HEAT AND MASS TRANSFER

ME 302

Course code	Course Name	L-T-P-Credits	Year of Introduction
ME302	Heat and Mass Transfer	3-1-0-4	2016
Prerequisites : ME203 Mechanics of fluid			

Text Books:

1. Sachdeva R C, Fundamentals of Engineering Heat and Mass Transfer, New Age Science Limited, 2009
2. R.K.Rajput. Heat and mass transfer, S.Chand& Co.,2015
3. Nag P K., Heat and Mass Transfer, McGraw Hill,2011
4. Kothandaraman, C.P., Fundamentals of Heat and Mass Transfer, New Age International, New Delhi, 2006

Data Book:

- Heat and Mass Transfer data book: C.P. Kothandaraman, S. Subramanya, New age International publishers,2014

References Books:

1. Yunus A Cengel, Heat Transfer: A Practical Approach, McGraw Hill,2015
2. Holman J P, Heat Transfer, McGraw Hill, 2011
3. Frank P. Incropera and David P. Dewitt, Heat and Mass Transfer, John Wiley and sons, 2011

Course Plan			
Module	**Contents**	**Hours**	**End Sem. Exam Marks**
I	Modes of Heat Transfer: Conduction: Fourier law of heat conduction-Thermal conductivity of solids, liquids and gases-Factors affecting thermal conductivity- Most general heat conduction equation in Cartesian, cylindrical and spherical coordinates One dimensional steady state conduction with and without heat generation conduction through plane walls, cylinders and spheres-variable thermal conductivity conduction shape factor- heat transfer through corners and edges. Critical radius of insulation.	12	15%
II	Elementary ideas of hydrodynamics and thermal boundary layers-Thickness of Boundary layer-Displacement, Momentum and Energy thickness (description only). Convection heat transfer: Newton's law of cooling- Laminar and Turbulent flow, Reynolds Number, Critical Reynolds Number, Prandtl Number, Nusselt Number, Grashoff Number and Rayleigh's Number. Dimensional analysis Buckingham's Pi theorem- Application of dimensional analysis to free and forced convection- empirical relations- problems using empirical relations	10	15%
FIRST INTERNAL EXAMINATIONEXAM			

III	Transient heat conduction-lumped heat capacity method. Fins: Types of fins - Heat transfer from fins of uniform cross sectional area- Fin efficiency and effectiveness. Boiling and condensation heat transfer(elementary ideas only).Introduction to heat pipe.	8	15%
IV	Combined conduction and convection heat transfer-Overall heat transfer coefficient - Heat exchangers: Types of heat exchangers, AMTD, Fouling factor, Analysis of Heat exchangers- LMTD method, Correction factor, Effectiveness-NTU method, Special type of heat exchangers (condenser and evaporator, simple problems only)	8	15%
SECOND INTERNAL EXAMINATION			

V	Radiation- Nature of thermal radiation-definitions and concepts- monochromatic and total emissive power-Intensity of radiation- solid angle- absorptivity, reflectivity and transmissivity-Concept of black body- Planck' law- Kirchoff's law- Wein's displacement law-Stefan Boltzmann's law- black, gray and real surfaces-Configuration factor (derivation for simple geometries only)- Electrical analogy- Heat exchange between black/gray surfaces- infinite parallel plates, equal and parallel opposite plates-perpendicular rectangles having common edge- parallel discs (simple problems using charts and tables). Radiation shields(no derivation).	10	20%
VI	Mass Transfer :Mass transfer by molecular diffusion- Fick's law of diffusion- diffusion coefficient Steady state diffusion of gases and liquids through solid- equimolar diffusion, Isothermal evaporation of water through air- simple problems. Convective mass transfer- Evaluation of mass transfer coefficient- empirical relations- simple problems- analogy between heat and mass transfer.	8	20%

EXPECTED OUTCOMES

1. Solve problems involving steady state heat conduction with and without heat generation in simple geometries[3]
2. Evaluate heat transfer coefficients for Natural convection and Forced convection situations using empirical relations[4]
3. Design Heat Exchangers and Fins and evaluate its performance[5]
4. Solve problems involving transient heat conduction and Understand the basics of Heat pipe, Boiling and Condensation[3]
5. Estimate radiation heat transfer between black body and gray body surfaces[4]
6. Solve problems involving mass transfer due to diffusion, chemical reaction, and convection[3]

BASICS OF HEAT TRANSFER

Basic concepts

- Heat is the form of energy that can be transferred from one system to another due to a temperature difference or gradient.

- The science which deals with the rates of such energy transfer is known as “heat transfer”.

- Heat is a vector quantity, flowing in the direction of decreasing temp, with a negative temp. gradient.

Thermodynamics vs. Heat Transfer

TD	HT
TD is concerned with the **amount** of heat and work transfer and it gives no indication about the **rate(how long).**	It helps to determine the rate at which energy is transferred to or from a system due to temp. difference.
The science of TD deals with the equilibrium states of matter and precludes the existence of a temp. gradient.	For HT, temp. gradient must exist and such HT is a non equilibrium process.
TD does not provide any information on the nature of interactions and the time rate at which interactions occur. Eg:- **Cooling of a hot steel bar in water**.	HT helps to predict the temp. distribution within the regions of matter.

