MCE415
Heat and Mass Transfer

Lecture 01: 11/09/2017

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Class: Monday (12 – 2 pm)
Venue: B13

Etiquettes and MOP

- Attendance is a requirement.
- There may be class assessments, during or after lecture.
- Computational software will be employed in solving problems
- Conceptual understanding will be tested
- Lively discussions are integral part of the lectures.

Lecture content

Heat Transfer

- Introduction
- Modes of heat transfer
- Physical mechanism of conduction, convection and radiation

Recommended textbook

- Heat and Mass Transfer: Fundamentals and Applications by Cengel Y.A.

Conceptual Understanding

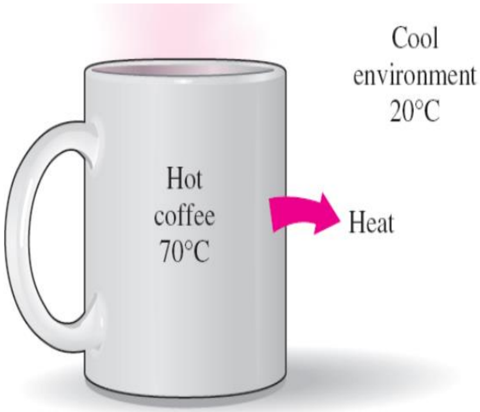
If the same volume of water is heated in this containers, which is likely to boil first?

WHY?

On a chilly night, in Omuaran, who feels the effect of the cold weather more?

Heat transfer: Introduction

Heat transfer (or heat) is energy in transition due to temperature difference.

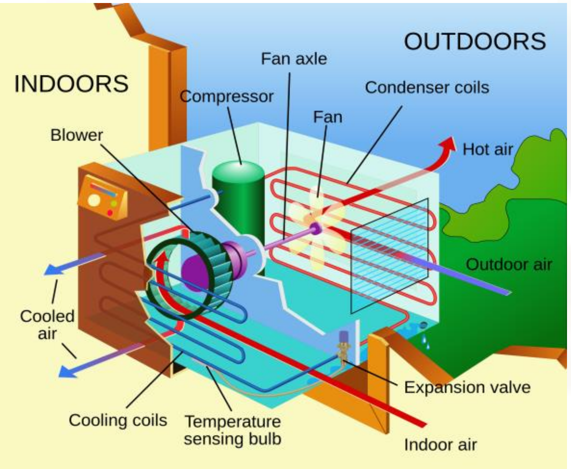


The study of heat transfer is important because it

i. gives information on how, i.e., the mode of heat transfer, and
ii. predicts the rate of energy transfer under certain specified conditions.

AREAS OF PRACTICAL ENGINEERING APPLICATIONS

Design of heat exchangers e.g. radiators, condensers



Refrigeration and air-conditioning units

Heat treatment of metals

Modes of Heat Transfer

- Heat transfer: the transition of energy on account of temperature difference may occur by any of these three modes:

i. Conduction ii. Convection iii. Radiation

- A combination of these three modes of heat transfer is usually responsible for heat transfer in most practical situations. Example of water in a boiler shell.

Heat always flows in the direction of lower temperature

- The above three modes are similar in the sense that a temperature difference must exist and heat exchange is in the direction of decreasing temperature.
- However, each method has a distinctive controlling law.

Heat Transfer by Conduction

- Conduction: is the mode of heat transfer that usually occurs in a stationary medium, either a solid or a fluid. The energy exchange is due to ***atomic or molecular activity*** within the medium due to ΔT.
- In solids, heat transfer is often a combination of:
  i. Lattice vibrations, and
  ii. Movement of free electrons
- For gases and liquids, the molecules are in a state of continuous random motion and thus energy transfer is primarily by ***collisions*** and ***diffusions*** of these molecules in the direction of lower temperature.
- The intermolecular spacing marks the difference between liquids and gases.

What is the implication of this?

