymbol{\varepsilon} < \mathbf{1}$) emit less radiation than a blackbody ($\boldsymbol{\varepsilon} = \mathbf{1}$) at the same temperature. The actual emitted radiation is given by the **Stefan–Boltzmann law:**

$$\boldsymbol{E = \varepsilon \sigma T^4}$$

Where:

$\boldsymbol{E}$: Emissive power of the surface (**W/m²**),

$\boldsymbol{\varepsilon}$: Emissivity of the surface (dimensionless, $\mathbf{0} \leq \boldsymbol{\varepsilon} \leq \mathbf{1}$).

$\boldsymbol{\sigma}$: $\sigma = 5.67 \times 10^{-8}\ W/m^2.K^4$ Stefan–Boltzmann constant

$\boldsymbol{T}$: Absolute temperature (K)