Modes of Heat Transfer

- There are basically three modes:

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

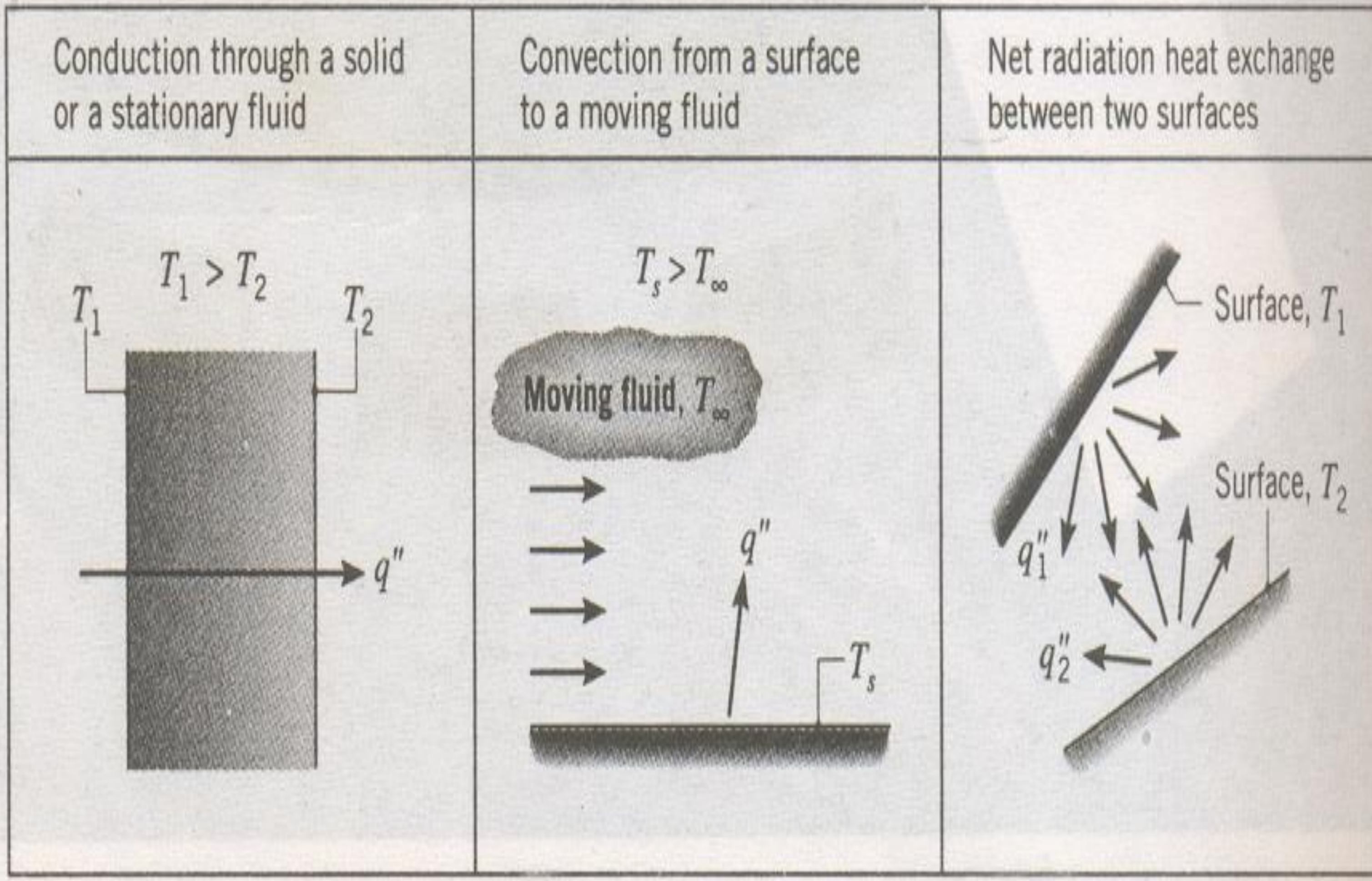


FIGURE 1.1 Conduction, convection, and radiation heat transfer modes.

- Conduction refer to the thermal energy transfer that will occur across a medium, which may be a solid or a fluid due to a temperature difference.