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- The rate of heat transfer may be expressed as Fourier's Law of Heat Conduction (Eq.1).

$$\frac{Q}{A} \alpha \frac{dT}{dx} \qquad (1)$$

Where q = heat transfer (W) rate, A = area (m^2), $\frac{dT}{dx}$ = temperature gradient

Introducing the proportionality constant, k (W/mK), a material property known as the *thermal conductivity* yields,

$$q = \frac{Q}{A} = -k\frac{dT}{dx} \qquad (2)$$

- The implication of the negative sign is that heat transfer is in the direction of decreasing temperature.

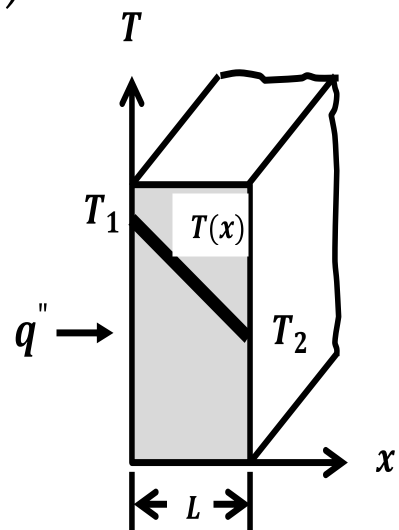

Fig. 1 One-dimensional heat transfer by conduction (diffusion of energy)

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ASSUMPTIONS

Fourier's law is based on the following assumptions:

i. Heat conduction takes place under *steady-state* conditions.
ii. The heat flow is unidirectional, i.e., one-dimensional
iii. The temperature gradient is *constant* and the temperature profile is *linear*.
iv. There is no internal heat generation.
v. The material is homogenous and isotropic(i.e. the value of thermal conductivity is *constant in all directions*)

Thermal Conductivity (TC)

- From Fourier's Law of Heat Conduction, TC, k is expressed as

$$k = \frac{Q}{A} \cdot \frac{dT}{dx} \left(\frac{W}{m.K}\right) \qquad (3)$$

- Materials are classified as thermal conductors or insulators depending on their thermal conductivities.
- ***Heat conduction occurs readily in metals, less so in alloys and much less readily in non-metals.***

TC of various materials at 0 °C

MATERIAL	TC ($W/m.$℃)
METALS:	
Silver (pure)	410
Copper (pure)	385
Nickel (pure)	93
Chrome-nickel steel (18% Cr, 8% Ni)	16.3
NOMETALLIC SOLIDS:	
Diamond	2300
Glass	0.78
Hard rubber	0.15
LIQUIDS:	
Mercury	8.21
Water	0.556
Lubricating oil, SAE 50	0.147
GASES	
Hydrogen	0.175
Air	0.024
Water vapour (saturated)	0.0206

Thermal Conductivity (TC)

- TC depends essentially on the following factors:

  (i) Material structure (ii) Moisture content (iii) Density of the material
  (iv) Pressure and temperature (operating conditions).

- TC of a material is due to flow of free electrons and lattice vibrational waves.
- TC in case of pure metals is the highest (k = 10 – 400 $W/m.K$). It decreases with increase in impurity.
- TC of a metal varies considerably when it is heated or mechanically processed.

Examine the '*k*' of different materials and see how the factors above come to play

