Advanced Heat Transfer

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Chapter 1 Introduction

OUTLINE

1-1 General Remarks

1-2 Conduction

1-3 Convection

1-4 Radiation

1-5 Simultaneous Heat Transfer Mechanism

1-6 Applications of Heat Transfer

1-7 Conservation of Energy

1-8 Problem Solving Technique

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

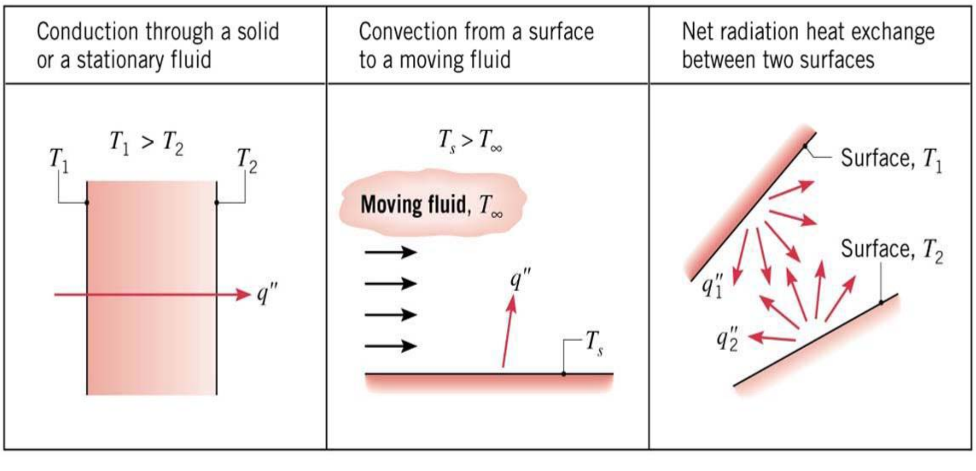

FIGURE 1.1 Conduction, convection, and radiation heat transfer modes.

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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:

$$q'' = \varepsilon\sigma(T_s^4 - T_\infty^4)$$

1-2 Conduction (1)

- 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.

1-2 Conduction (2)

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

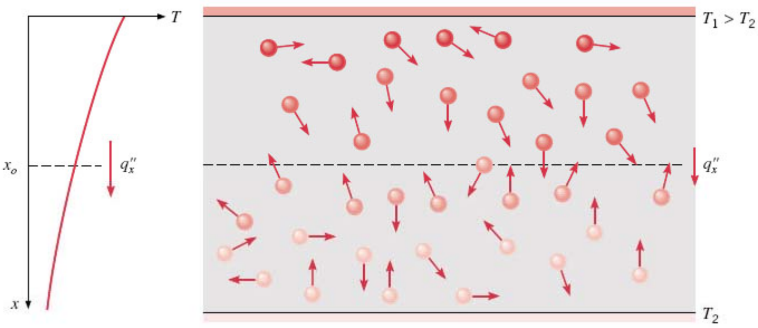

FIGURE 1.2 Association of conduction heat transfer with diffusion of energy due to molecular activity.

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

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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.

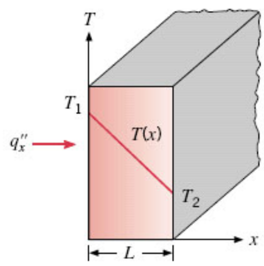

FIGURE 1.3
One-dimensional heat transfer by conduction (diffusion of energy).

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1-2 Conduction (4)

- Rate of heat conduction

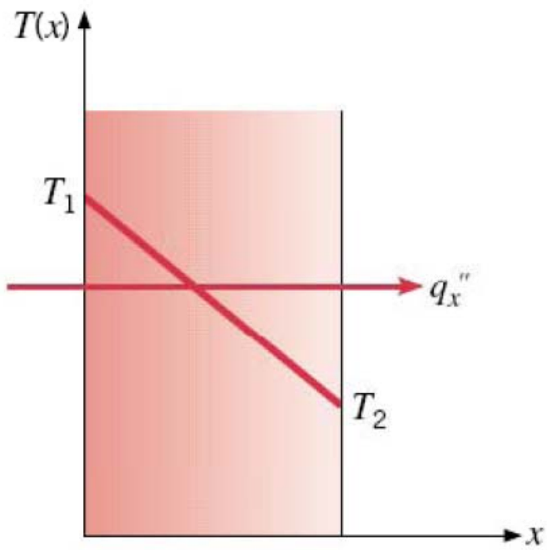
$$\propto \frac{(Area)(Temperature \quad difference)}{Thickness}$$

$$or \qquad \dot{Q} = kA\frac{\Delta T}{\Delta x}$$

- Fourier's law of heat conduction

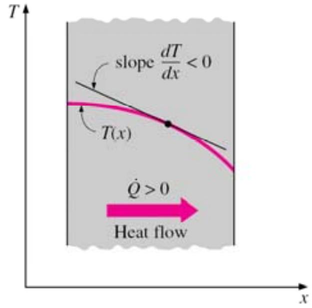
$$\dot{Q}_{cond} = -kA\frac{dT}{dx}$$

k: thermal conductivity



1-2 Conduction (5)

- 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.



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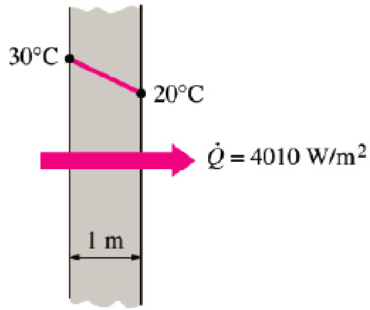
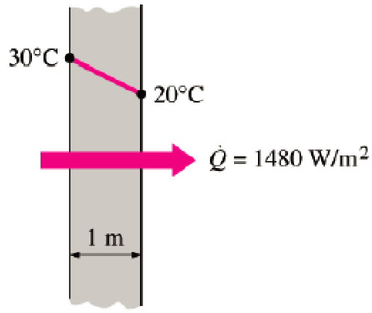
1-2 Conduction (6)

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



(a) Copper (k = 401 W/m·°C)



(b) Silicon (k = 148 W/m·°C)

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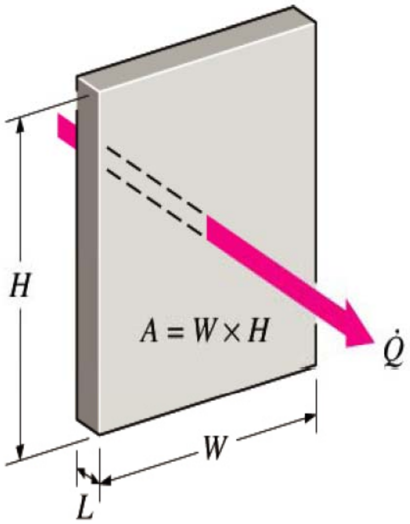
1-2 Conduction (7)

- In heat conduction analysis, *A* represents the area normal to the direction of heat transfer



