CHAPTER 1
INTRODUCTION AND BASIC CONCEPTS

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Objectives

- Understand how thermodynamics and heat transfer are related to each other,

- Perform general energy balances as well as surface energy balances,

- Understand the basic mechanisms of heat transfer, which are conduction, convection, and radiation, and Fourier's law of heat conduction, Newton's law of cooling, and the Stefan–Boltzmann law of radiation

- Identify the mechanisms of heat transfer that occur simultaneously in practice

- Develop an awareness of the cost associated with heat losses

- Solve various heat transfer problems encountered in practice

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INTRODUCTION

Heat: The form of energy that can be transferred from one system to another as a result of temperature difference.

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 two mediums reach the same temperature.

Thermos bottle

Hot coffee

Insulation
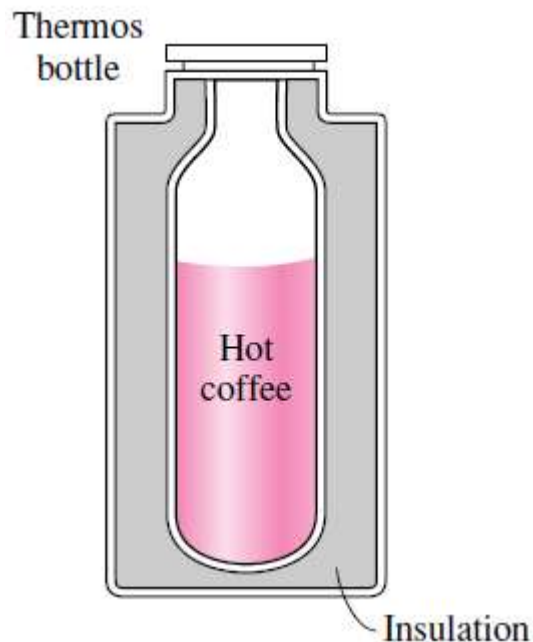
We are normally interested in how long it takes for the hot coffee in a thermos bottle to cool to a certain temperature, which cannot be determined from a thermodynamic analysis alone.

Thermodynamics concerned with the *amount* of heat transfer as a system undergoes a process from one equilibrium state to another, and makes no reference to how long the process will take.

Thermodynamics deals with equilibrium states and changes from one equilibrium state to another. Heat transfer deals with systems that lack thermal equilibrium, and thus it is a nonequilibrium phenomenon

Cool environment 20°C

Hot coffee 70°C
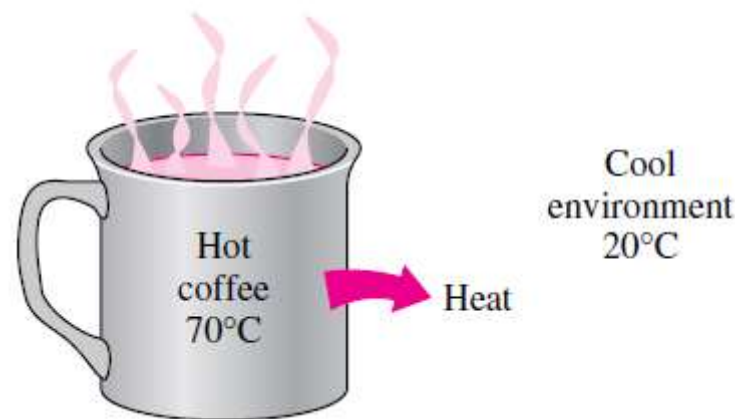
Heat

Heat flows in the direction of decreasing temperature.
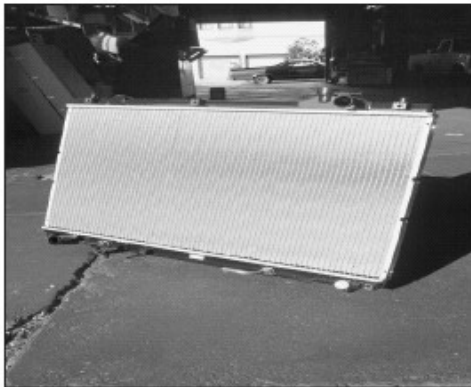
APPLİCATİON AREAS OF HEAT TRANSFER

The human body

Air conditioning systems

Airplanes

Car radiators

Power plants

Refrigeration systems

HEAT AND OTHER FORMS OF ENERGY

Energy can exist in numerous forms such as thermal, mechanical, kinetic, potential, electric, magnetic, chemical, and nuclear, and their sum constitutes the **total energy, *E*** of a system.

Thermodynamics deals only with the *change* of the total energy.

Macroscopic forms of energy: Those a system possesses as a whole with respect to some outside reference frame, such as kinetic and potential energies.

Microscopic forms of energy: Those related to the molecular structure of a system and the degree of the molecular activity.

Internal energy, *U*: The sum of all the microscopic forms of energy.

•**Kinetic energy, KE:** The energy that a system possesses as a result of its motion relative to some reference frame.

•**Potential energy, PE:** The energy that a system possesses as a result of its elevation in a gravitational field.

The macroscopic energy of an object changes with velocity and elevation.

SOME PHYSİCAL INSİGHT TO INTERNAL ENERGY

Sensible energy: The portion of the internal energy of a system associated with the kinetic energies of the molecules.

Latent energy: The internal energy associated with the phase of a system.

Chemical energy: The internal energy associated with the atomic bonds in a molecule.

Nuclear energy: The tremendous amount of energy associated with the strong bonds within the nucleus of the atom itself.
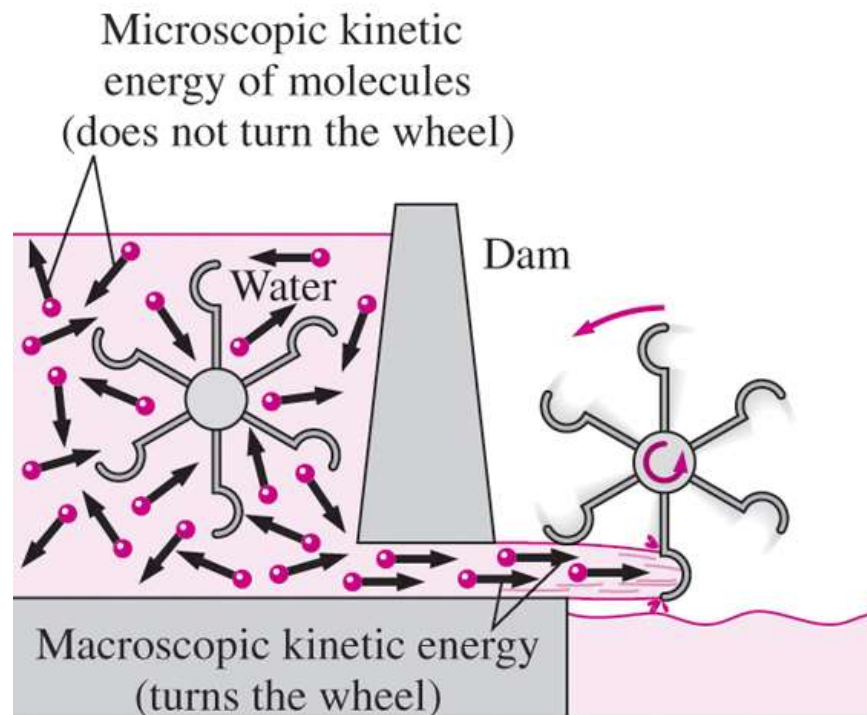
Thermal = Sensible + Latent

Internal = Sensible + Latent + Chemical + Nuclear

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The total energy of a system, can be *contained* or *stored* in a system, and thus can be viewed as the *static* forms of energy.

