Chapter 1: Introduction

Advanced Heat Transfer

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1-1 General Remarks (1)

- Heat: the form of energy that can be transferred from one system to another as a result of temperature difference.
- Thermodynamic analysis concerns the amount of heat transfer during a process.
- Heat transfer deals with the rates of such energy transfers.
- Modes of heat transfer: conduction, convection and radiation.
1-1 General Remarks (2)

- Conduction, convection, and radiation heat transfer modes

![Diagram showing heat transfer modes: Conduction through a solid or a stationary fluid, Convection from a surface to a moving fluid, and Net radiation heat exchange between two surfaces.]

**Figure 1.1** Conduction, convection, and radiation heat transfer modes.
1-1 General Remarks (3)

- Governing equations of heat transfer modes
  - Conduction---Fourier’s law:
    \[ q'' = -k \frac{\partial T}{\partial x} \]
  - Convection---Newton’s cooling law:
    \[ q'' = h(T_s - T_\infty) \]
  - Radiation:
    \[ q'' = \varepsilon \sigma (T_s^4 - T_\infty^4) \]
Conduction may be viewed as the transfer of energy from the more energetic to the less energetic particles of a substance due to interactions between the particles.

Conduction can take place in solids, liquids, or gases.
In liquids and gases, 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.
1-2 Conduction (3)

The rate of heat conduction through a medium depends on the geometry of the medium, its thickness, and the material of the medium, as well as the temperature difference across the medium.
1-2 Conduction (4)

- Rate of heat conduction

\[ \dot{Q} \propto \frac{(Area)(Temperature \ difference)}{Thickness} \]

or \( \dot{Q} = kA \frac{\Delta T}{\Delta x} \)

- Fourier’s law of heat conduction

\[ \dot{Q}_{cond} = -kA \frac{dT}{dx} \]  
(14 – 2)

\( k \): thermal conductivity
The sign convention used is based on the second law of thermodynamics with the flux being positive when it flows in the direction of decreasing temperature.

Mathematically it may be more appropriate to state that the heat flux is positive when the temperature gradient is negative. This statement requires that the negative sign be introduced in the above equation.
The rate of heat conduction through a solid is directly proportional to its thermal conductivity.
In heat conduction analysis, \( A \) represents the area normal to the direction of heat transfer.
Example

Concrete roof
8 m
4°C
6 m
0.25 m
15°C

FIGURE 14-4
The range of $k$ for various materials at room temperature
The mechanism of heat conduction in different phases of a substance
1-2 Conduction (11)

- The variation of $k$ of various solids, liquids, and gases with temperature

![Diagram showing the variation of thermal conductivity ($k$) for various materials with temperature ($T$)].
The thermal conductivity, $\kappa$, is a thermophysical property of the material through which the heat flows and has the units of W/m-$^\circ$C or Btu/hr-ft-$^0$F.

The values of the thermal conductivity for most substances must be obtained experimentally. Usually, $k_{\text{solid}} > k_{\text{liq}} > k_{\text{gas}}$. 

1-15
1-2 Conduction (13)

-Thermal diffusivity:
\[
\alpha = \frac{\text{Heat conducted}}{\text{Heat stored}} = \frac{k}{\rho C_p} \quad (m^2 / s)
\]

Analog to \( v = \frac{\mu}{\rho} \quad m^2 / s \)

-The larger the thermal diffusivity, the faster the propagation of heat into the medium. A small value of thermal diffusivity means that heat is mostly absorbed by the material and a small amount of heat will be conducted further.
Convection is the mode of energy transfer between a solid surface and the adjacent liquid or gas that is in motion.

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.
Heat transfer from a hot surface to air by convection
1-3 Convection (3)

- **Convection** = **Conduction** + **Advection**
  (fluid motion)

- Convection is the mode of energy transfer between a solid surface and the adjacent liquid or gas that is in motion.

- Convection is commonly classified into three sub-modes:
  - Forced convection,
  - Natural (or free) convection,
  - Change of phase (liquid/vapor, solid/liquid, etc.)
1-3 Convection (4)

- Forced convection: the fluid is forced to flow over the surface by external means such as a fan, pump, or the wind.
- Natural (free) convection: the fluid motion is caused by buoyancy forces that are induced by density differences due to the variation of temperature in the fluid.
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 vapor bubbles during boiling or the fall of the liquid droplets during the condensation.
1-3 Convection (6)

- Newton’s law of cooling: \( \dot{Q}_{\text{conv}} = hA(T_s - T_\infty) \)
  
  \( h \): convection heat transfer coefficient (W/m\textsuperscript{2}\textdegree C)

  \( T_s \): surface temperature
  
  \( T_\infty \): the temperature of the fluid sufficiently far from the surface
1-3 Convection (7)

- $h$ is not a property of fluid, but is a flow property.
- 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, and the bulk fluid velocity.
Radiation is the energy emitted by matter in the form of electromagnetic waves (or photons) as a result of the changes in the electronic configurations of the atoms or molecules.

Unlike conduction or convection, radiation does not require the presence of an intervening medium.

Energy transfer by radiation is fastest (at the speed of light) and it suffers no attenuation in a vacuum. This is how the energy of the sun reaches the earth.
In heat transfer, we are interested in thermal radiation, which is in the form of radiation emitted by bodies because of their temperature.