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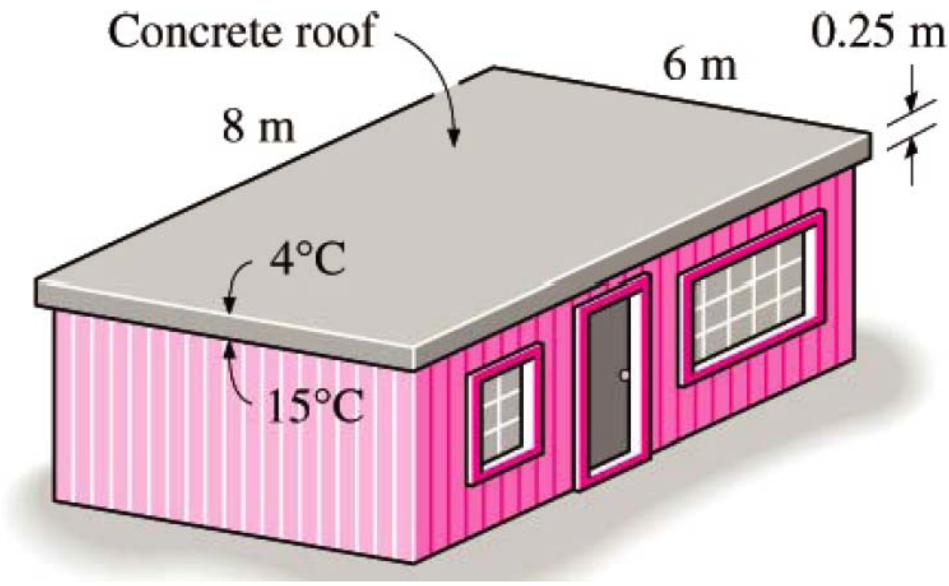
1-2 Conduction (8)

■ Example



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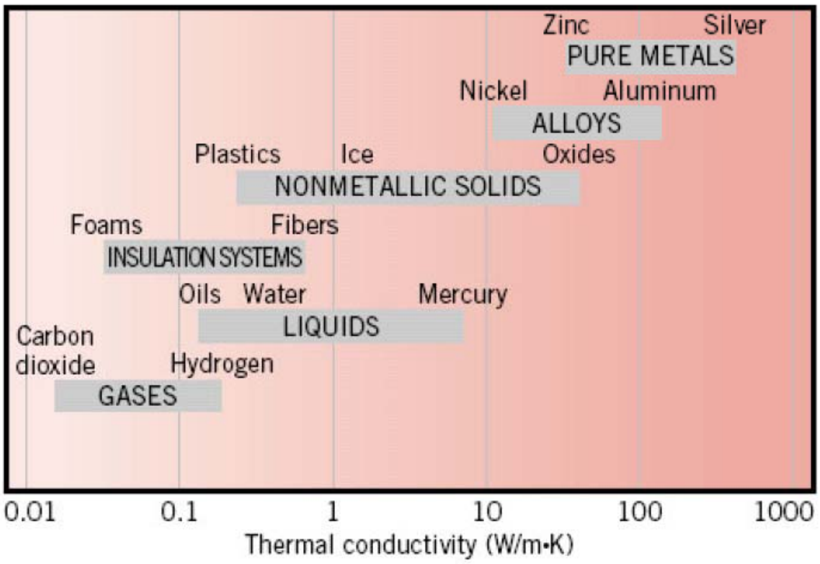
1-2 Conduction (9)

- The range of *k* for various materials at room temperature



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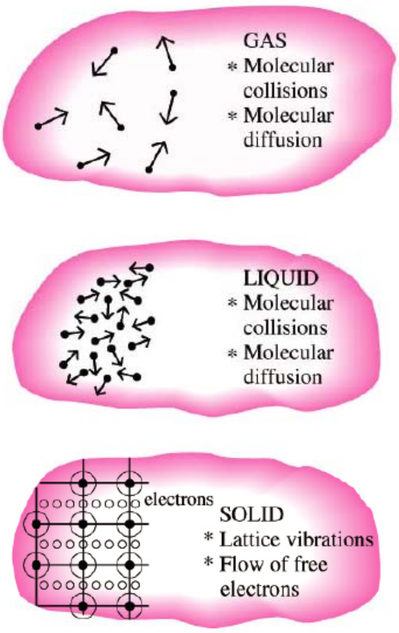
1-2 Conduction (10)

- The mechanism of heat conduction in different phases of a substance



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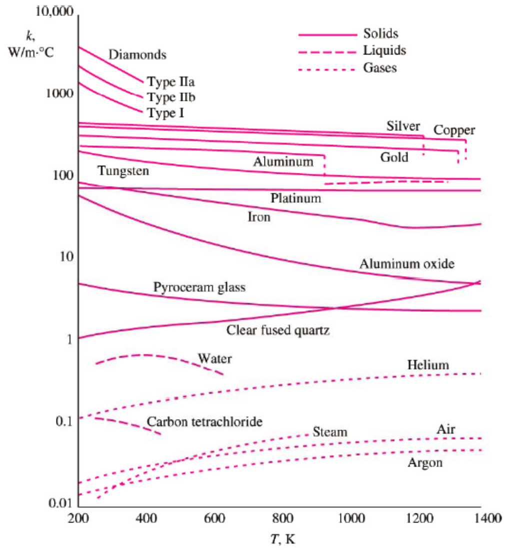
1-2 Conduction (11)

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



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1-2 Conduction (12)

- The thermal conductivity, *k*, is a thermophysical property of the material through which the heat flows and has the units of W/m-℃ or Btu/hr-ft-^{0}F.
- The values of the thermal conductivity for most substances must be obtained experimentally. Usually, $k_{soild}>k_{liq}>k_{gas}$

1-2 Conduction (13)

- Thermal diffusivity:

$$\alpha = \frac{Heat \quad conducted}{Heat \quad stored} = \frac{k}{\rho C_p} \quad (m^2/s) \quad \text{Analog to} \quad \nu = \frac{\mu}{\rho} \quad m^2/s$$

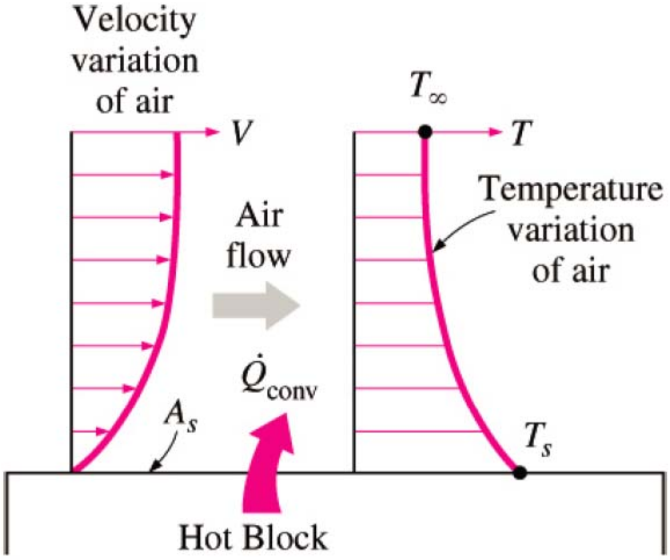
- The larger the thermal diffusivity, the faster the propagation of heat into the medium. A small value of thermal diffusivity means that heat is mostly absorbed by the material and a small amount of heat will be conducted further.

1-3 Convection (1)

- 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.