The forms of energy not stored in a system can be viewed as the *dynamic forms of energy* or as *energy interactions*.

The dynamic forms of energy are recognized at the system boundary as they cross it, and they represent the energy gained or lost by a system during a process.

Microscopic kinetic
energy of molecules
(does not turn the wheel)

Dam

Water

Macroscopic kinetic energy
(turns the wheel)

The *macroscopic* kinetic energy is an organized form of energy and is much more useful than the disorganized *microscopic* kinetic energies of the molecules.

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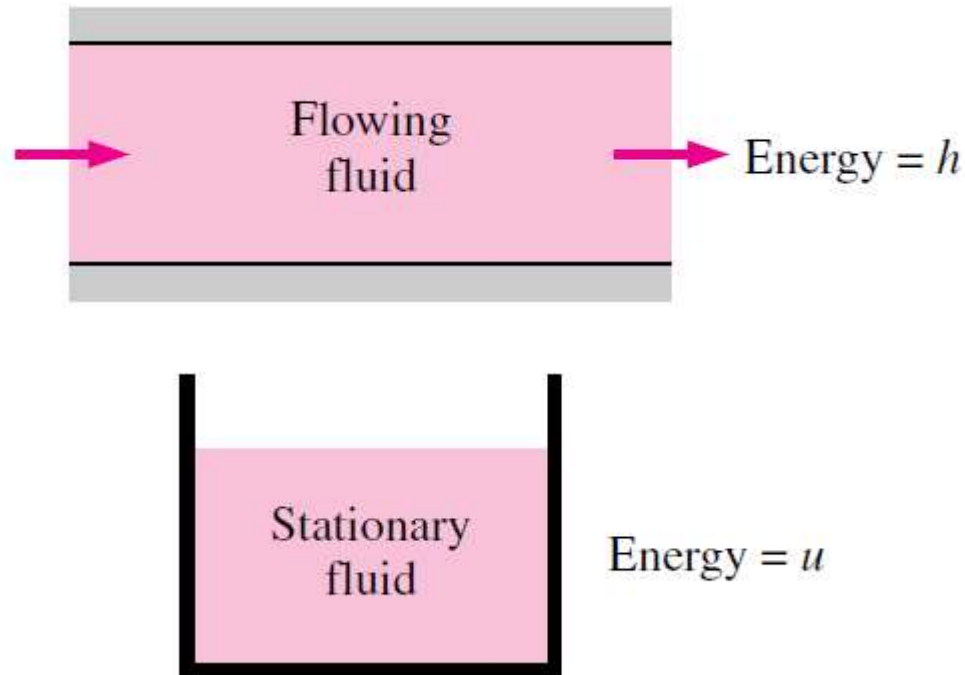
The *internal energy u* represents the microscopic energy of a nonflowing fluid, whereas *enthalpy h* represents the microscopic energy of a flowing fluid.

In the analysis of systems that involve fluid flow, we frequently encounter the combination of properties u and Pv. For the sake of simplicity and convenience, this combination is defined as **enthalpy** h.

$h=u+Pv$ where the term Pv represents the *flow energy* of the fluid (also called the *flow work*), which is the energy needed to push a fluid and to maintain flow.

Specific Heats of Gases, Liquids, and Solids

ideal gas

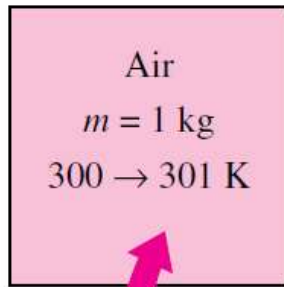$$P\mathrm{v} = RT \quad \text{or} \quad P = \rho RT$$

specific heat

$$m = 1\ \text{kg}$$
$$\Delta T = 1^\circ C$$
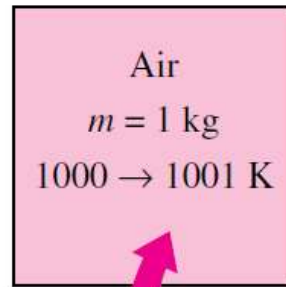$$\text{Specific heat} = 5\ \text{kJ/kg·K}$$

5 kJ

Specific heat is the energy required to raise the temperature of a unit mass of a substance by one degree in a specified way.

C_v : Specific heat at constant volume
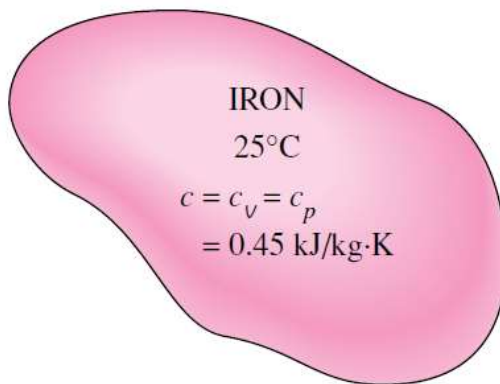C_p : Specific heat at constant pressure.

Air
m = 1 kg
300 → 301 K

0.718 kJ

Air
m = 1 kg
1000 → 1001 K

0.855 kJ

The specific heat of a substance changes with temperature.

$$du = c_v\, dT \quad \text{and} \quad dh = c_p\, dT$$

$$\Delta u = c_{v,\,avg}\Delta T \quad \text{and} \quad \Delta h = c_{p,\,avg}\Delta T \qquad (\text{J/g})$$

$$\Delta U = mc_{v,\,avg}\Delta T \quad \text{and} \quad \Delta H = mc_{p,\,avg}\Delta T \qquad (\text{J})$$

IRON
25°C
$c = c_v = c_p$
$= 0.45$ kJ/kg·K

the change in the internal energy of **solids and liquids** can be expressed as

The c_v and c_p values of incompressible substances are identical.

$$\Delta U = mc_{avg}\Delta T \qquad (\text{J})$$

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HEAT TRANSFER

The basic **requirement for heat transfer** is the presence of a **temperature difference**.

The second law requires that **heat be transferred** in the direction of **decreasing temperature**.

The **temperature difference** is the **driving force** for heat transfer.

The rate of **heat transfer** in a certain direction depends on the **magnitude of the temperature gradient** in that direction.

The **larger** the temperature **gradient**, the **higher** the rate of **heat transfer**.

