Heat Transfer - Third Year

مدرس المادة: د. أحمد جاسم الحمد
قسم هندسة ميكانيك القوى

مفردات منهاج انتقال الحرارة للسنة الدراسية الثالثة هندسة تقنيات التبريد والسيارات

الفصل الاول:

1- Introduction, Basic Concepts of Heat Transfer, Heat Transfer Mechanisms.
2- Steady State one Dimensional Heat Conduction in a Large Plane Wall, and in a Cylinder.
3- Conduction through Multilayer Plane Wall and Cylinder, Thermal Resistances.
4- Critical Radius of Insulation.
5- Thermal Contact Resistance.
6- The Fins.
7- Transient Heat Conduction, (Lumped System Analysis).
8- Convection Heat Transfer, Introduction

الفصل الثانى :

9- Convection Heat Transfer, Review to the Fluid Flow, Non-Dimensional Group Numbers Analysis.
10- Forced Convection on Flat Plate, External Flow.
11- Internal forced convection, in duct and tubes- Empirical equations.
12- Natural Convection Heat Transfer.
13- Heat Exchangers**.**
14- Radiation Heat Transfer, Introduction, Basic Concepts, View factor, Heat Transfer between two Black and Gray Surfaces.

References:

1. **Heat Transfer** (Yunus A. Cengel), Second Edition

2. **Heat Transfer** (J. P. Holman), Tenth Edition

Heat Transfer - Basic Concepts and Heat Transfer Mechanisms

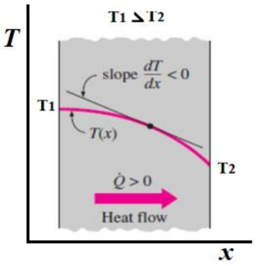
The Objective:

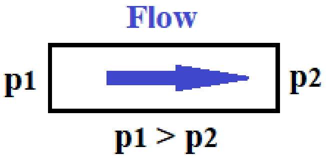
Studying the main scientific principles in the field of heat transfer and its mechanisms.

Introduction:

Heat can be transferred in three different modes:

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





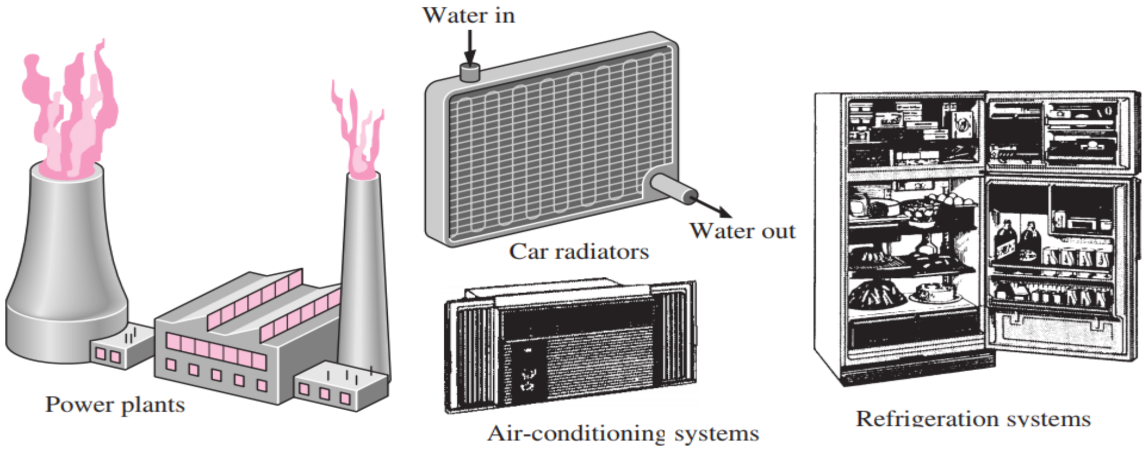
All ***modes of heat transfer*** require the existence of a ***temperature difference***, and all modes are from the high-temperature medium to a lower-temperature one.
The basic requirement for heat transfer is the presence of a *temperature difference*. There can be no net heat transfer between two mediums that are at the same temperature. The temperature difference is the ***driving force*** for heat transfer, just as the ***voltage difference*** is the driving force for electric current flow and ***pressure difference*** is the driving force for fluid flow. The rate of heat transfer in a certain direction depends on the magnitude of the ***temperature gradient*** (the temperature difference per unit length or the rate of change of temperature ***dT/dx***) in that direction. The larger the temperature gradient, the higher the rate of heat transfer.