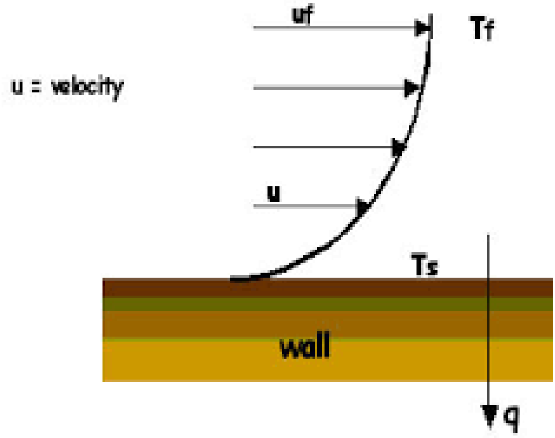
Heat Transfer by Convection

- Convection heat transfer that occurs between a surface and a moving fluid at different temperatures or by the macroscopic motion of aggregates of molecules within the fluid *(advection)*.
- Convection heat transfer may be categorised according to the nature of flow, either as (i) free (or natural) or as (ii) forced convection.
- Free (or natural) convection is induced by buoyancy effects which arises from density differences caused by temperature variation in the fluid. A free convection heat transfer that occurs from hot components on a vertical array of circuit boards in still air is an example.
- Forced convection occurs when an external means such as a fan, pump or atmospheric winds is used to propel the flow. For instance, the use of a fan to provide forced convection air cooling of hot electrical components on a stack of printed circuit boards.

Heat Transfer by Convection (Convec.)

- The rate equation for convection heat transfer is defined by *Newton's law of cooling*

$$Q = hA(T_s - T_f) \qquad (4)$$



Where Q = convec. heat transfer rate (W), h = coefficient of convec. heat transfer (or film coefficient) (W/m^{2}K), A = area (m^2), T_s = surface and T_f is the fluid temperatures (K).

- The value of h depends on the following factors:
  i. Viscosity of the fluid
  ii. Fluid thermal properties (thermal conductivity, density, specific heat)
  iii. Nature of fluid flow (free or forced flow)
  iv. Geometry of the surface

Since 'h' depends on several factors. It is difficult to frame a single equation to satisfy all the variations, however, by dimensional analysis an equation for the purpose can be obtained.

Cont'd

- Thermal Radiation: is energy emitted by matter that is at a finite temperature. All bodies at temperature above absolute zero (−273.15℃ or 0 K) radiate heat. The energy of the radiation field is transported by electromagnetic waves (or alternatively, photons). While the exchange of energy by conduction or convection requires the presence of a material medium, radiation does not. In fact, radiation transfer occurs most efficiently in a vacuum.
- The wavelength of heat radiation is longer than that of light waves, hence they are invisible to the eye.

Heat Transfer by Radiation

- The maximum flux (W/m^2) at which radiation may be emitted from a surface is given by the *Stefan-Boltzmann law*

$$q = \sigma T_s^{\,4} \qquad (5)$$

Where T_s = absolute temperature (K) of the surface and σ = Stefan-Boltzmann constant (σ = 5.67 x 10-8 W/m2.K^4) for an ideal radiator

- The heat flux emitted by a real surface is less than an ideal one and is given by

$$q = \varepsilon \sigma T_s^{\,4} \qquad (6)$$

Where ε is a radiative property of the surface called *emissivity*.

This property, whose value is in the range $0 \leq \varepsilon \geq 1$, indicates how efficiently the surface emits compared to an ideal radiator.

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- The net rate of radiation heat exchange between the surface and its surroundings, expressed per unit area of the surface, is

$$q = \frac{Q}{A} = \sigma\varepsilon({T_s}^4 - {T_{sr}}^4) \qquad (7)$$

Where A = surface area, ε = surface emissivity and T_{sr} = temperature of the surroundings

- There are many applications for which it is convenient to express the net radiation heat exchange in the form

$$Q_{rad} = h_r A\,(T_s - T_{sr}) \qquad (8)$$

Where the radiation heat transfer coefficient, h_r is

$$h_r \equiv \varepsilon\sigma(T_s + T_{sr})({T_s}^2 + {T_{sr}}^2) \qquad (9)$$

- The radiation rate equation has been linearized and the heat rate is proportional to a temperature difference rather than to the difference between two temperatures to the fourth power.