1-3 Convection (2)

- Heat transfer from a hot surface to air by convection



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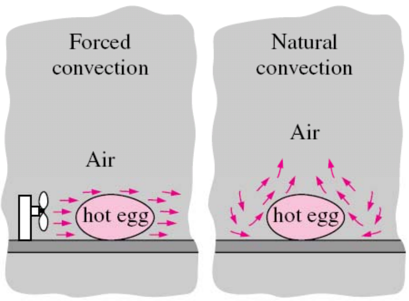
1-3 Convection (3)

- **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.)



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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.

1-3 Convection (5)

- 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)

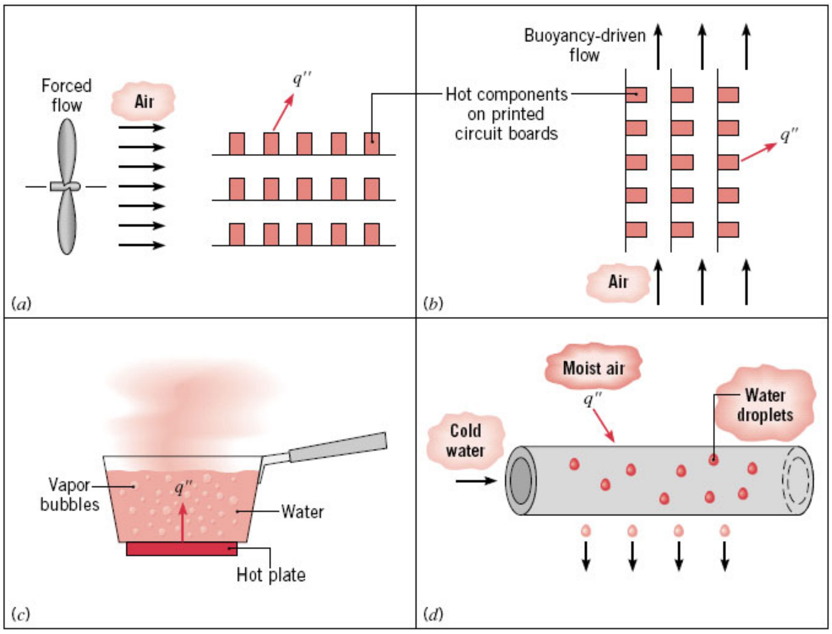

FIGURE 1.5 Convection heat transfer processes. (a) Forced convection. (b) Natural convection. (c) Boiling. (d) Condensation.

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1-3 Convection (7)

- Newton's law of cooling: $\dot{Q}_{conv} = hA(T_s - T_\infty)$

  h: convection heat transfer coefficient (W/m^2•^{0}C)

  T_s:surface temperature

  T_∞: the temperature of the fluid sufficiently far from the surface

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1-3 Convection (8)

- *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.

1-3 Convection (9)

TABLE 1.1 Typical values of the convection heat transfer coefficient

Process	h ($W/m^2 \cdot K$)
Free convection	
Gases	2–25
Liquids	50–1000
Forced convection	
Gases	25–250
Liquids	100–20,000
Convection with phase change	
Boiling or condensation	2500–100,000

1-25

1-4 Radiation (1)

- 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.

1-4 Radiation (2)

- 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.

1-4 Radiation (3)

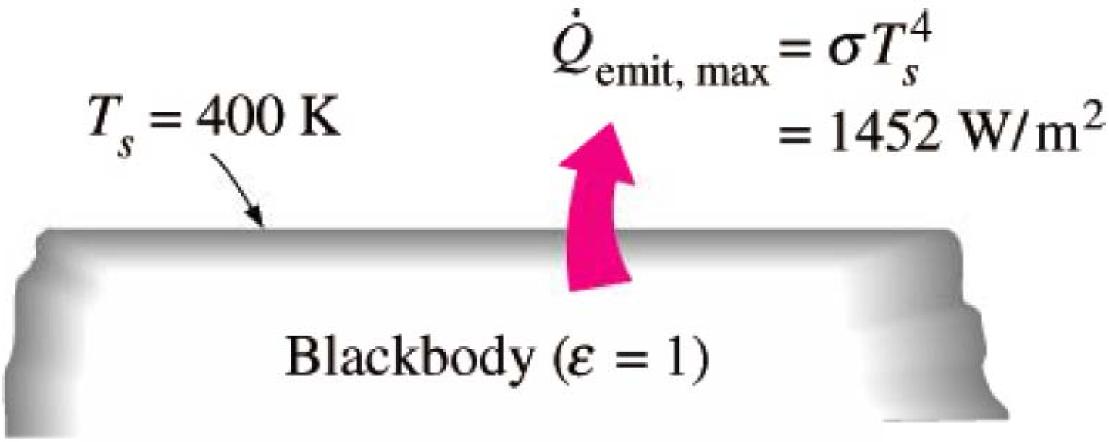
- Stefan-Boltzmann law: the maximum rate of radiation that can be emitted from a surface at an absolute temperature T_s is given by

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

σ: Stefan-Boltzmann constant=5.67x10^{-8} W/m^2•K^4

1-4 Radiation (4)

- Blackbody radiation:



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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

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

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

ε=1 for blackbody

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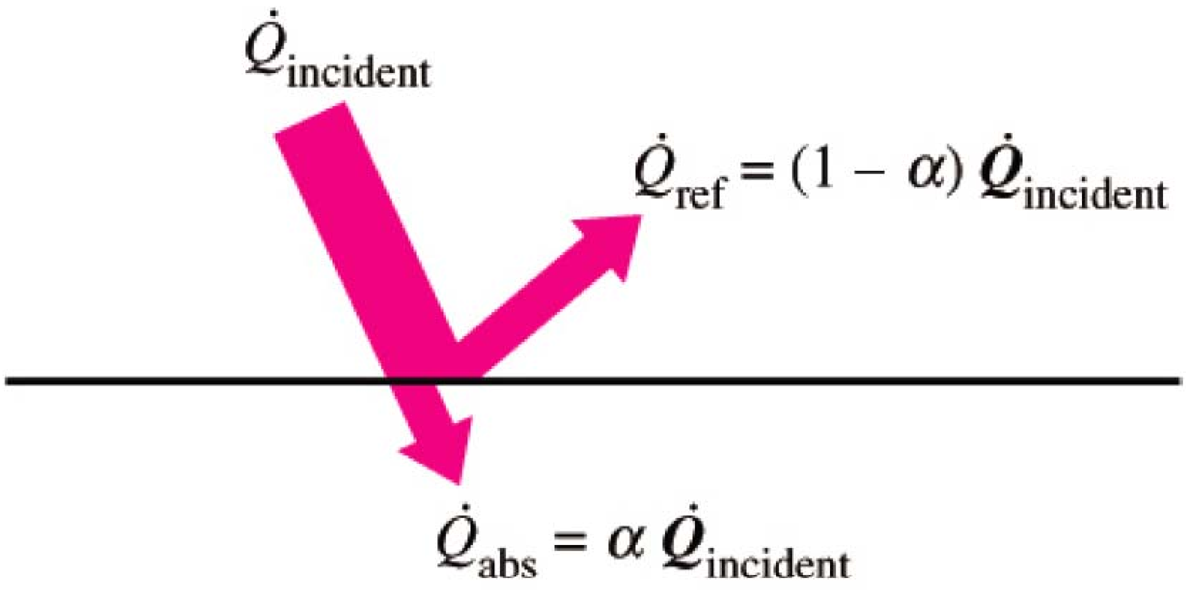
1-4 Radiation (6)

- Absorptivity, α: the fraction of the radiation energy incident on a surface that is absorbed by the surface. $0 \le \alpha \le 1$
- A blackbody absorbs the entire radiation incident on it, i.e., α=1.