Application Areas of Heat Transfer

Heat transfer is commonly encountered in engineering systems and other aspects of life, and one does not need to go very far to see some application area of heat transfer. The ***human body*** is constantly rejecting heat to its surroundings, and human comfort is closely tied to the rate of this heat rejection. We try to ***control this heat transfer rate by adjusting our clothing*** to the ***environmental conditions***.
Many ordinary household appliances are designed, ***some examples include, the heating and air-conditioning system, the refrigerator and freezer, the water heater, the iron, and even the computer, the TV, and the VCR.*** Of course, ***energy-efficient homes are designed on the basis of minimizing heat loss in winter and heat gain in summer***. Heat transfer plays a major role in the design of many **other devices**, such as ***car radiators, solar collectors, various components of power plants, and even spacecraft***. The optimal insulation thickness in the walls and roofs of the houses, on hot water or steam pipes, or on water heaters is again determined on the basis of a heat transfer analysis with economic consideration.

Engineering Heat Transfer

Heat transfer equipment such as ***heat exchangers, boilers, condensers, radiators, heaters, furnaces, refrigerators, and solar collectors are designed primarily on the basis of heat transfer analysis.*** The heat transfer problems encountered in practice can be considered in two groups: ***(1) rating*** and ***(2) sizing problems.*** The ***rating problems deal*** with the ***determination of the heat transfer rate for an existing system at a specified temperature difference***. The ***sizing problems deal with the determination of the size of a system in order to transfer heat at a specified rate for a specified temperature difference***.



A heat transfer process or equipment can be studied either ***experimentally*** (testing and *taking measurements) or* ***analytically*** *(by analysis or calculations). The experimental approac*h has the advantage that we deal with the actual physical system, and the desired quantity is determined by measurement, within the limits of experimental error. However, this ***approach is expensive***, ***time-consuming***. For example, the size of a ***heating system of a building must usually be determined before the building is actually built*** on the basis of the dimensions and specifications given. The ***analytical approach (including numerical approach) has the advantage that it is fast and inexpensive, but the results obtained are subject to the accuracy of the assumptions*** and ***idealizations made in the analysis***.

The First Law of Thermodynamics

The ***first law of thermodynamics*****,** also known as the ***conservation of energy principle*****,** states that ***energy can neither be created nor destroyed; it can only change forms***. Therefore, every bit of energy must be accounted for during a process. The conservation of energy principle (***or the energy balance***) for ***any system*** undergoing ***any process*** may be expressed as follows: *The net change (increase or decrease) in the total energy of* ***the system during a process*** *is equal to the difference between the total energy entering and the total energy leaving the system during that process*. That is,

$$\begin{pmatrix}\text{Total energy}\\ \text{entering the}\\ \text{system}\end{pmatrix} - \begin{pmatrix}\text{Total energy}\\ \text{leaving the}\\ \text{system}\end{pmatrix} = \begin{pmatrix}\text{Change in the}\\ \text{total energy of}\\ \text{the system}\end{pmatrix}$$

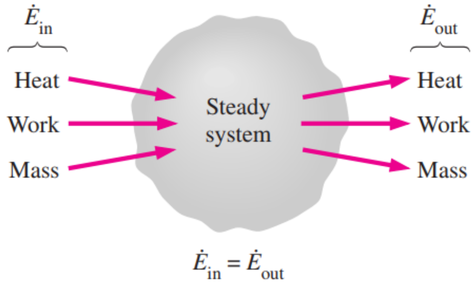
Noting that energy can be transferred to or from a system by ***heat, work***, and ***mass flow***, and that the total energy of a simple ***compressible system*** consists of ***internal, kinetic, and potential energies***.