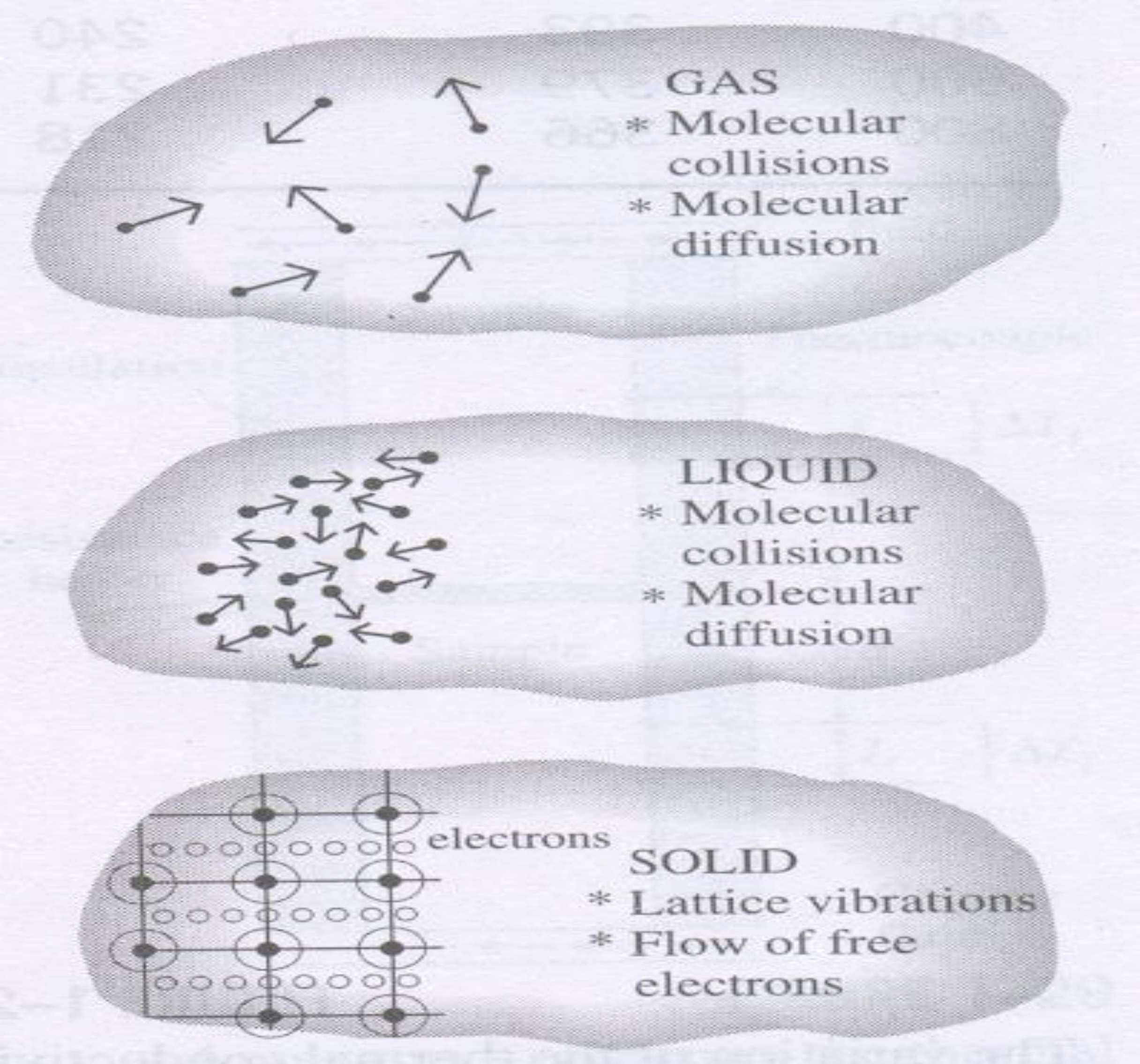
- Convection refer to the thermal energy transfer between a surface and a moving fluid when they are at different temperature levels.

- Thermal radiation refer to the net transfer of thermal energy between two surfaces at different temperature levels, in the absence of an intervening medium between them. This occurs due to electromagnetic waves emitted from a hot body.

Physical mechanisms for different modes of HT

CONDUCTION

- Thermal conduction is the transfer of thermal energy from the high energetic to the low energetic particles of a stationary medium(solids, liquids or gas) due to interactions between the particles.
- **In solids** ,conduction may be attributed to atomic activity in the form of **lattice vibrations** and **energy transport by the free electrons.**
- **In fluids**, conduction occurs due to the **collisions and diffusion of the molecules** during their random motion.
- It is a **microscopic** form of heat transfer.


GAS
* Molecular collisions
* Molecular diffusion
LIQUID
* Molecular collisions
* Molecular diffusion
electrons
SOLID
* Lattice vibrations
* Flow of free electrons

- The basic equation for thermal conduction is the **Fourier's law**.
- It states that the heat flux(Heat Transfer rate per unit area) is directly proportional to the temperature gradient.

$$\mathbf{q \propto dT/dx} \quad \textbf{or}$$

$$\mathbf{q = - k \; dT/dx}$$

- Where, k - thermal conductivity (W/m.K)

  dT/dx - temperature gradient

  q - heat flux (W/sq. m)

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

Assumptions of Fourier’s Law

1. Steady state conduction – temp. does not change with time.
2. Uni-directional heat flow.
3. Constant temp. gradient and linear temp. profile.
4. No internal heat generation.
5. Bounding surfaces are isothermal in character.
6. Isotropic and homogeneous material.