1-4 Radiation (7)

- The absorption of radiation incident on an



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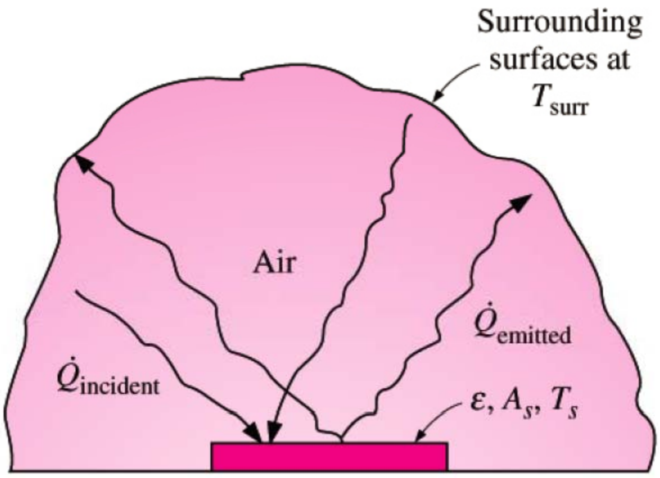
1-4 Radiation (8)

- Kirchhoff's law: ε and α of a surface are equal at the same temperature and wavelength.
- In most practical application, the dependence of ε and α on the temperature and wavelength is ignored, and the average absorptivity of a surface is taken to be equal to its average emissivity.

1-4 Radiation (9)

- Radiation heat transfer between a surface and the surfaces surrounding it.



$$\dot{Q}_{rad} = \varepsilon\sigma A_s(T_s^4 - T_{surr}^4)$$

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1-4 Radiation (10)

- Combined heat transfer coefficient:

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

$$h_{combined} = h + \varepsilon\sigma(T_s^2 + T_\infty^2)(T_s + T_\infty)$$

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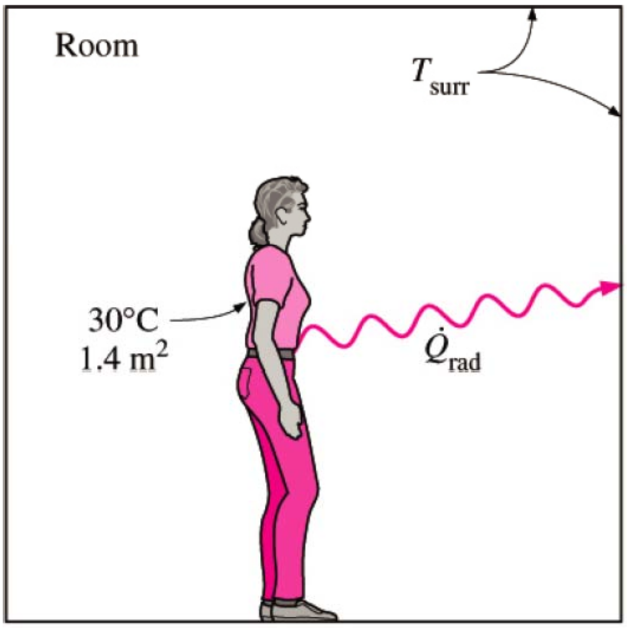
1-4 Radiation (11)

- Example



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1-5 Simultaneous Heat Transfer Mechanism (1)

- Although there are three mechanisms of heat transfer, a medium may involve only two of them simultaneously.

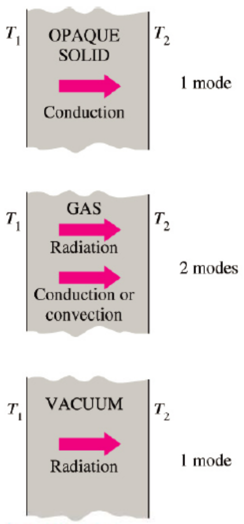
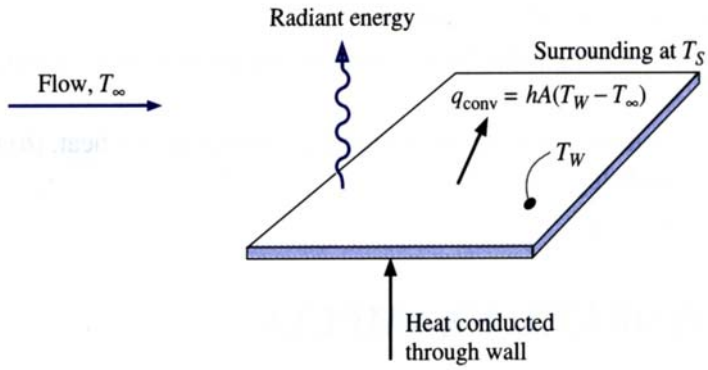


Figure 1-9 | Combination of conduction, convection, and radiation heat transfer.



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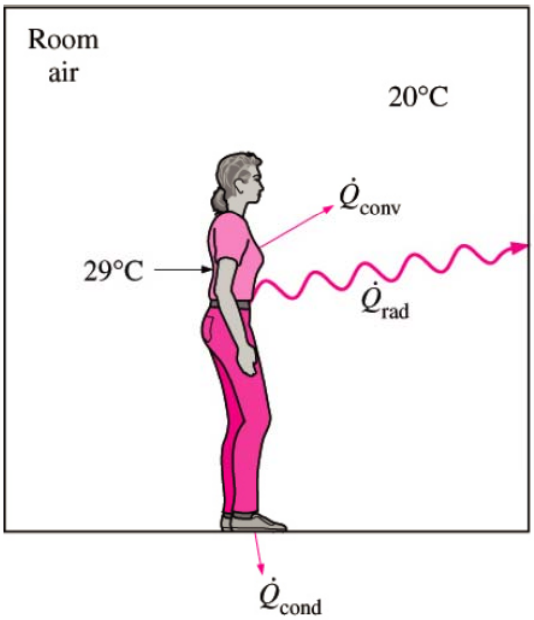
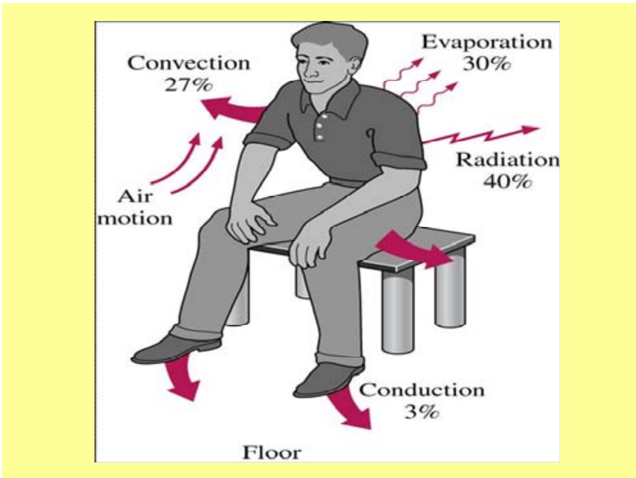
1-5 Simultaneous Heat Transfer Mechanism (2)