ENERGY TRANSFER

Energy can be transferred to or from a given mass by two mechanisms:

- heat transfer
- Work

Q : The amount of heat transferred during a process

$\dot{Q}$: **The amount of heat transferred per unit time called heat transfer rate**

The total amount of heat transfer Q

$$Q = \int_0^{\Delta t} \dot{Q}\, dt$$

The rate of heat transfer per unit area normal to the direction of heat transfer is called heat flux, and the average heat flux is expressed as

THE FİRST LAW OF THERMODYNAMİCS

The *first law of thermodynamics* (*the conservation of energy principle*) provides a sound basis for studying the relationships among the various forms of energy and energy interactions.

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

The *First Law:* For all adiabatic processes between two specified states of a closed system, the net work done is the same regardless of the nature of the closed system and the details of the process.

$$\left(\begin{array}{c} \text{Total energy} \\ \text{entering the system} \end{array} \right) - \left(\begin{array}{c} \text{Total energy} \\ \text{leaving the system} \end{array} \right) = \left(\begin{array}{c} \text{Change in the total} \\ \text{energy of the system} \end{array} \right)$$

$$\boxed{E_{\text{in}} - E_{\text{out}} = \Delta E_{\text{system}}}$$

ENERGY CHANGE OF A SYSTEM, ΔE_{SYSTEM}

Energy change = Energy at final state − Energy at initial state

$$\Delta E_{system} = E_{final} - E_{initial} = E_2 - E_1$$

$$\Delta E = \Delta U + \Delta KE + \Delta PE$$

Internal, kinetic, and potential energy changes

$$\Delta U = m(u_2 - u_1)$$

$$\Delta KE = \tfrac{1}{2}m(V_2^2 - V_1^2)$$

$$\Delta PE = mg(z_2 - z_1)$$

Stationary Systems

$$z_1 = z_2 \rightarrow \Delta PE = 0$$

$$V_1 = V_2 \rightarrow \Delta KE = 0$$

$$\Delta E = \Delta U$$

$$E_{in} - E_{out} = (Q_{in} - Q_{out}) + (W_{in} - W_{out}) + (E_{mass,\,in} - E_{mass,\,out}) = \Delta E_{system}$$

$$\underbrace{E_{in} - E_{out}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{system}}_{\substack{\text{Change in internal, kinetic,} \\ \text{potential, etc., energies}}} \quad \text{(kJ)}$$

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{dE_{system}/dt}_{\substack{\text{Rate of change in internal,} \\ \text{kinetic, potential, etc., energies}}} \quad \text{(kW)}$$
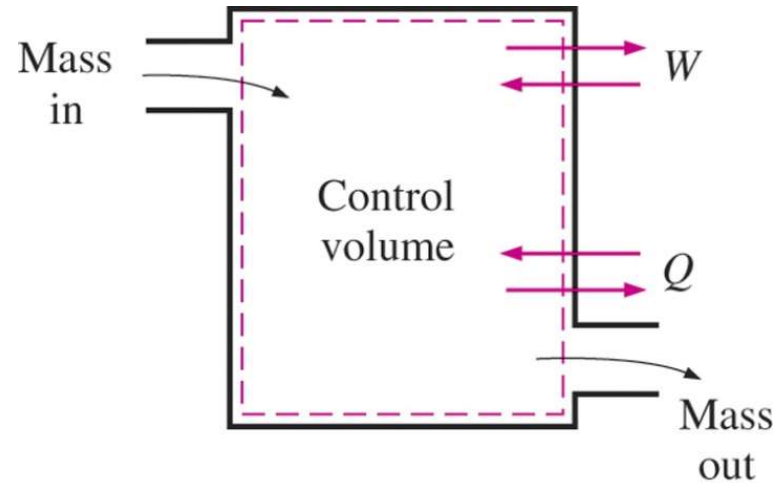
A closed mass involves only *heat transfer* and *work*.

$$Q = \dot{Q}\,\Delta t, \quad W = \dot{W}\,\Delta t, \quad \text{and} \quad \Delta E = (dE/dt)\,\Delta t \qquad \text{(kJ)}$$
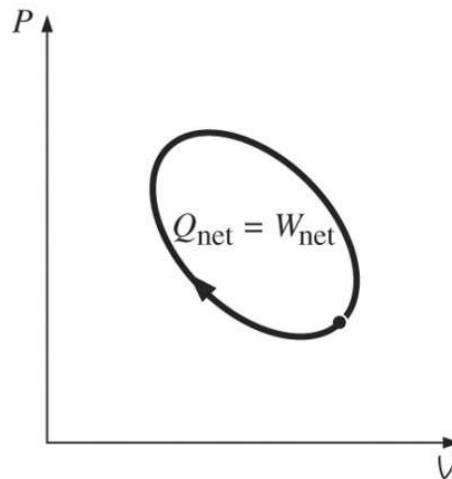
$$e_{in} - e_{out} = \Delta e_{system} \qquad \text{(kJ/kg)}$$

$$\delta E_{in} - \delta E_{out} = dE_{system} \quad \text{or} \quad \delta e_{in} - \delta e_{out} = de_{system}$$

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The energy content of a control volume can be changed by mass flow as well as heat and work interactions.

$$Q_{net} = W_{net}$$

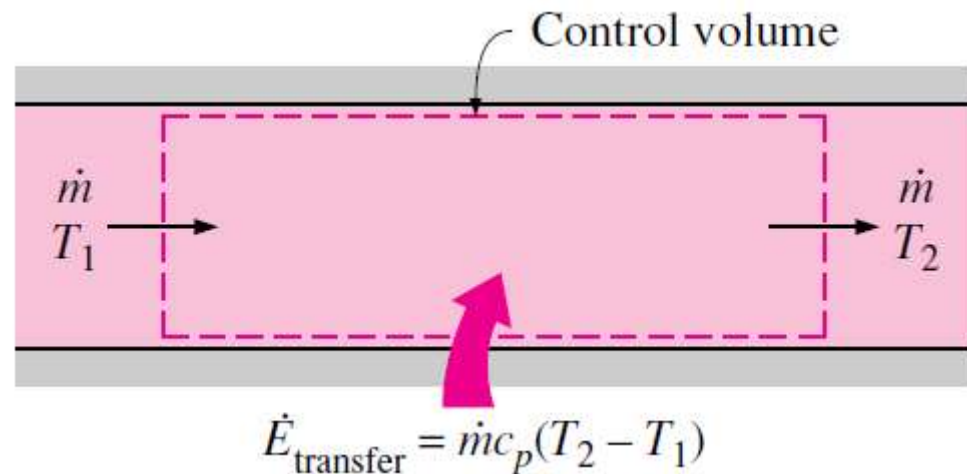**For a cycle $\Delta E = 0$, thus $Q = W$.**