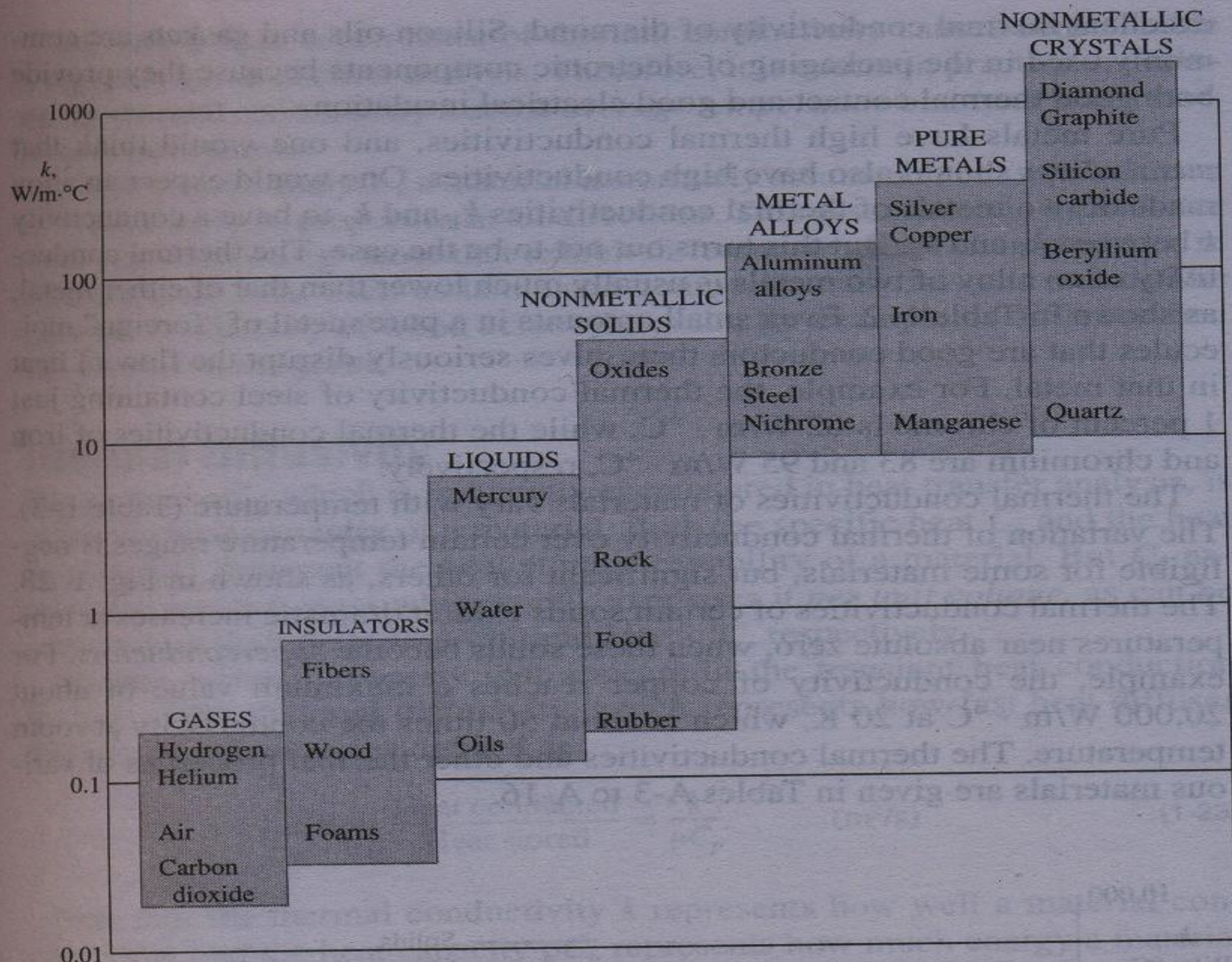
Thermal Conductivity(k)

- It is the measure of the ability of a material to conduct heat.
- It is one of the transport properties of a material.
- Its unit is $W/m^{o}C$ or $W/m.\ K$
- For Solids and Liquids, $k = f(T)$
- For gases/vapor, $k = f(p, T)$

- Metals are best conductors.
- Alloying of metals will reduce ‘k’
- ‘k’ decreases with increase in temp in most of metals except Aluminum and Uranium.
- In Aluminum. ‘k’ is constant between -130^0C to 370^0C
- In Uranium it is increases with temp.
- Gases with high molecular weight have small ‘k’.
- Materials having crystalline structure have high ‘k’ than amorphous form.
- For most materials $k = k_0(1+\beta t)$