- Example





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1-6 Applications of Heat Transfer (1)

The human body

Air conditioning systems

Airplanes

Car radiators

Power plants

Refrigeration systems

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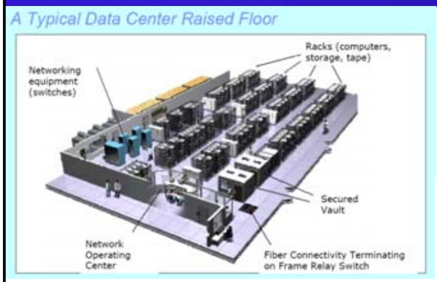
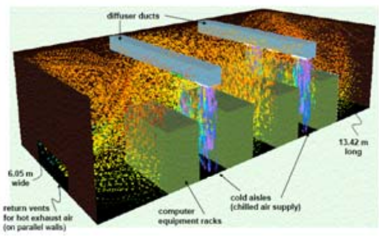
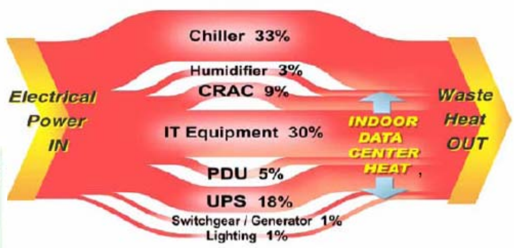
1-6 Applications of Heat Transfer (2)
Data Centers-1

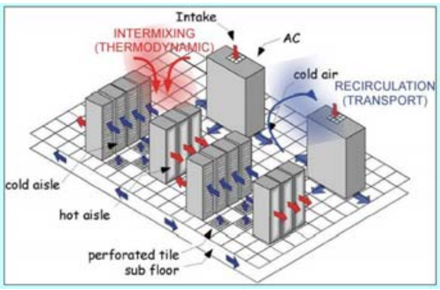


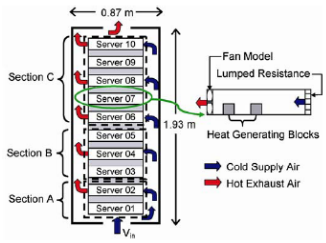




Brouillard, APC, 2006

Future datacenters dominated by energy cost; half energy spent on cooling





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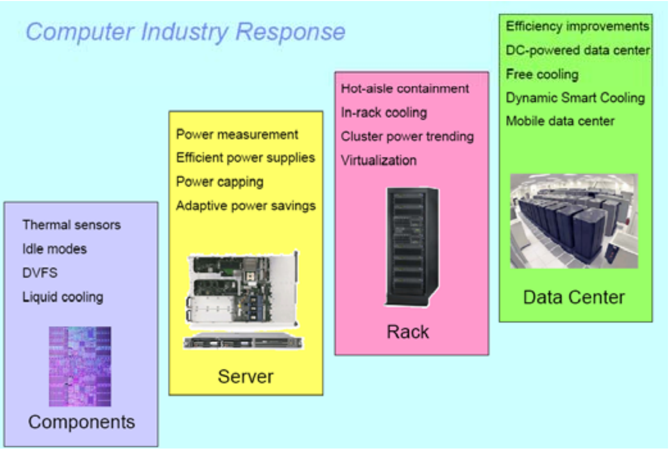
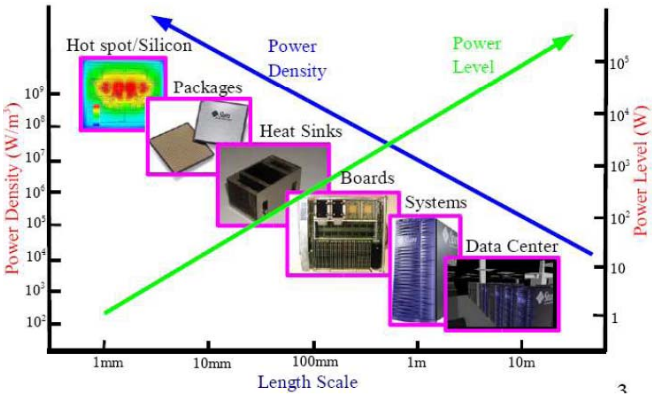
1-6 Applications of Heat Transfer (3)
Data Centers-2





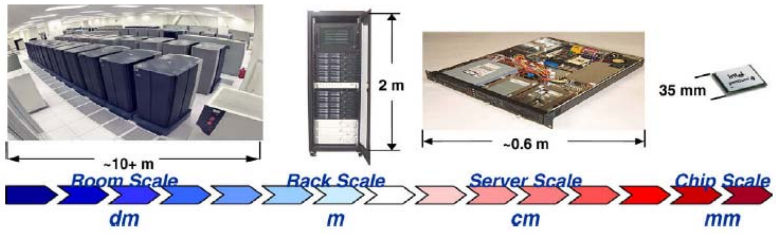
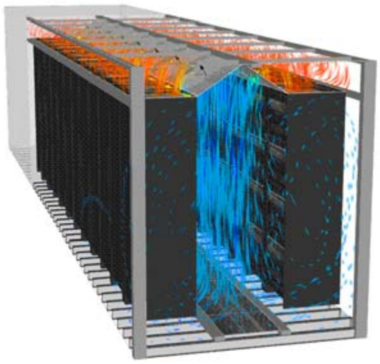


Fig. 1. Typical data center and its multi-scale nature.



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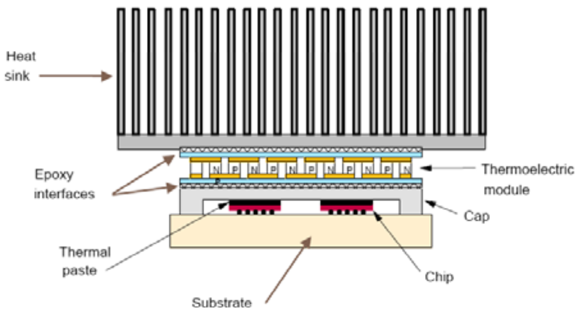
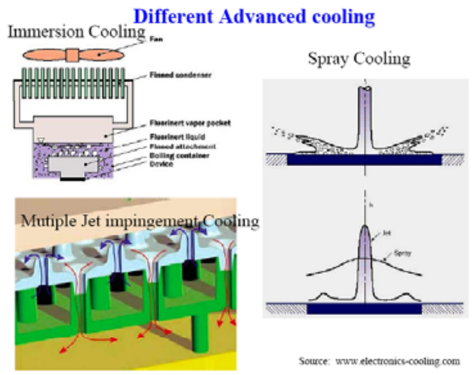
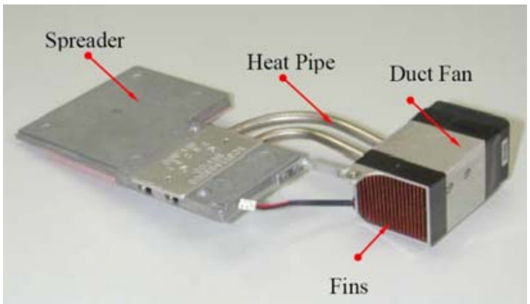
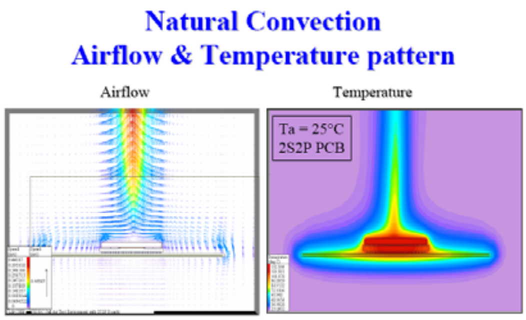
1-6 Applications of Heat Transfer (4) Electronic Cooling