Energy Balance for Closed Systems *(Fixed Mass)*

A ***closed system consists of a fixed mass***. The ***total energy E for most systems encountered in practice consists of the internal energy U***. This is especially the case for stationary systems since ***they don't involve any changes in their velocity*** or elevation during a process. The energy balance relation in that case reduces to

Stationary closed system: $$E_{\text{in}} - E_{\text{out}} = \Delta U = mC_v\Delta T \qquad \text{(J)}$$

where we expressed the internal energy change in terms of mass m, the specific heat at constant volume Cv, and the temperature change ΔT of the system.



Energy Balance for Steady-Flow Systems

A large number of ***engineering devices such as water heaters and car radiators involve mass flow in and out of a system***, and are modeled as ***control volumes***. Most control volumes are analyzed under steady operating conditions. The term ***steady means no change with time at a specified location. The opposite of steady is unsteady or transient***.

Also, the term ***uniform implies no change with position*** throughout a surface or region at a specified time.

The amount of fluid mass flowing through a cross section of a flow device per unit time is called the ***mass flow rate,*** and is denoted by $\dot{m}$. A fluid may flow in and out of a control volume through pipes or ducts. The mass flow rate of a fluid flowing in a pipe or duct is proportional to the cross-sectional area A_c of the pipe or duct, the density ρ, and the velocity υ. of the fluid,

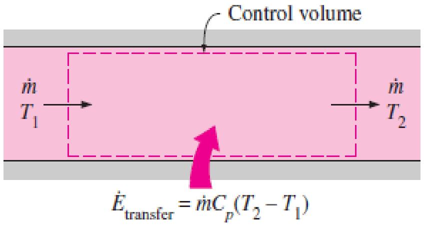
$$\dot{m} = \rho\upsilon A_c \quad \text{(kg/s)}.$$

For a steady-flow system with one inlet and one exit, the rate of mass flow into the control volume must be equal to the rate of mass flow out of it. That is, $\dot{m}_{in} = \dot{m}_{out} = \dot{m}$.

When the changes in kinetic and potential energies are negligible, which is usually the case, and there is no work interaction, the energy balance for such a steady-flow system reduces to,

$$\dot{Q} = \dot{m}C_p\Delta T$$

where C_p is the specific heat (kJ/kg.°C)



Heat Transfer Mechanisms

Heat can be transferred in three different modes:
conduction, ***convection***, and ***radiation***.

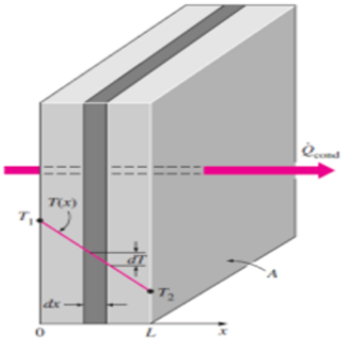
Conduction: *is the transfer of energy from the more energetic particles of a substance to the adjacent less energetic ones as a result of interactions between the particles*, and is expressed by ***Fourier's law of heat conduction*** as:

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

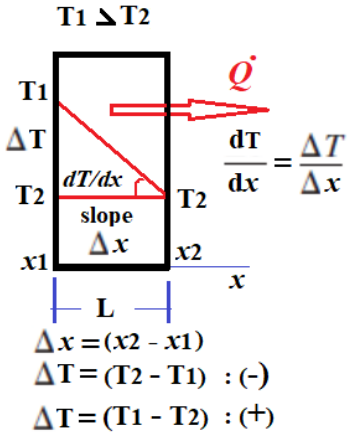
Where: $\boldsymbol{Q^{\cdot}}$ is rate of heat transfer (W), $\boldsymbol{k}$ is the ***thermal conductivity*** (W/m·°C) of the material, ***A is the area*** *(m^2)* normal to the direction of heat transfer, and **dT/dx** is the ***temperature gradient***. The magnitude of the rate of heat conduction across a ***plane layer of thickness L*** *(m)* is given by