Example

1. Consider a person standing in a breezy room at 20 °C. Determine the total rate of heat transfer from this person if the exposed surface area and the average outer surface temperature of the person are 1.6 m^2 and 29 °C, respectively, and the convection heat transfer coefficient is 6 W$/m^2.K$. Take emissivity $\varepsilon = 0.95$, $\sigma = 5.67 \times 10^{-8} W/m^2.K^4$
2. Two infinite black plates at 800 °C and 300 °C exchange heat by radiation. Calculate the heat transfer per unit area.
3. Hot air at 80°C is blown over a 2-m _ 4-m flat surface at 30°C. If the average convection heat transfer coefficient is 55 W/m2 ·°C, determine the rate of heat transfer from the air to the plate, in kW. *Answer:* 22 kW
4. Reconsider Problem 1–74. Using EES (or other) software, plot the rate of heat transfer as a function of the heat transfer coefficient in the range of 20 W/m2 ·°C to 100 W/m2 ·°C. Discuss the results.

Classwork

Attempt any of the questions

1. An electric current is passed through a wire 1 mm in diameter and 10 cm long. The wire is submerged in liquid water at atmospheric pressure, and the current is increased until the water boils. For this situation $h = 5000\ W/m^2.°C$, and the water temperature will be 100 °C. How much electric power must be supplied to the wire to maintain the wire surface at 114 °C?
2. Air at 20°C blows over a hot plate 50 by 75 cm maintained at 250 °C. The convection heat-transfer coefficient is 25 W/m^2. °C.

(a) Calculate the heat transfer.

Assuming that the plate is made of carbon steel (1%) 2 cm thick and that 300 W is lost from the plate surface by radiation,

(b) calculate the inside plate temperature.

Assignment

Heat and Mass Transfer: Fundamentals and Applications by Cengel Y.A.

From the above textbook, P.47, answer 1-3

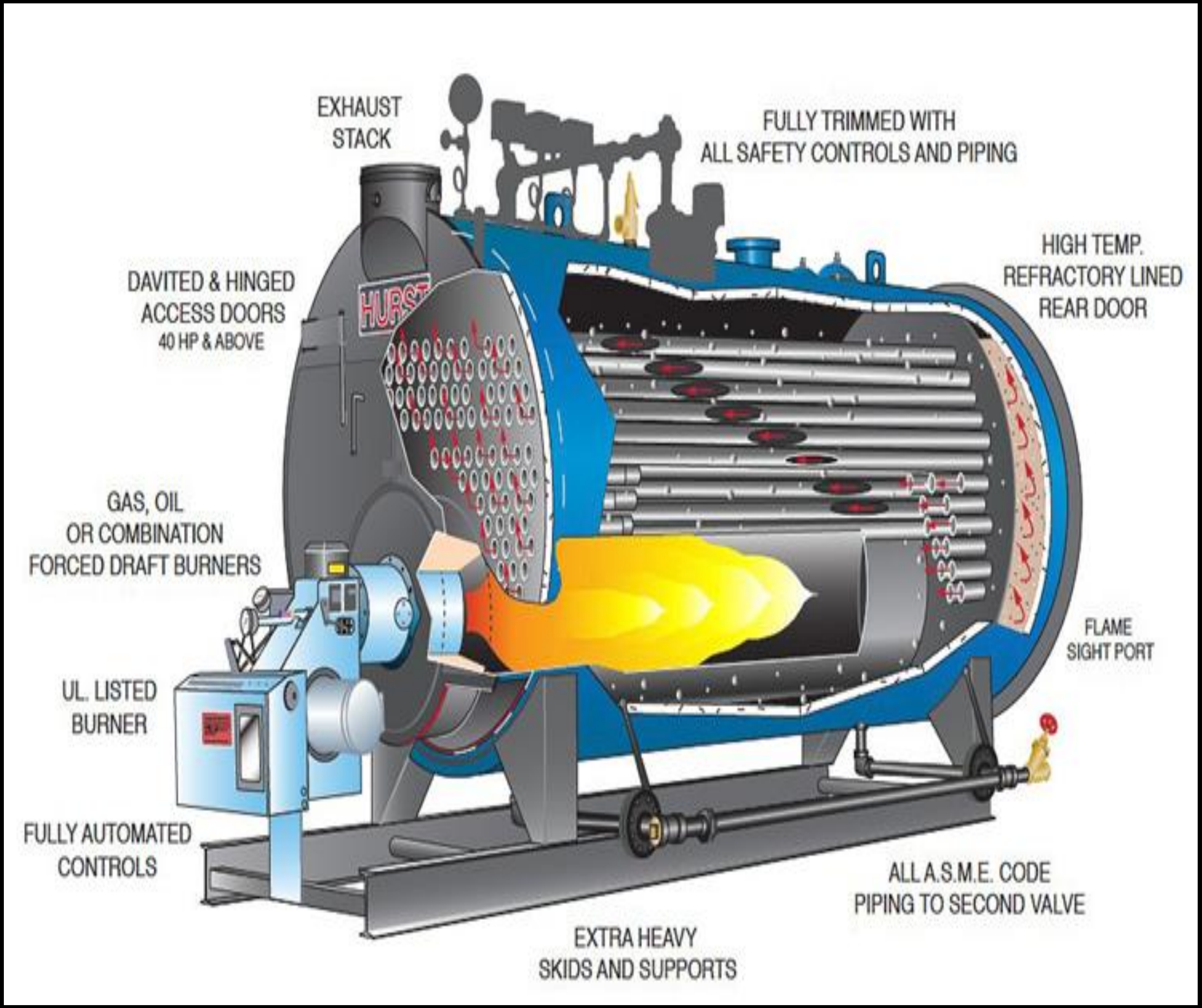
1. Question 1-44C to 1-53C
2. Question 1-63 & 1-64
3. Question 1-71 & 1-72