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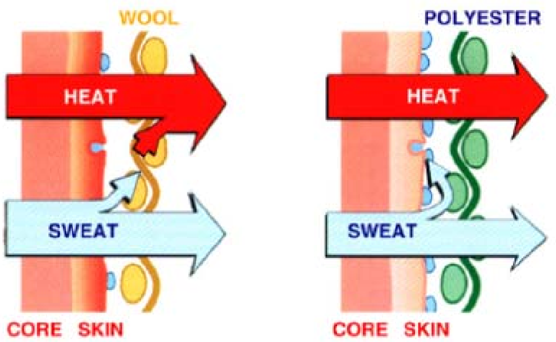
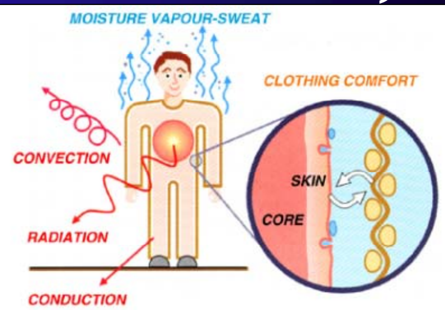
1-6 Applications of Heat Transfer (5)
Human Body-Clothing-Environment, HCE





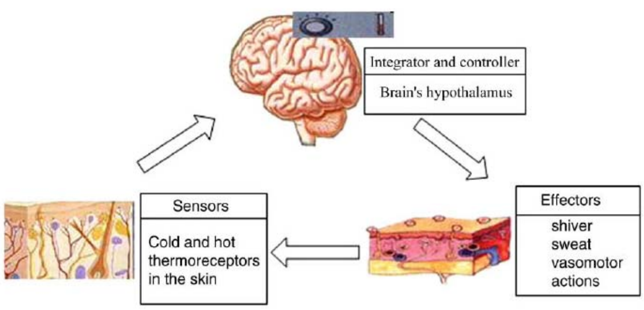


Fig. 4. The human body thermoregulation system.

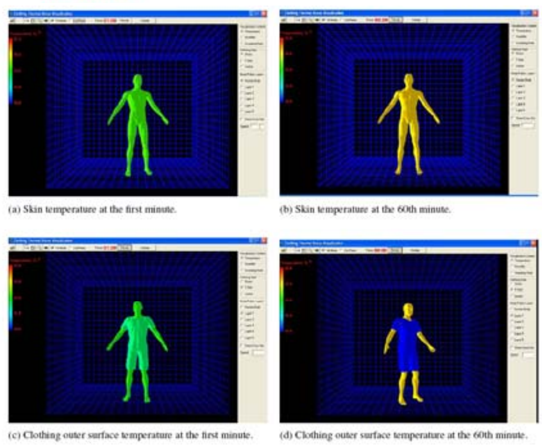


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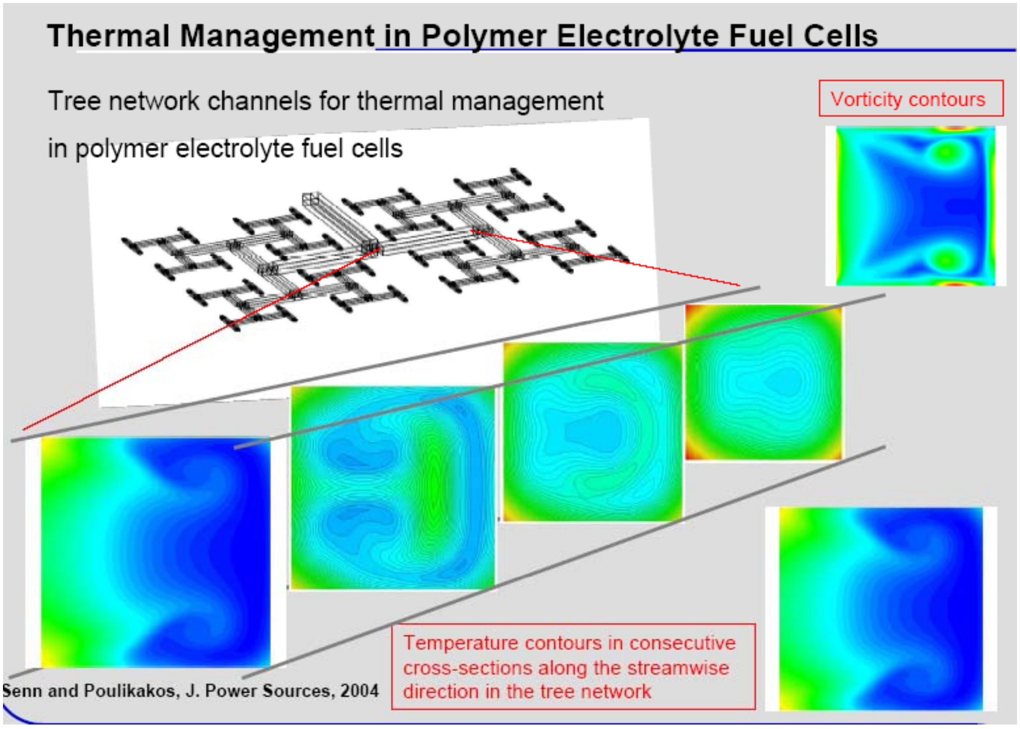
Fig. 17. 4 Snapshots of 3D temperature visualization in a thermal virtual space.