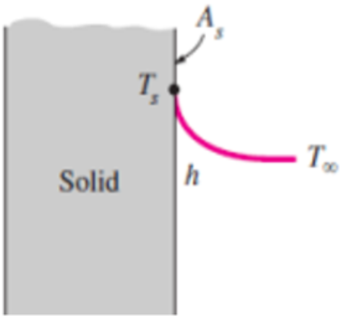
$$\dot{Q}_{\text{cond}} = kA\frac{\Delta T}{L}$$

where ΔT is the temperature difference across the layer.



Conduction heat transfer





Convection heat transfer

Convection:

is the mode of ***heat transfer between a solid surface and the adjacent liquid or gas that is in motion***, and involves the combined effects of ***conduction and fluid motion***. The rate of convection heat transfer is expressed by ***Newton's law of cooling*** as:

$$\dot{Q}_{\text{convection}} = hA_s\,(T_s - T_\infty)$$

Where $\boldsymbol{h}$ is the ***convection heat transfer coefficient*** in **W/m^2·°C**, $\boldsymbol{A_s}$ is the *surface area* through which convection heat transfer takes place, $\boldsymbol{T_s}$ is the *surface temperature*, and $\boldsymbol{T_\infty}$ is the *temperature of the fluid* sufficiently far from the surface. Convection is called ***forced convection*** if the fluid is forced ***to flow over the surface by external means such as a fan, pump***, or the wind. In contrast, convection is called ***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***. Heat transfer processes that involve ***change of phase of a*** fluid are also considered to be ***convection*** because of ***vapor bubbles during boiling or the fall of the liquid droplets during condensation*** the fluid motion induced during the process, such as the rise of the.

Radiation:

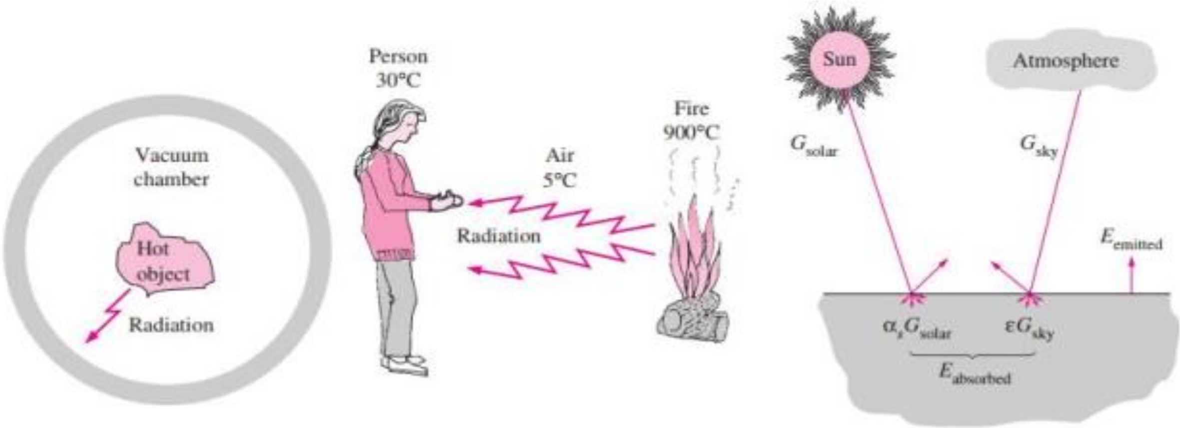
is the ***energy emitted by matter in the form of electromagnetic waves (or photons) as a result of the changes in the electronic configurations of the atoms or molecules***. The maximum rate of radiation that can be emitted from a surface at an ***absolute temperature*** *Ts* (K) is given by the ***Stefan–Boltzmann law*** as:

$$\dot{Q}_{\text{emit, max}} = \sigma A_s T_s^4 \text{ where } \sigma = 5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4$$