Energy Balance for Steady-Flow Systems

$$\dot{m} = \rho V A_c \qquad (\text{kg/s})$$

$$\dot{V} = V A_c = \frac{\dot{m}}{\rho} \qquad (\text{m}^3/\text{s})$$

$A_c = \pi D^2/4$ for a circular pipe

V
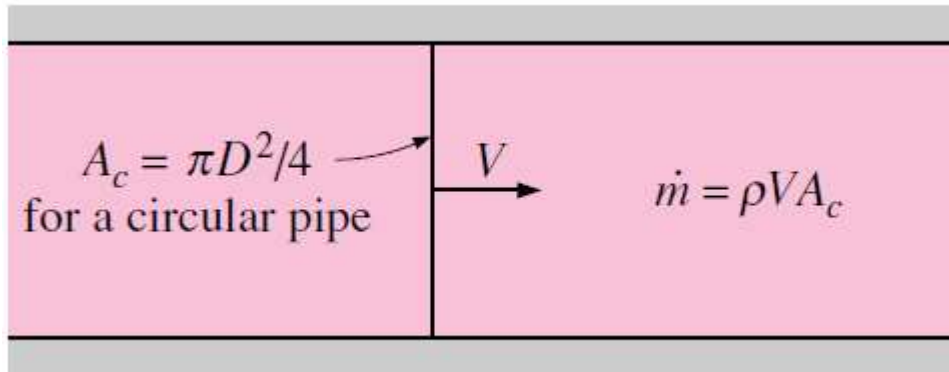
$\dot{m} = \rho V A_c$

Under steady conditions, the net rate of energy transfer to a fluid in a control volume is equal to the rate of increase in the energy of the fluid

$$\dot{Q} = \dot{m}\,\Delta h = \dot{m} c_p \Delta T \qquad (\text{kJ/s})$$

Control volume

$\dot{m}$
T_1

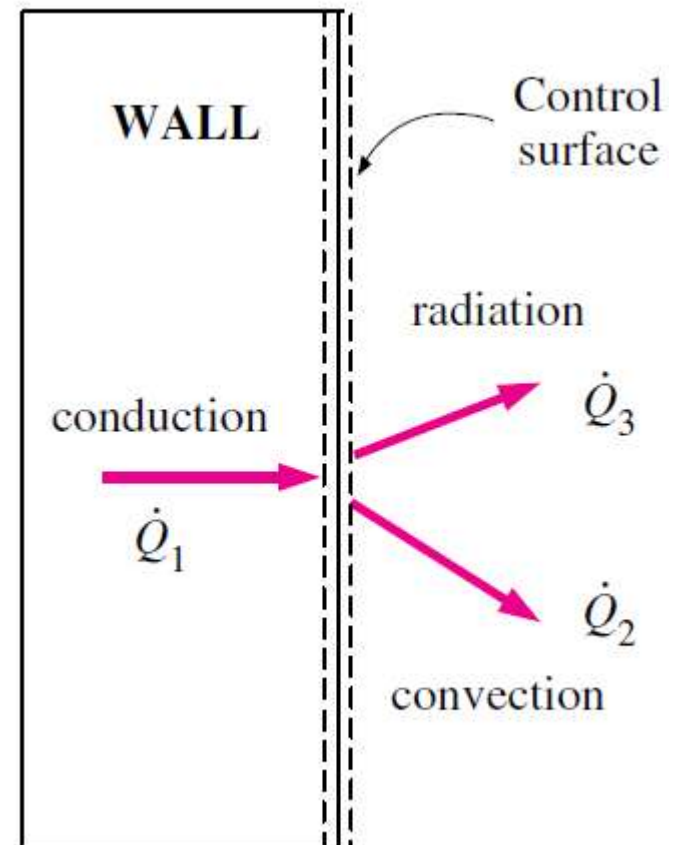$\dot{m}$
T_2

$$\dot{E}_{\text{transfer}} = \dot{m} c_p (T_2 - T_1)$$

Surface Energy Balance

Energy interactions at the outer wall surface of a house.

Surface energy balance:

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

$$\dot{Q}_1 = \dot{Q}_2 + \dot{Q}_3$$

CONDUCTION

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*.

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.

$$\text{Rate of heat conduction} \propto \frac{(\text{Area})(\text{Temperature difference})}{\text{Thickness}}$$

$$\dot{Q}_{cond} = kA\frac{T_1 - T_2}{\Delta x} = -kA\frac{\Delta T}{\Delta x} \qquad (\text{W})$$
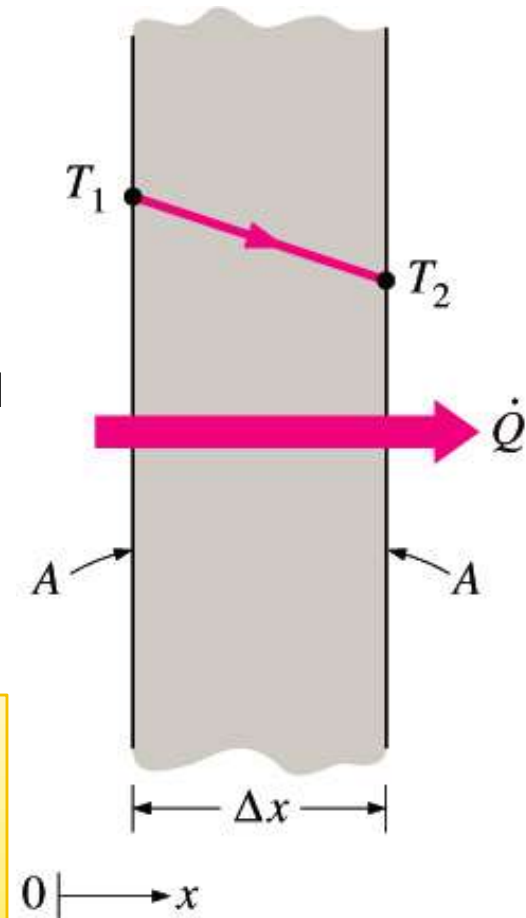
Fourier's law of heat Conduction

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

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.

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.

30°C

20°C

$\dot{Q} = 4010 \text{ W/m}^2$

1 m

(a) Copper ($k = 401$ W/m·°C)