Where k_0 is thermal conductivity at 0^0C

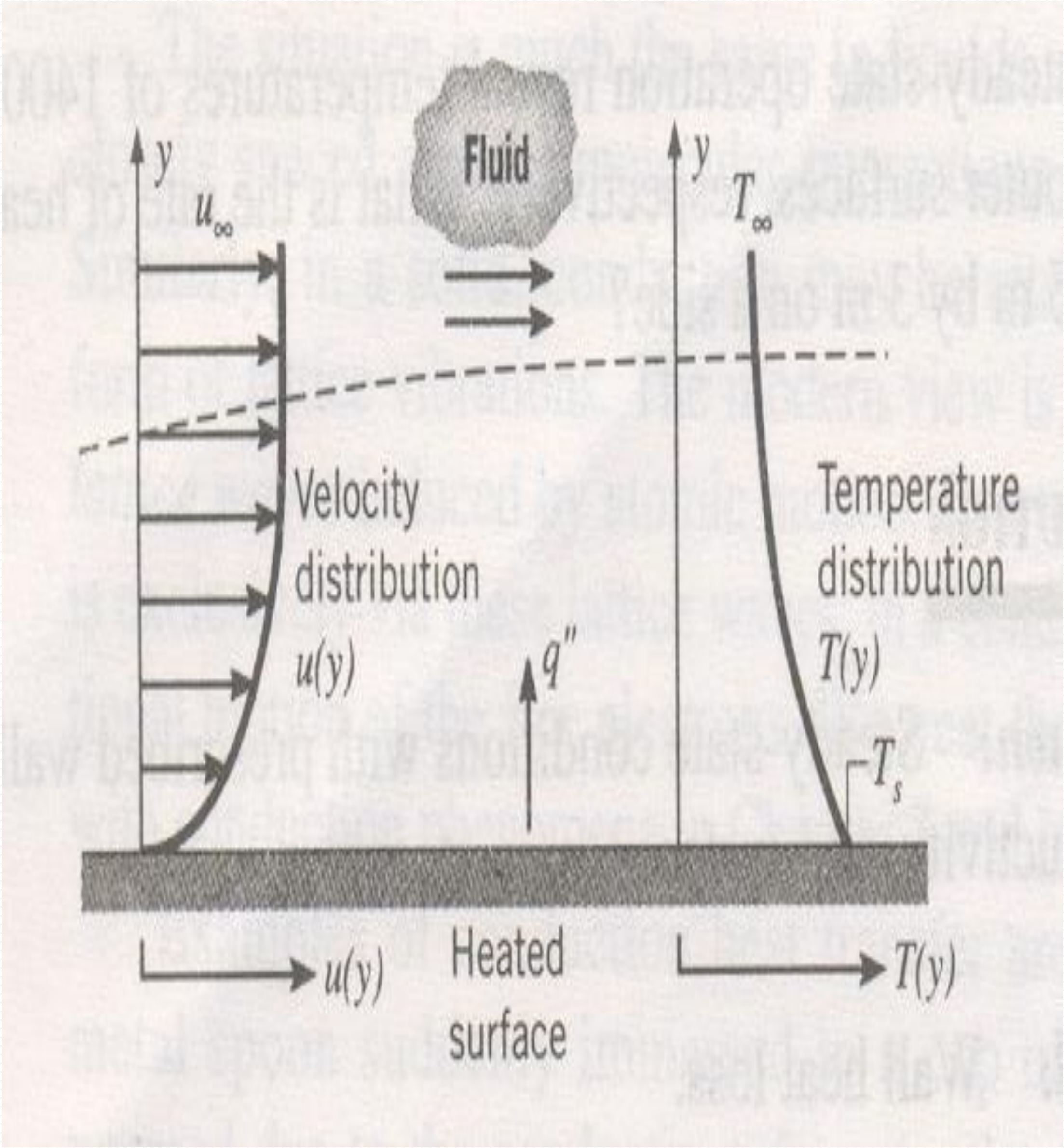
β is a constant (+ve or –ve)



k, W/m·°C
1000
100
10
1
0.1
0.01
NONMETALLIC CRYSTALS
Diamond
Graphite
Silicon carbide
Beryllium oxide
Quartz
PURE METALS
Silver
Copper
Iron
Manganese
METAL ALLOYS
Aluminum alloys
Bronze
Steel
Nichrome
NONMETALLIC SOLIDS
Oxides
Rock
Food
Rubber
LIQUIDS
Mercury
Water
Oils
INSULATORS
Fibers
Wood
Foams
GASES
Hydrogen
Helium
Air
Carbon dioxide

CONVECTION

- Convection refer to the thermal energy transfer between a solid surface and a moving fluid when they are at different temperature levels.
- It involves the combined effect of conduction and fluid motion.
- Heat is transfer from the solid surface to the fluid layer which is in contact with it by conduction.
- Then to the adjacent layers heat will transfer by the random molecular motion.


Fluid
y
u_∞
Velocity distribution $u(y)$
y
T_∞
Temperature distribution $T(y)$
q''
T_s
$u(y)$
Heated surface
$T(y)$

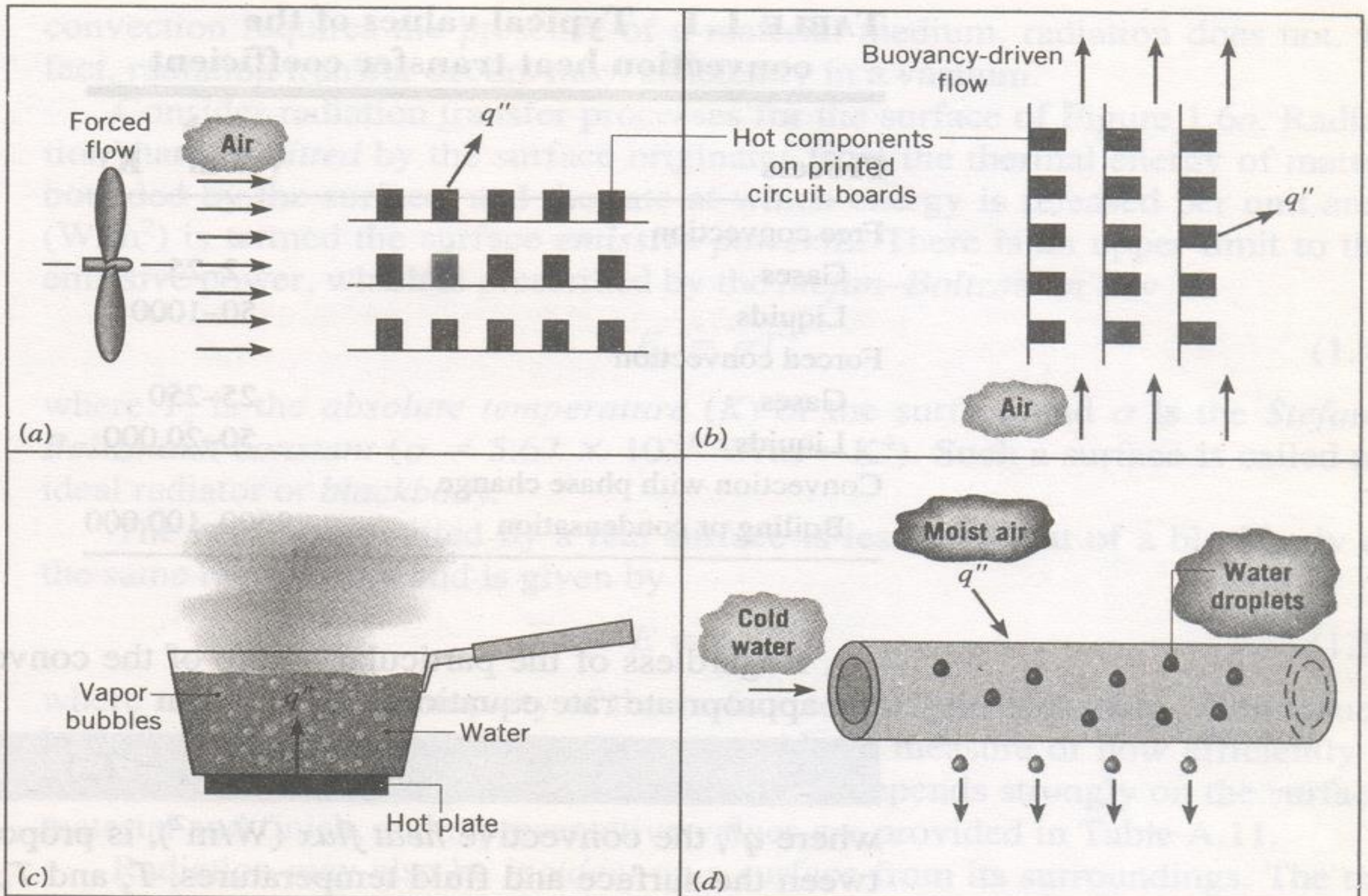
- Due to the fluid-surface interaction, a hydrodynamic boundary layer is developed with zero velocity at the wall and a finite velocity level at the boundary.