Where: σ is the ***Stefan Boltzmann constant***. When a surface of emissivity **Ɛ** and surface area A_s at an absolute temperature T_s (K) is completely enclosed by a much larger (or black) surface at absolute temperature T_{surr} (K) separated ***by a gas (such as air) that does not intervene with radiation***, the net rate of radiation heat transfer between these two surfaces is given by,

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

(Emissivity**: Ɛ = 1** for black body)



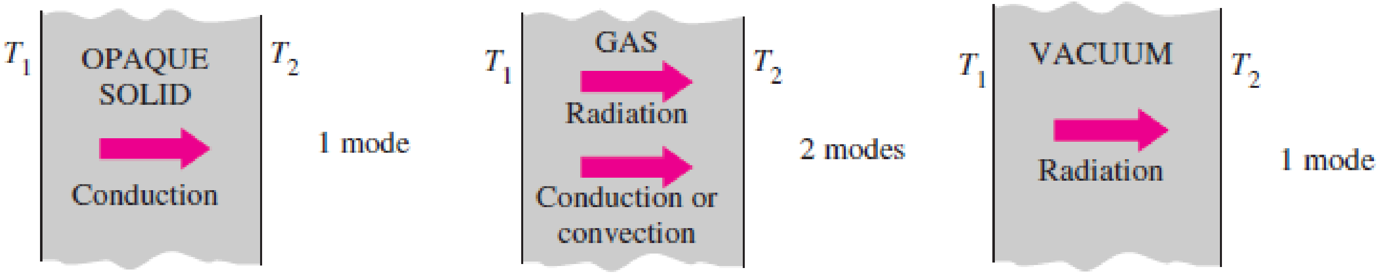
Simultaneous Heat Transfer Mechanisms

We mentioned that there are three mechanisms of heat transfer, but not all three can exist simultaneously in a medium. For example, ***heat transfer is only by conduction in opaque solids***, but by ***conduction and radiation in semitransparent solids***. Thus, a ***solid may involve conduction*** and ***radiation*** but not ***convection***. However, a solid may involve heat transfer by convection and/or radiation on its surfaces exposed to 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 can be viewed as combined conduction and fluid motion, and conduction in a fluid can be viewed as a special case of convection in the absence of any fluid motion.

Thus, when ***we deal with heat transfer through a fluid, we have either conduction or convection, but not both***. Also, ***gases*** are practically ***transparent to radiation***, except that some *gases are known to absorb radiation strongly at certain wavelengths*. ***Ozone, for example***, strongly ***absorbs ultraviolet radiation***. But in most cases, a gas between two solid surfaces does not interfere with radiation and acts effectively as a vacuum. ***Liquids, on the other hand, are usually strong absorbers of radiation***.

Finally, ***heat transfer through a vacuum is by radiation only*** since conduction or convection requires the presence of a material medium.



Steady State One Dimensional Heat Conduction in a Large Plane Wall, and in a Cylinder

Heat conduction through a large plane wall such as the ***wall of a house***, the ***glass of a single pane window***, the ***metal plate*** at the bottom of a pressing iron, ***a cast iron steam pipe***, a ***cylindrical nuclear fuel element***, an ***electrical resistance wire***, the wall of a ***spherical container***, or a spherical metal ball that is being quenched or tempered. ***Heat conduction in these*** and much other geometry can be approximated as being ***one-dimensional*** since *heat conduction through these geometries will be dominant in* **one direction** and **negligible in other directions**.

General Concepts in Conduction Heat Transfer

1- Heat conduction in a medium is ***three-dimensional*** and ***time dependent***, T=T(x,y,z,t).

2- Heat conduction in a medium is said to be ***steady*** when the temperature does not very with time, and ***unsteady or transient*** when it does very with time.

3- Heat conduction in a medium is said to be ***one-dimensional*** when conduction is significant in ***one dimension only*** and negligible in the other dimensions, ***two-dimensional*** when conduction in the third dimension is negligible and ***three-dimensional*** when conduction in all dimensions is significant.