30°C

20°C

$\dot{Q} = 1480 \text{ W/m}^2$

1 m
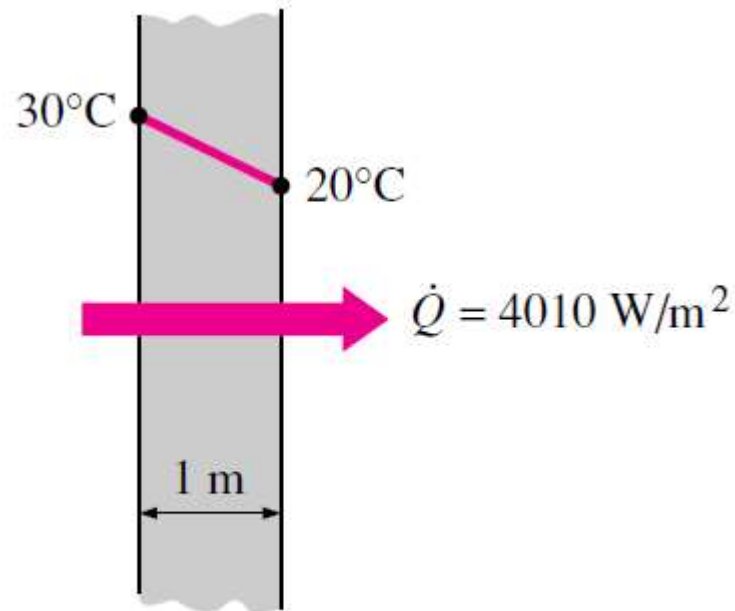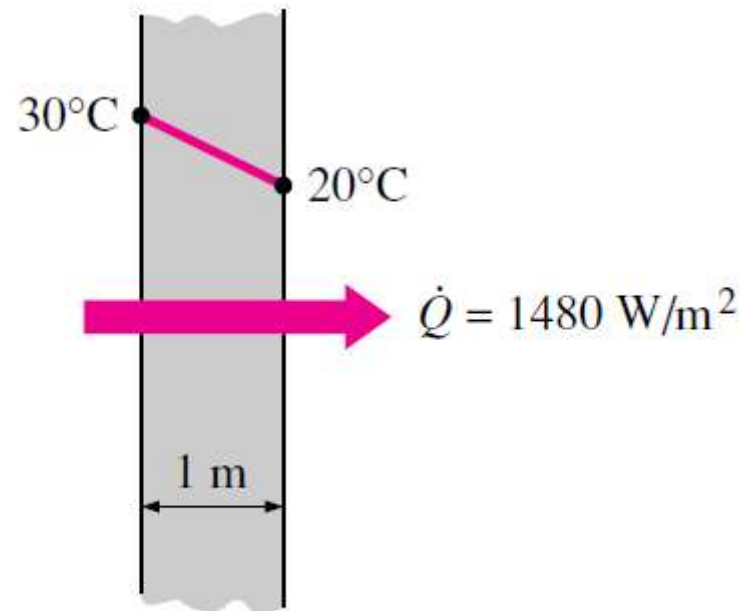
(b) Silicon ($k = 148$ W/m·°C)

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.

H

$A = W \times H$

$\dot{Q}$

W

L
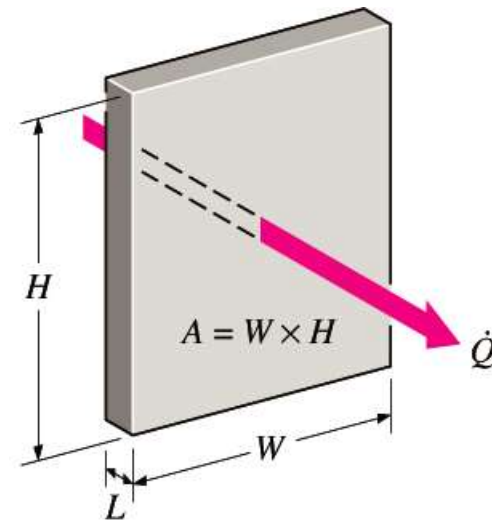
Thermal Conductivity

k (W/m.ºC)

The rate of heat transfer through a unit thickness of the material per unit area per unit temperature difference.

$$k = 0.607 \text{ W/m} \cdot {}^{\circ}\text{C for water}$$

$$k = 80.2 \text{ W/m} \cdot {}^{\circ}\text{C for iron}$$

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.*

TABLE 1–1

The thermal conductivities of some materials at room temperature

Material	k, W/m · °C
Diamond	2300
Silver	429
Copper	401
Gold	317
Aluminum	237
Iron	80.2
Mercury (l)	8.54
Glass	0.78
Brick	0.72
Water (l)	0.607
Human skin	0.37
Wood (oak)	0.17
Helium (g)	0.152
Soft rubber	0.13
Glass fiber	0.043
Air (g)	0.026
Urethane, rigid foam	0.026
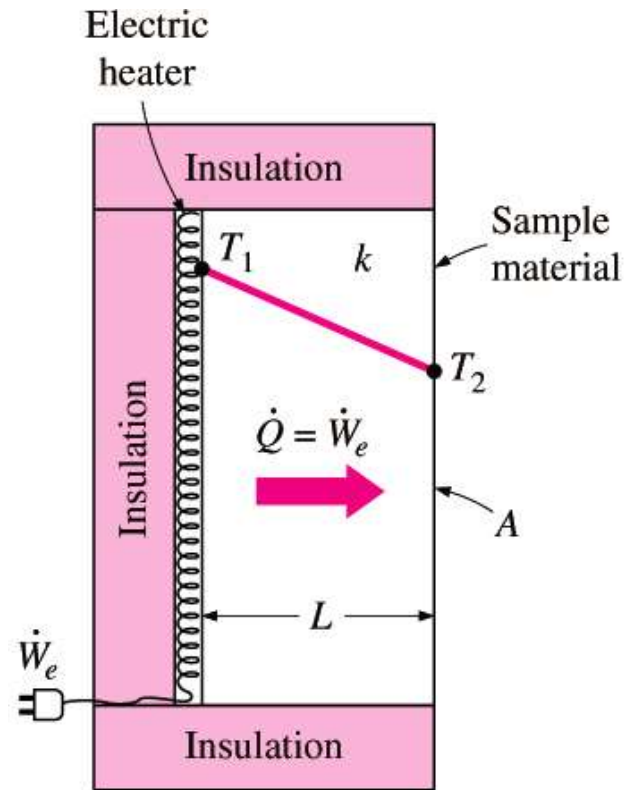
A simple experimental setup to determine the thermal conductivity of a material.

$$k = \frac{L}{A(T_1 - T_2)} \dot{Q}$$

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.

GAS
* Molecular collisions
* Molecular diffusion

LIQUID
* Molecular collisions
* Molecular diffusion

electrons
SOLID
* Lattice vibrations
* Flow of free electrons
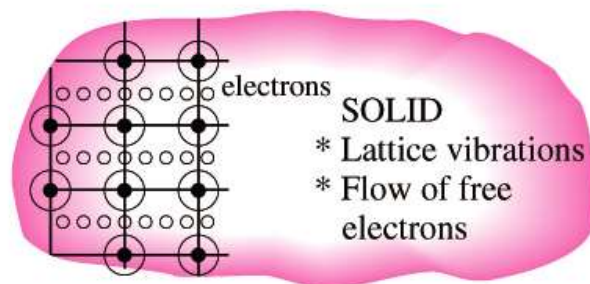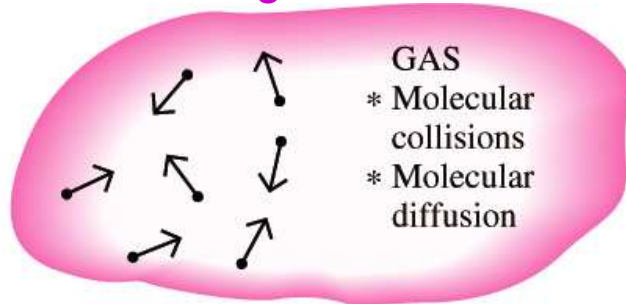
The mechanisms of heat conduction in different phases of a substance.