1-6 Applications of Heat Transfer (6)
Fuel Cell



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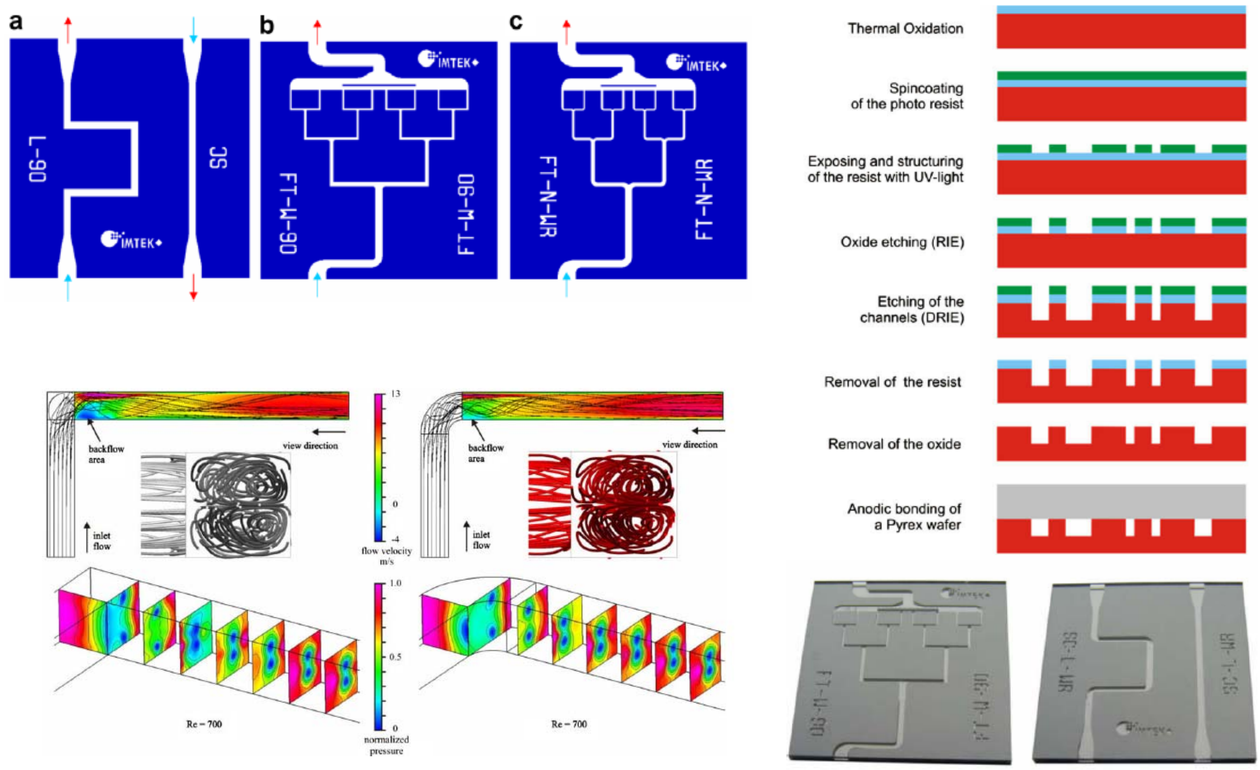
1-6 Applications of Heat Transfer (7)
Microchannel



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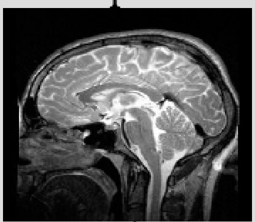
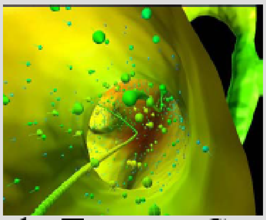
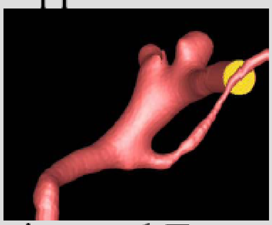
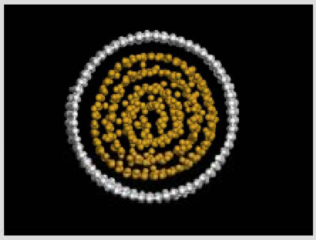
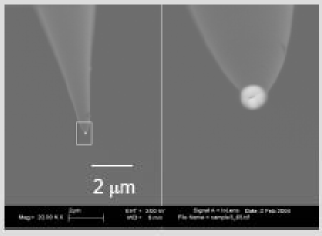
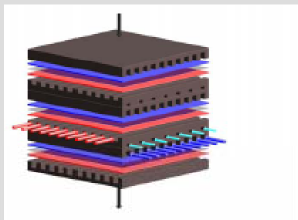
1-6 Applications of Heat Transfer (8)
Micro- and Nanoscale Heat Transfer

- Bio- Trasport Phenomena for Medical Applications

- Micro- and Nanosclale Energy Conversion and Transport including Physics at the Molecular level



1-6 Applications of Heat Transfer (9)
Indoor Airflow

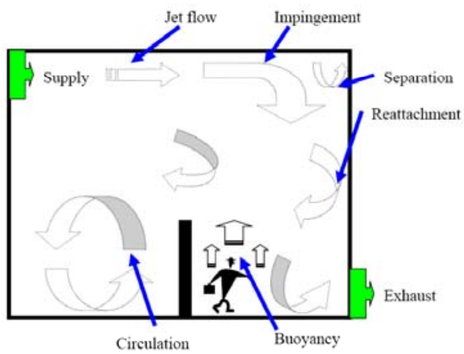


Figure 1. Typical flow characteristics in an enclosed environment with various flow mechanisms.

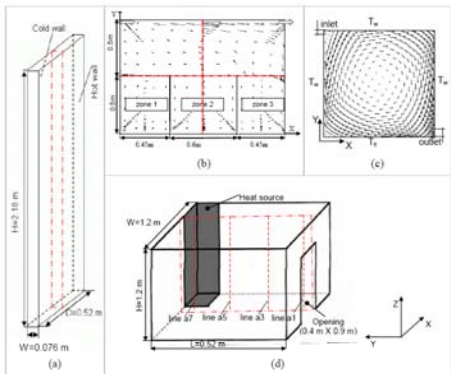
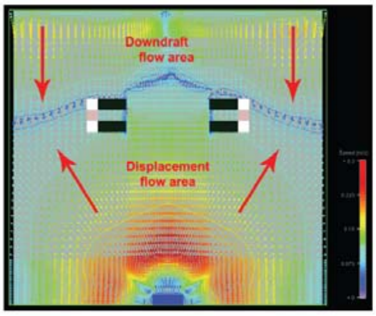
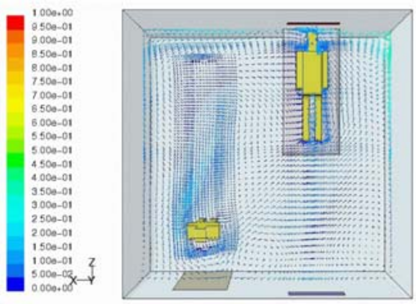


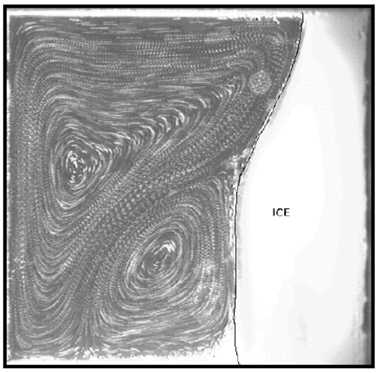
Figure 1. Sketches of the four cases tested: a) natural convection in a tall cavity (Betts and Bokhari, 2000); b) forced convection in a room with partitions (Ito et al., 2000); c) mixed convection in a square cavity (Blay et al., 1992); d) strong buoyant flow in a fire room (Murakami et al., 1995).