(To be submitted latest 18 /09/2017)

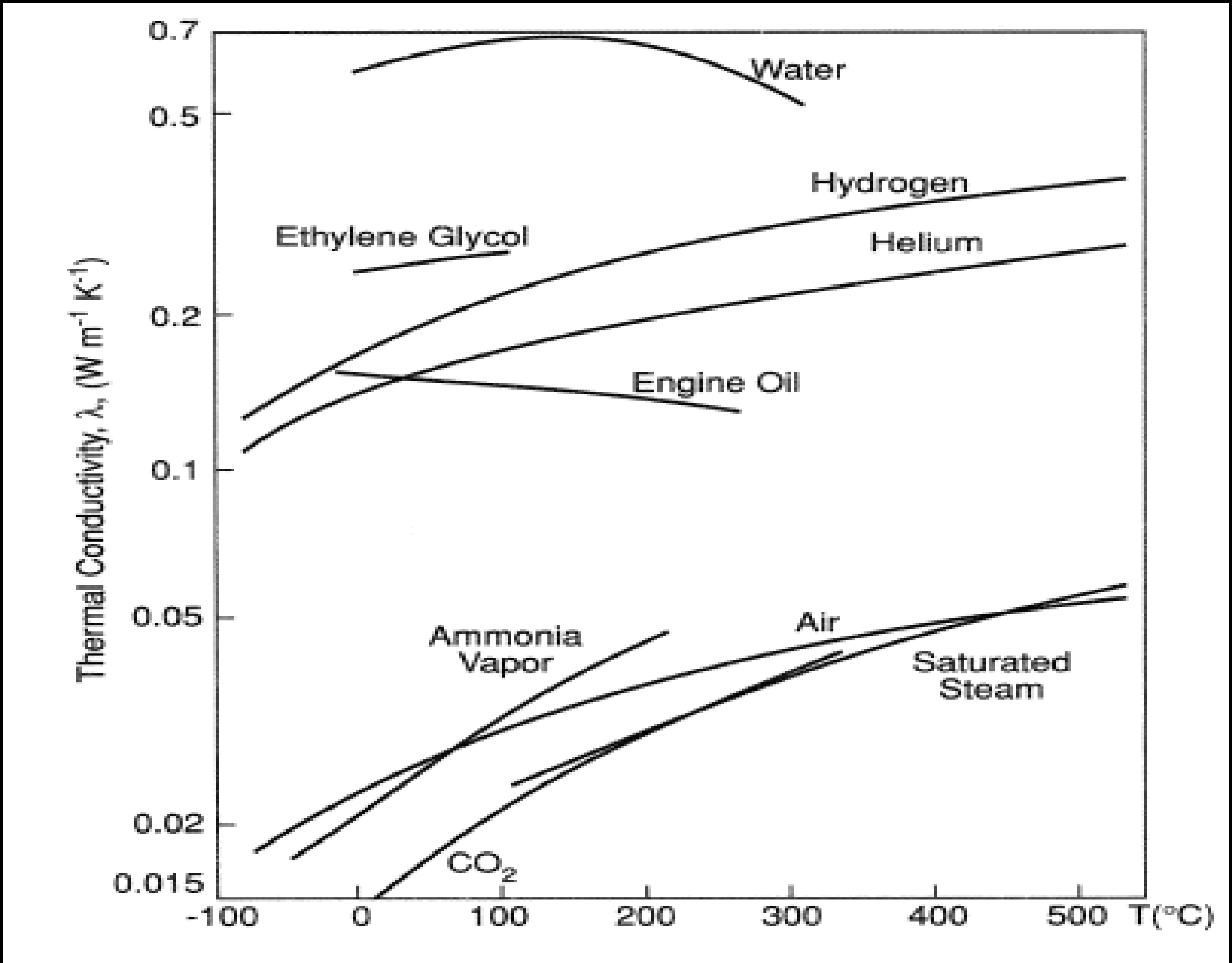
Essay Questions

Write an essay on how microwave ovens work, and explain how they cook much faster than conventional ovens. Discuss whether conventional electric or microwave ovens consume