TABLE 16–2

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

Pure metal or alloy	k, W/m · °C, at 300 K
Copper	401
Nickel	91
Constantan (55% Cu, 45% Ni)	23
Copper	401
Aluminum	237
Commercial bronze (90% Cu, 10% Al)	52
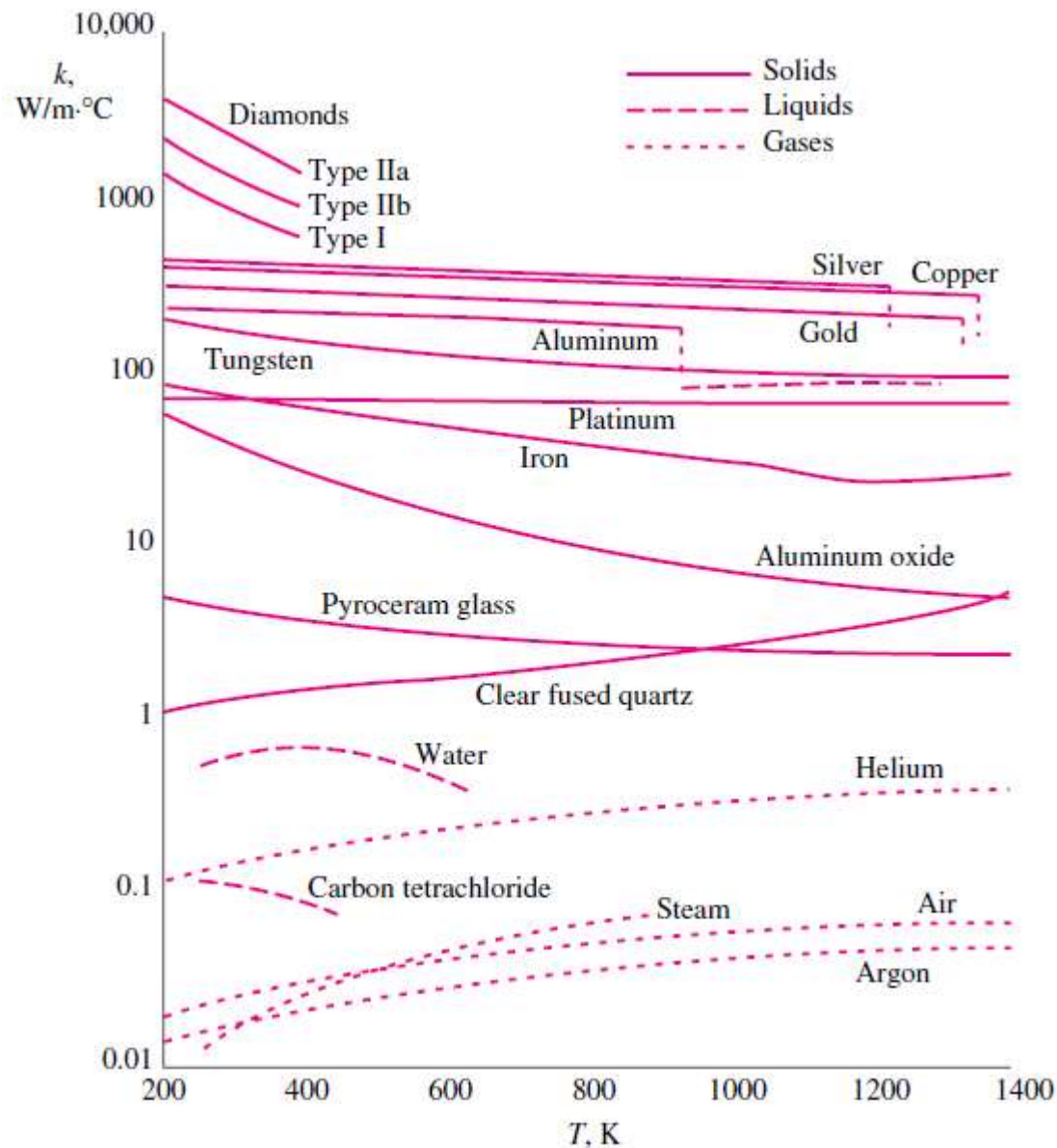
TABLE 16–3

Thermal conductivities of materials vary with temperature

	k, W/m · °C	
T, K	Copper	Aluminum
100	482	302
200	413	237
300	401	237
400	393	240
600	379	231
800	366	218

The variation of the thermal conductivity of various solids, liquids, and gases with temperature.

Thermal Diffusivity

c_p **Specific heat, J/kg · °C:** Heat capacity per unit mass

ρc_p **Heat capacity, J/m³ · °C:** Heat capacity per unit volume

α **Thermal diffusivity, m²/s:** Represents how fast heat diffuses through a material

$$\alpha = \frac{\text{Heat conducted}}{\text{Heat stored}} = \frac{k}{\rho c_p} \quad (\text{m}^2/\text{s})$$

A material that has a high thermal conductivity or a low heat capacity will obviously have a large thermal diffusivity.

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 is conducted further.

TABLE 16–4

The thermal diffusivities of some materials at room temperature

Material	α, m²/s*
Silver	149×10^{-6}
Gold	127×10^{-6}
Copper	113×10^{-6}
Aluminum	97.5×10^{-6}
Iron	22.8×10^{-6}
Mercury (l)	4.7×10^{-6}
Marble	1.2×10^{-6}
Ice	1.2×10^{-6}
Concrete	0.75×10^{-6}
Brick	0.52×10^{-6}
Heavy soil (dry)	0.52×10^{-6}
Glass	0.34×10^{-6}
Glass wool	0.23×10^{-6}
Water (l)	0.14×10^{-6}
Beef	0.14×10^{-6}
Wood (oak)	0.13×10^{-6}

CONVECTION = Conduction + Advection (fluid motion)

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.

Heat transfer from a hot surface to air by convection.
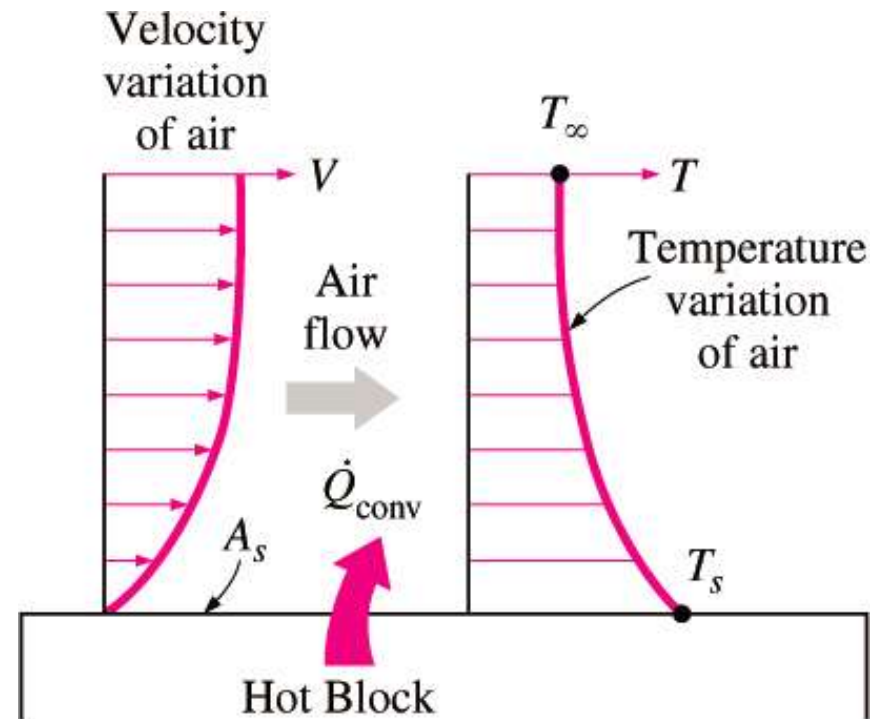
Forced convection: If the fluid is forced to flow over the surface by external means such as a fan, pump, or the wind.