All bodies at a temperature above absolute zero emit thermal radiation.
Stefan-Boltzmann law: the maximum rate of radiation that can be emitted from a surface at an absolute temperature $T_s$ is given by

$$\dot{Q}_{\text{emit, max}} = \sigma A T_s^4 \quad (W)$$

$\sigma$: Stefan-Boltzmann constant = $5.67 \times 10^{-8}$ W/m$^2$•K$^4$
Blackbody radiation:

\[ T_s = 400 \text{ K} \]

\[ \dot{Q}_{\text{emit, max}} = \sigma T_s^4 \]

\[ = 1452 \text{ W/m}^2 \]

**Figure 14-14**
1-4 Radiation (5)

The radiation emitted by all real surfaces is less than the radiation emitted by a blackbody at the same temperature, and is expressed as

$$\dot{Q}_{\text{emit}} = \varepsilon \sigma A T_s^4 \quad (W)$$

$\varepsilon$ : the emissivity of the surface ($0 \leq \varepsilon \leq 1$)

$\varepsilon = 1$ for blackbody
Absorptivity, $\alpha$: the fraction of the radiation energy incident on a surface that is absorbed by the surface. $0 \leq \alpha \leq 1$

A blackbody absorbs the entire radiation incident on it, i.e., $\alpha = 1$. 
The absorption of radiation incident on an opaque surface of absorptivity, $\alpha$
1-4 Radiation (8)

- Kirchhoff’s law: $\varepsilon$ and $\alpha$ of a surface are equal at the same temperature and wavelength.

- In most practical application, the dependence of $\varepsilon$ and $\alpha$ on the temperature and wavelength is ignored, and the average absorptivity of a surface is taken to be equal to its average emissivity.
Radiation heat transfer between a surface and the surfaces surrounding it.

\[ \dot{Q}_{\text{rad}} = \varepsilon \sigma A (T_s^4 - T_{\text{surr}}^4) \]

**FIGURE 14-16**
Combined heat transfer coefficient:

\[ \dot{Q}_{\text{total}} = \dot{Q}_{\text{convection}} + \dot{Q}_{\text{radiation}} = hA(T_s - T_\infty) + \varepsilon\sigma A(T_s^4 - T_\infty^4) \]

\[ h_{\text{combined}} = h + \varepsilon\sigma(T_s^2 + T_\infty^2)(T_s + T_\infty) \]
Example

FIGURE 14-17
Schematic for Example 14-5.

30°C
1.4 m²

\( Q_{\text{rad}} \)

Room

\( T_{\text{surr}} \)
Although there are three mechanisms of heat transfer, a medium may involve only two of them simultaneously.

**Figure 1-9** Combination of conduction, convection, and radiation heat transfer.

- OPAQUE SOLID: 1 mode
- GAS: 2 modes
- VACUUM: 1 mode
Example
The first law of thermodynamics states that energy can neither be created nor destroyed during a process; it can only change forms. The energy balance for any system undergoing any process can be expressed as (in the rate form)

\[ \dot{E}_{in} - \dot{E}_{out} = \frac{dE_{system}}{dt} \] (W)

Rate of net energy transfer by heat, work, and mass

Rate of change in internal kinetic, potential, etc., energies
In heat transfer problems it is convenient to write a heat balance and to treat the conversion of nuclear, chemical, mechanical, and electrical energies into thermal energy as heat generation.

The energy balance in that case can be expressed as

\[ Q_{in} - Q_{out} + E_{gen} = \Delta E_{thermal, system} \] (J)

- Net heat transfer
- Heat generation
- Change in thermal energy of the system
1-6 Conservation of Energy (3)

Application to a Control Volume

- At an Instant of Time:

  Surface Phenomena \( \dot{E}_{in}, \dot{E}_{out} \)

  Volumetric Phenomena \( \dot{E}_g, \dot{E}_{st} \)

  \[ \dot{E}_{in} - \dot{E}_{out} + \dot{E}_g = \dot{E}_{st} = \frac{dE_{st}}{dt} \]  --- Energy Conservation

  Each term has units of J/s or W.

- Over a Time Interval

  \[ E_{in} - E_{out} + E_g = E_{st} \]  Each term has units of J.
1-6 Conservation of Energy (4)

- **Special Case (1): Closed System**

  Transient Process for a Closed System of Mass (M) Assuming Heat Transfer to the System (Inflow) and Work Done by the System (Outflow).

  \[
  \dot{Q} - \dot{W} = \frac{dU}{dt} \quad \text{or} \quad Q - W = \Delta U
  \]

- **Special Case (2): Control Volume**

  Steady State for Flow through an Open System without Phase Change or Generation:

  \[
  \dot{Q} + \dot{m}(h_i + \frac{V_i^2}{2} + gz_i) - W - \dot{m}(h_e + \frac{V_e^2}{2} + gz_e) = 0
  \]
The Surface Energy Balance

A special case for which no volume or mass is encompassed by the control surface.

- Applies for steady-state and transient conditions.
- With no mass and volume, energy storage and generation are not pertinent to the energy balance, even if they occur in the medium bounded by the surface.

\[
\dot{E}_{\text{in}} - \dot{E}_{\text{out}} = 0
\]

Consider surface of wall with heat transfer by conduction, convection and radiation.

\[
q''_{\text{cond}} - q''_{\text{conv}} - q''_{\text{rad}} = 0
\]

\[
k \frac{T_1 - T_2}{L} - h(T_2 - T_{\infty}) - \varepsilon\sigma(T_2^4 - T_{\text{sur}}^4) = 0
\]
Methodology of Analysis of Energy Conservation

- On a schematic of the system, represent the control surface by dashed line(s).

- Choose the appropriate time basis.

- Identify relevant energy transport, generation and/or storage terms by labeled arrows on the schematic.

- Write the governing form of the Conservation of Energy requirement.

- Substitute appropriate expressions for terms of the energy equation.

- Solve for the unknown quantity.