more electricity for the same task. (Not more than 500 words)

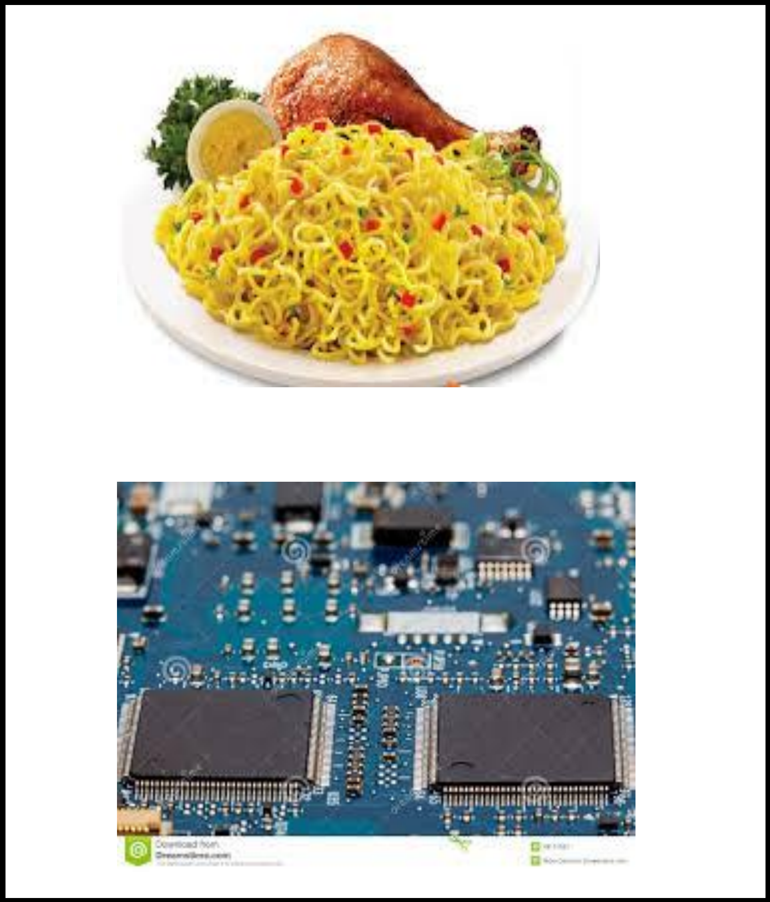
(To be submitted latest 25 /09/2017)



Cut away view of a steam boiler



Variation of thermal conductivity with temperature



Free convection

Forced convection