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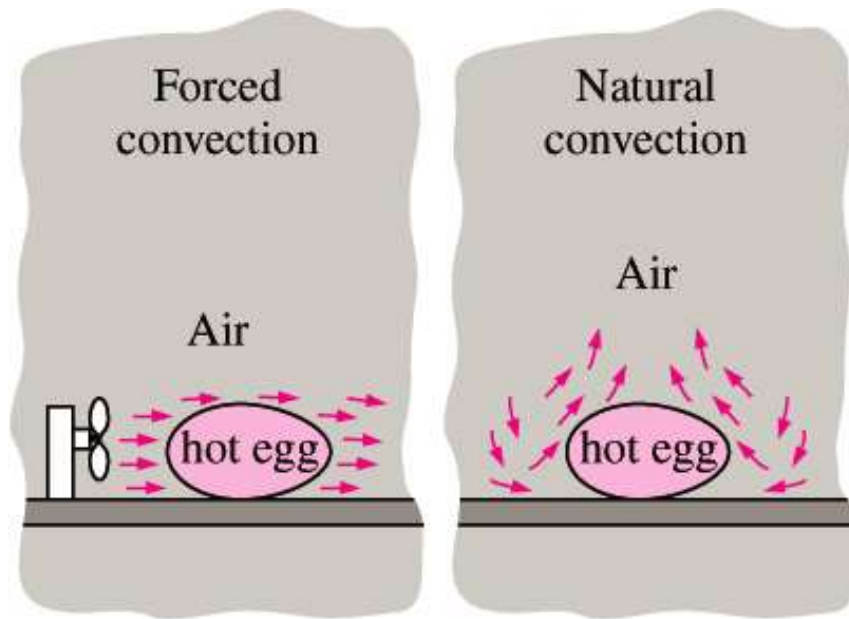
The cooling of a boiled egg by forced and natural convection.

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.

Newton's law of cooling

$$\dot{Q}_{conv} = hA_s (T_s - T_\infty) \qquad (W)$$

h convection heat transfer coefficient, W/m² · °C
A_s the surface area through which convection heat transfer takes place
T_s the surface temperature
T_∞ the temperature of the fluid sufficiently far from the surface.

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

TABLE 16–5

Typical values of convection heat transfer coefficient

Type of convection	h, W/m² · °C*
Free convection of gases	2–25
Free convection of liquids	10–1000
Forced convection of gases	25–250
Forced convection of liquids	50–20,000
Boiling and condensation	2500–100,000

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RADIATION

- **Radiation:** 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 and convection, the transfer of heat by radiation does not require the presence of an *intervening medium.*

- In fact, heat 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 studies we are interested in *thermal radiation,* which is the form of radiation emitted by bodies because of their temperature.

- All bodies at a temperature above absolute zero emit thermal radiation.

- Radiation is a *volumetric phenomenon,* and all solids, liquids, and gases emit, absorb, or transmit radiation to varying degrees.

- However, radiation is usually considered to be a *surface phenomenon* for solids.

Stefan–Boltzmann law
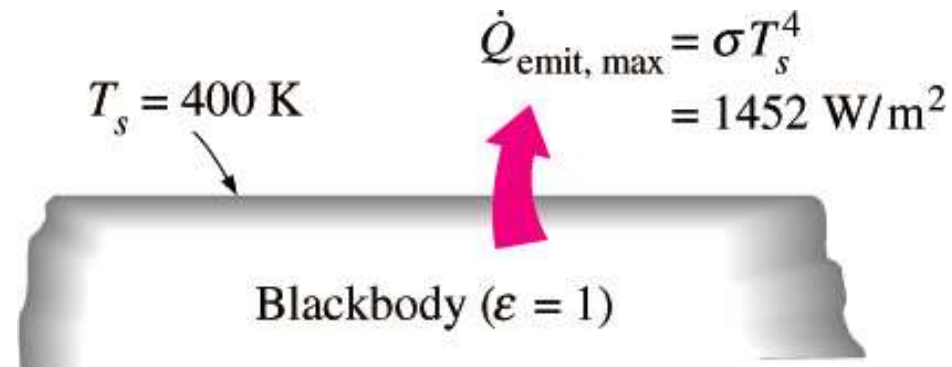
$$\dot{Q}_{emit,\,max} = \sigma A_s T_s^4 \qquad (W)$$

$\sigma = 5.670 \times 10^{-8}$ W/m² · K⁴ *Stefan–Boltzmann constant*

Blackbody: The idealized surface that emits radiation at the maximum rate.

Radiation emitted by real surfaces

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

Emissivity ε **:** A measure of how closely a surface approximates a blackbody for which $\varepsilon = 1$ of the surface. **0$\leq$ ε $\leq$ 1**.

$T_s = 400$ K

$\dot{Q}_{emit,\,max} = \sigma T_s^4$
$= 1452$ W/m²

Blackbody ($\varepsilon = 1$)

Blackbody radiation represents the *maximum amount of radiation that can be emitted from a surface at a specified temperature.*

Emissivities of some materials at 300 K

Material	Emissivity
Aluminum foil	0.07
Anodized aluminum	0.82
Polished copper	0.03
Polished gold	0.03
Polished silver	0.02
Polished stainless steel	0.17
Black paint	0.98
White paint	0.90
White paper	0.92–0.97
Asphalt pavement	0.85–0.93
Red brick	0.93–0.96
Human skin	0.95
Wood	0.82–0.92
Soil	0.93–0.96
Water	0.96
Vegetation	0.92–0.96

Absorptivity α: The fraction of the radiation energy incident on a surface that is absorbed by the surface. $\mathbf{0 \le \alpha \le 1}$

A blackbody absorbs the entire radiation incident on it ($\alpha = 1$).