- Since the free stream temperature of the fluid and the temperature at the wall are different, a thermal boundary layer will also be developed as shown above.

- Thermal energy transfer by convection is classified as:

1. Natural (Free) convection and
2. Forced convection.

- **Forced convection** is the transfer of thermal energy when the flow is caused by external means, such as a fan, a pump or atmospheric winds.
- **Natural convection** is induced by buoyancy forces due to density variations as a result of temperature differences.
- There are thermal energy convection by **latent heat exchange**. This latent heat is due to change of phase from liquid to vapor or vice-versa.
- Boiling and condensation are examples for such processes.



Forced flow
Air
q''
Hot components on printed circuit boards
(a)
Buoyancy-driven flow
q''
Air
(b)
Vapor bubbles
q''
Water
Hot plate
(c)
Moist air
q''
Water droplets
Cold water
(d)

- The basic equation for convection heat transfer is known as **Newton's law of cooling**:

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

Where,

T_s is the surface temperature,

T_∞ is the fluid temperature and

A is the surface area of the solid.

h is the convection heat transfer coefficient in $\left(W/_{m^2K}\right)$

- h is also called **film heat transfer coefficient** or **surface conductance**.

- The value of ‘h’ depends upon:
  1. Surface condition: roughness and cleanliness
  2. Geometry and orientation of the surface: plate, cylinder or sphere, placed vertically or horizontally.
  3. Thermophysical properties of the fluid: density, viscosity, specific heat, thermal conductivity etc.
  4. Nature of fluid flow: laminar or turbulant
  5. Boundary layer configuration
  6. Prevailing temp. conditions.

RADIATION

- Thermal energy transfer by radiation is caused by electromagnetic waves(or photons).
- Thermal radiation is emitted by all surfaces which are kept at a finite temperature level.
- This happens from solids, liquids and gases.
- Rate of emission increases with temp. level.
- Radiant energy does not require a material medium for its transport.
- Moreover, radiation transfer will occur effectively in vacuum.

- The mechanism of heat flow by radiation consists three distinct phases:

1. **Conversion of thermal energy of the hot source into electromagnetic waves.**

- Photons are propagated through the space as rays.

2. **Passage of wave motion through intervening space**

- Photons travel with unchanged frequency in straight paths with speed equal to that of light.

3. **Transformation of waves into heat.**

- Reconversion of wave motion into energy occurs in the receiving surface which may partly absorbed, reflected or transmitted through.

- The basic rate equation for radiation HT is the **Stefan-Boltzman law**:

$$\boldsymbol{E_b = \sigma_b A T^4}$$

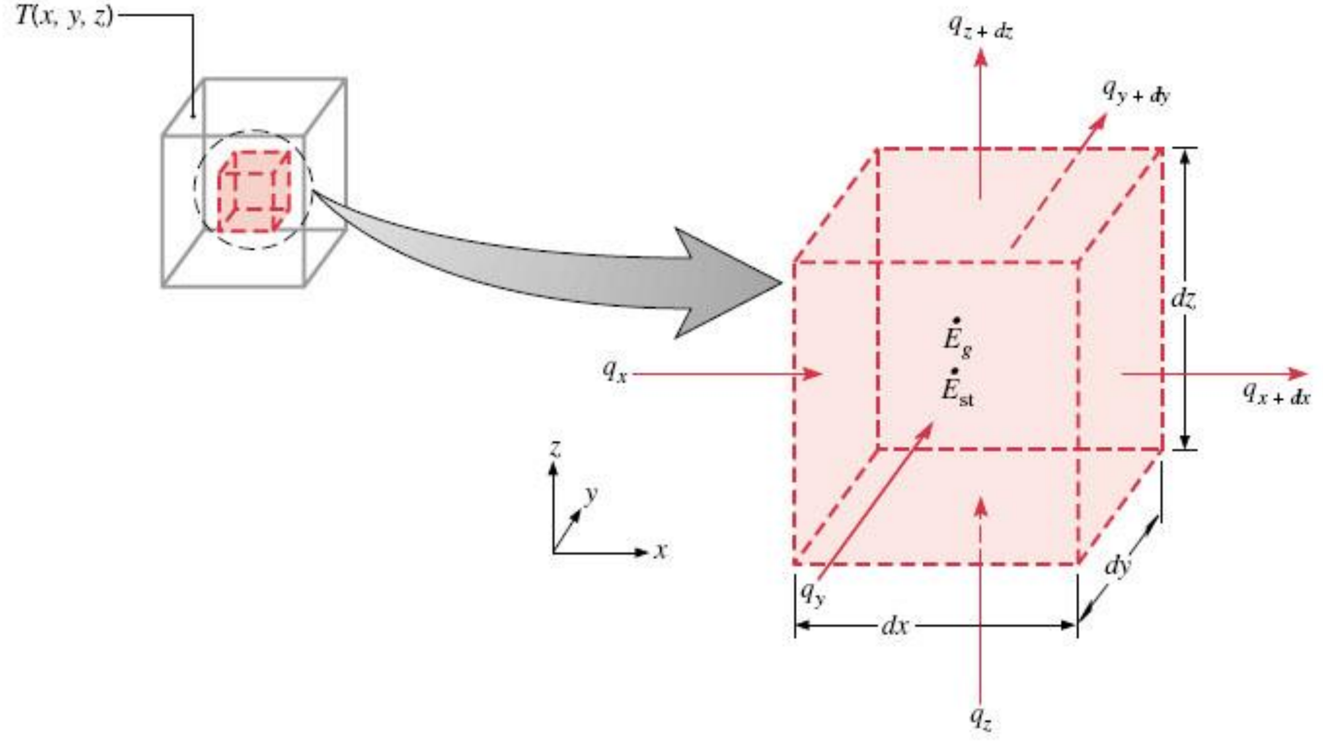
Where, E_b is the energy radiated per unit time.