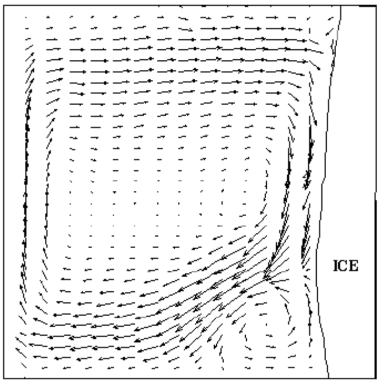


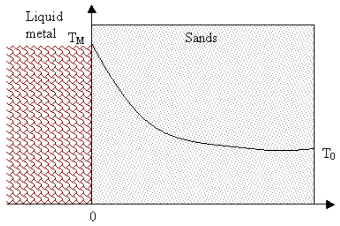


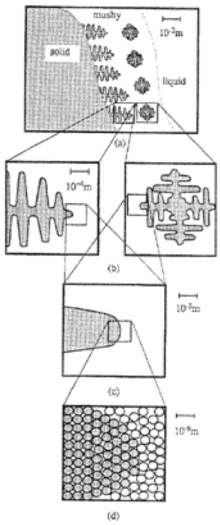
1-47

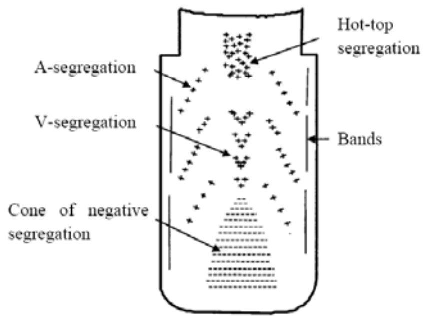
1-6 Applications of Heat Transfer (10)
Phase Change---Solidification/Melting

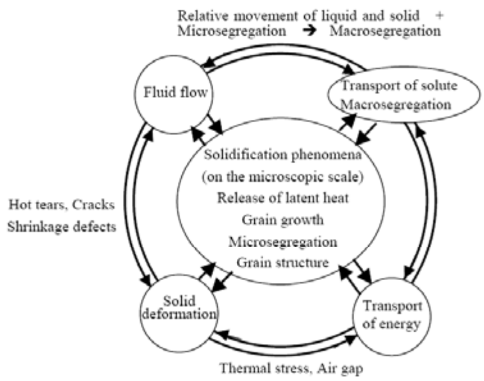












1-48

1-7 Conservation of Energy (1)

- The **first law of thermodynamics** states that *energy can neither be created nor destroyed during a process; it can only change forms.*

(Total energy entering the system) - (Total energy leaving the system) = (Change in the total energy of the system)

- The **energy balance** for any system undergoing any process can be expressed as (in the rate form)

$$\dot{E}_{in} - \dot{E}_{out} = dE_{system}/dt \quad \text{(W)}$$

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

Rate of change in internal kinetic, potential, etc., energies

1-49

1-7 Conservation of Energy (2)

- 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

$$Q_{in} - Q_{out} \quad + \quad E_{gen} = \quad \Delta E_{thermal,system} \qquad \text{(J)}$$

Net heat transfer — Heat generation — Change in thermal energy of the system

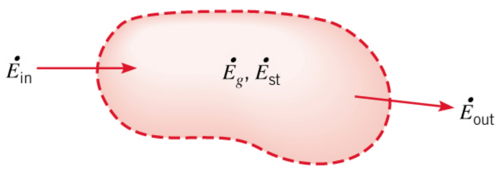
1-7 Conservation of Energy (3)

■ Application to a Control Volume

- At an Instant of Time:

Surface Phenomena $\dot{E}_{in}, \dot{E}_{out}$

Volumetric Phenomena $\dot{E}_{g}, \dot{E}_{st}$



$\dot{E}_{in}, \dot{E}_{out}$: rate of thermal and/or mechanical energy transfer across the control surface due to heat transfer, fluid flow and/or work interactions.

$\dot{E}_{g}$: rate of thermal energy generation due to conversion from another enegy form (e.g., electrical, nuclear, or chemical); energy conversion process occurs within the system.

$\dot{E}_{st}$: rate of change of energy storage in the system.

$$\dot{E}_{in} - \dot{E}_{out} + \dot{E}_{g} = \dot{E}_{st} = \frac{dE_{st}}{dt}$$ --- Energy Conservation

Each term has units of J/s or W.

- Over a Time Interval

$$E_{in} - E_{out} + E_{g} = E_{st}$$

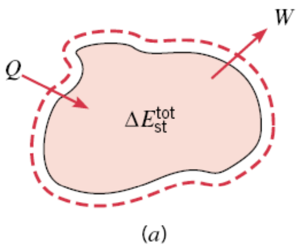
Each term has units of J.

1-51

1-7 Conservation of Energy (4)

- Special Case (1): Closed System

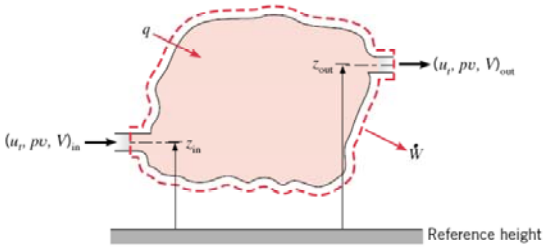
Transient Process for a Closed System of Mass *(M) Assuming Heat Transfer to the System (Inflow) and Work Done by the System (Outflow).*



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

- Special Case (2): Control Volume

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



$$\dot{Q} + \dot{m}(h_i + \frac{V_i^2}{2} + gz_i) - W - \dot{m}(h_e + \frac{V_e^2}{2} + gz_e) = 0$$

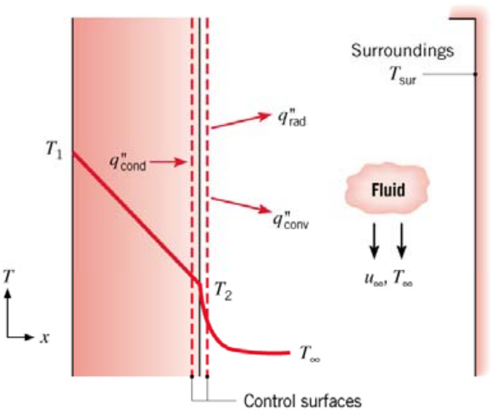
1-52

1-7 Conservation of Energy (5)

- 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.



$$\dot{E}_{in} - \dot{E}_{out} = 0$$

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

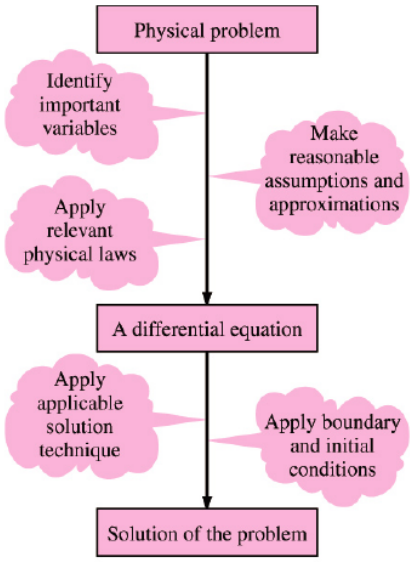
$$q''_{cond} - q''_{conv} - q''_{rad} = 0$$

$$k\frac{T_1 - T_2}{L} - h(T_2 - T_\infty) - \varepsilon\sigma(T_2^4 - T_{sur}^4) = 0$$

1-53

1-8 Problem Solving Technique

- Step1: ***Problem Statement***
  Step2: ***Schematic***
  Step3: ***Assumptions***
  Step4: ***Physical Laws***
  Step5: ***Properties***
  Step6: ***Calculations***
  Step7: ***Reasoning,Verification,and Discussion***



1-54