Kirchhoff's law: The emissivity and the absorptivity of a surface at a given temperature and wavelength are equal.

$$\dot{Q}_{absorbed} = \alpha \dot{Q}_{incident} \qquad (W)$$

$\dot{Q}_{incident}$

$\dot{Q}_{ref} = (1 - \alpha)\,\dot{Q}_{incident}$

$\dot{Q}_{abs} = \alpha\,\dot{Q}_{incident}$
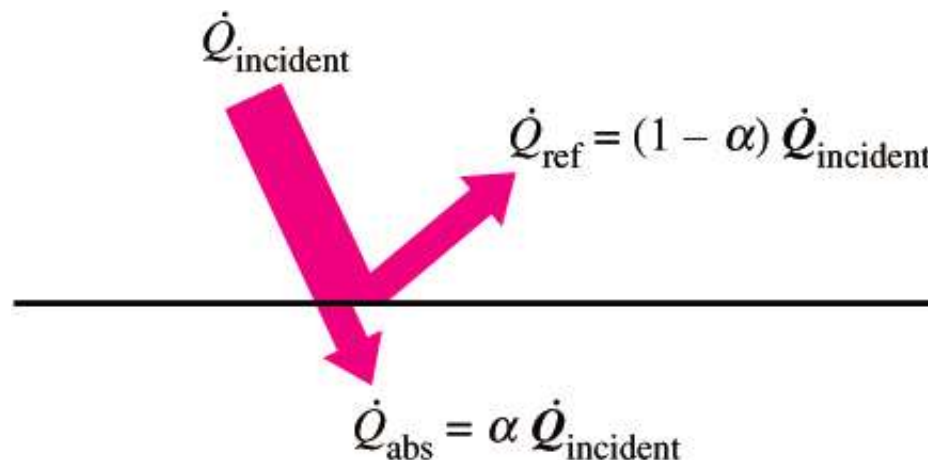
The absorption of radiation incident on an opaque surface of absorptivity .

Net radiation heat transfer: The difference between the rates of radiation emitted by the surface and the radiation absorbed.

The determination of the net rate of heat transfer by radiation between two surfaces is a complicated matter since it depends on

- **the properties of the surfaces**
- **their orientation relative to each other**
- **the interaction of the medium between the surfaces with radiation**

Radiation is usually significant relative to conduction or natural convection, but negligible relative to forced convection.
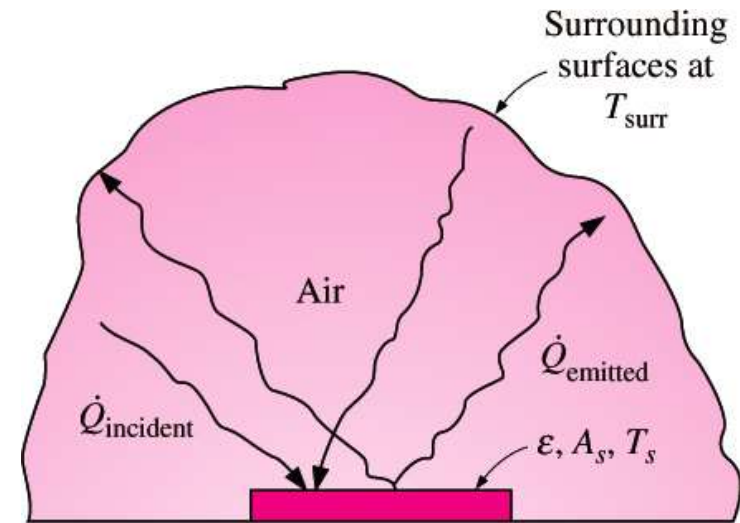
$$\dot{Q}_{rad} = \varepsilon \sigma A_s (T_s^4 - T_{surr}^4)$$

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

When radiation and convection occur between a surface and a gas

$$\dot{Q}_{total} = h_{combined} A_s (T_s - T_\infty) \qquad (W)$$

Combined heat transfer coefficient : $h_{combined}$ Convection +Radiation

SIMULTANEOUS HEAT TRANSFER MECHANISMS

Heat transfer is only by conduction in *opaque solids,* but by conduction and radiation in *semitransparent solids.*

A solid may involve conduction and radiation but not convection. A solid may involve convection and/or radiation on its surfaces exposed to a fluid or other surfaces.

Heat transfer is by conduction and possibly by radiation in a *still fluid* (no bulk fluid motion) and by convection and radiation in a *flowing fluid.*
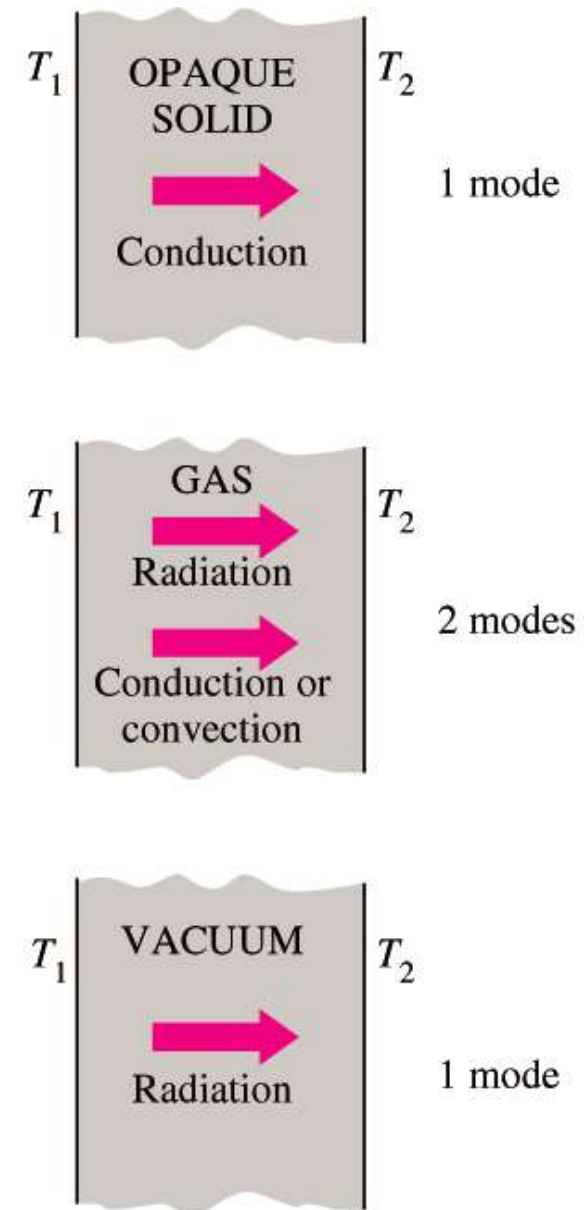
In the absence of radiation, heat transfer through a fluid is either by conduction or convection, depending on the presence of any bulk fluid motion.

Convection = Conduction + Fluid motion

Heat transfer through a *vacuum* is by radiation.

Most gases between two solid surfaces do not interfere with radiation.

Liquids are usually strong absorbers of radiation.

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

SUMMARY

Introduction

Conduction

- Fourier's law of heat conduction

- Thermal Conductivity

- Thermal Diffusivity

Convection

- Newton's law of cooling

Radiation

- Stefan–Boltzmann law

Simultaneous Heat Transfer Mechanisms