T is the absolute temp of the surface

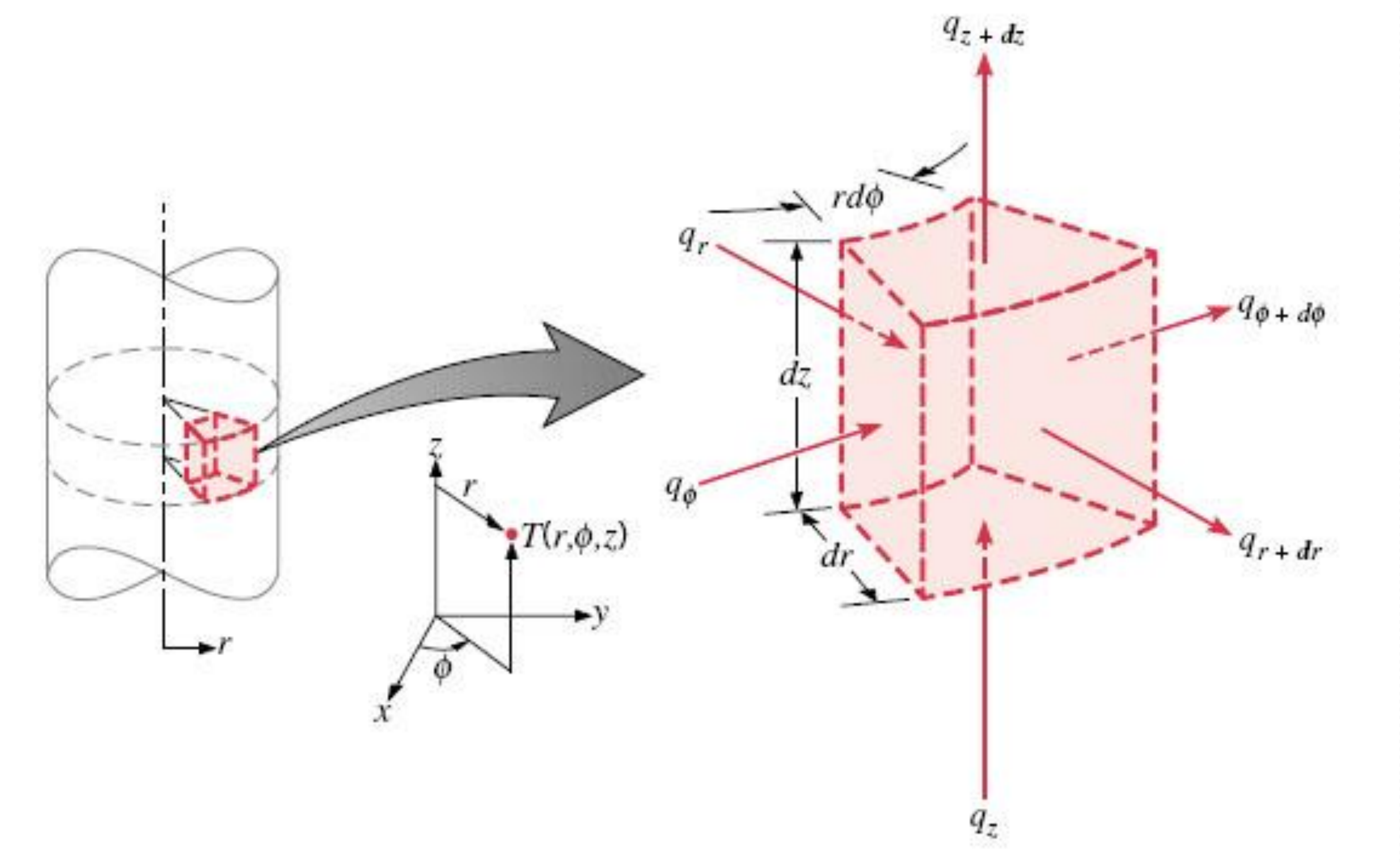
σ_b is the Stefan-Boltzman constant

$$\sigma_b = 5.67\ x\ 10^{-8}\ W/m^2K^4$$

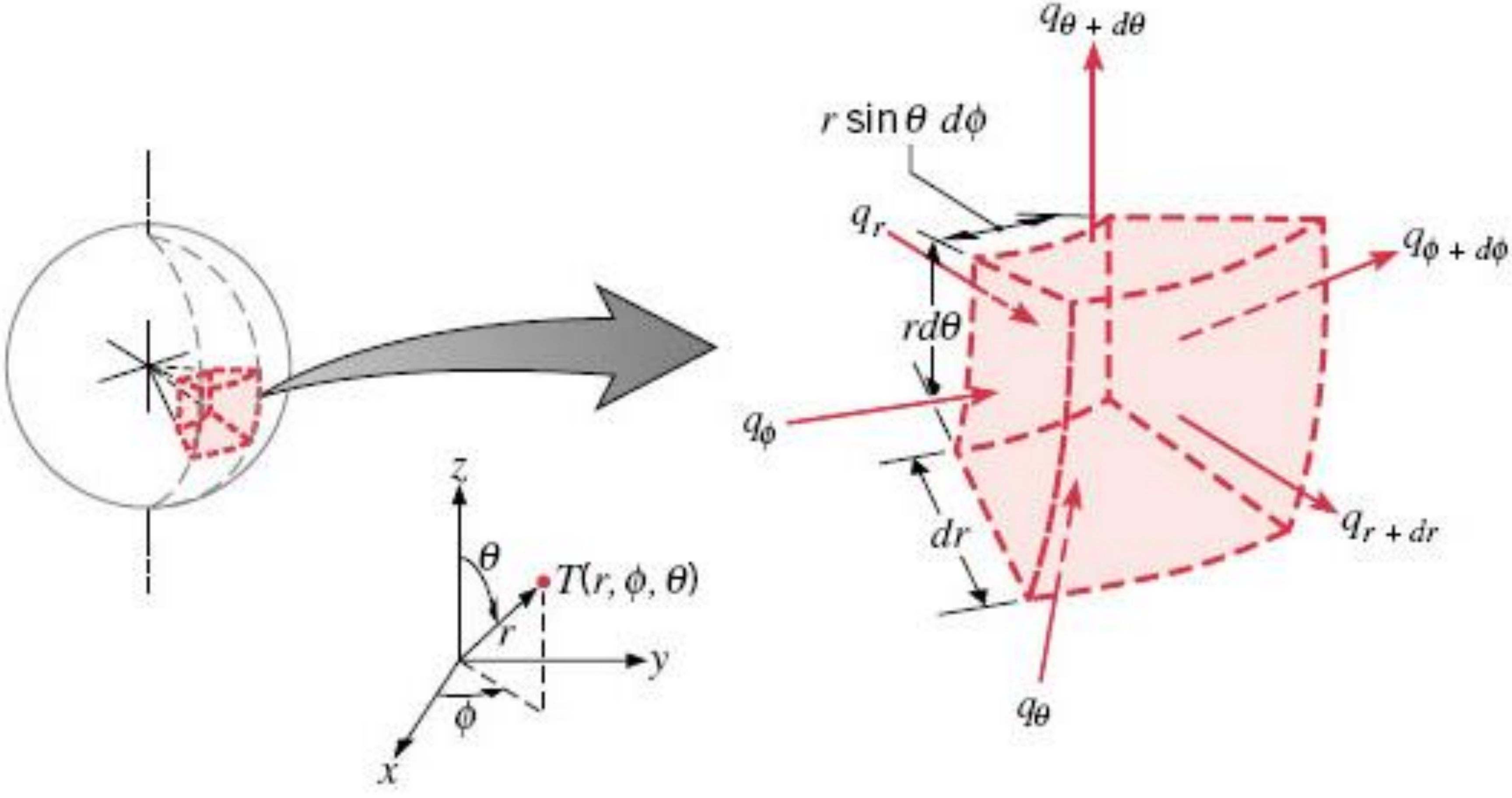
CARTESIAN COORDINATES



CYLINDRICAL



SPHERICAL



$q_{\theta + d\theta}$
$r \sin\theta \, d\phi$
q_r
$q_{\phi + d\phi}$
$rd\theta$
q_ϕ
z
θ
$T(r, \phi, \theta)$
r
y
ϕ
x
dr
$q_{r + dr}$
q_θ