4- Conduction can take place in ***liquids and gases as well as solids*** provided that ***there is no bulk motion*** involved in the liquid or gas.

5- Heat transfer ***has direction*** as well as ***magnitude***, and thus it is a ***vector quantity***.

6- In coordinate system, a positive quantity indicates heat transfer in the ***positive direction*** and a ***negative quantity*** indicates heat transfer in the ***negative direction***.

7- The ***driving force*** for any form of heat transfer is the ***temperature difference***. The larger the temperature difference, the larger the rate of heat transfer.

8- The ***specification of the temperature at a point in a medium*** first requires the specification of the location of that point, by choosing a suitable ***coordinate system*** such as ***rectangular***, ***cylindrical*** or ***spherical coordinates***.

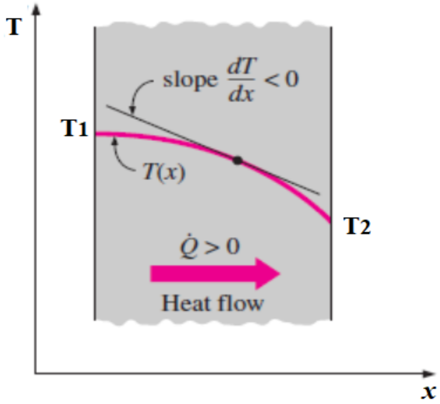
9- The ***location of a point*** is specified as **(x,y,z)** in ***rectangular coordinates***, or as **(r,φ,z)** in ***cylindrical coordinates***, and or **(r,φ,θ)** in ***spherical coordinates***.

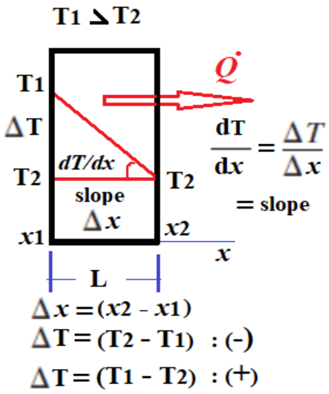
10- The ***best coordinate system*** for a given geometry is the one that describes the surfaces of the ***geometry best***.

11- ***Thermal conductivity*** of the material is a ***measure of the ability of a material to conduct heat.*** It is in general, ***varies with temperature***, but sufficiently accurate results can be obtained by ***using a constant value for thermal conductivity*** at the average temperature.

Fourier' Law

The ***rate of heat conduction*** through a medium in a specified direction (say, in the *x*-direction) is *proportional to the temperature difference across the medium and the area normal to the direction of heat transfer, but is inversely proportional to the distance in that direction*. This was expressed in the differential form by **Fourier's law of heat conduction** for ***one-dimensional*** heat conduction as:





$$\dot{Q}_{\text{cond}} = -kA\frac{dT}{dx} \qquad (\text{W})$$

Heat flux (***q***):

$$q = \frac{\dot{Q}}{A} \qquad (\text{W/m}^2)$$

where ***k*** is the ***thermal conductivity*** of the material, which is a measure of the ability of a material to conduct heat, and ***dT/dx*** is the ***temperature gradient***, which is the ***slope of the temperature curve on a T-x diagram***.

Heat is conducted in the ***direction of decreasing temperature***, and thus the ***temperature gradient is negative*** when heat is conducted in the ***positive x-direction***. The ***negative sign in the equation*** ensures that ***heat transfer*** in the positive **x-direction is a positive quantity**.

General Relation for Fourier's Law

To obtain a ***general relation for Fourier's law of heat conduction***, consider a medium in which the temperature distribution is ***three-dimensional***. The ***heat flux vector*** at a point ***P*** on this surface must be ***perpendicular to the surface***, and it must point in the direction of decreasing temperature. If ***n*** *is the* ***normal*** *of the isothermal surface at point* ***P***, the rate of heat conduction at that point ***can be expressed by Fourier's law*** as:

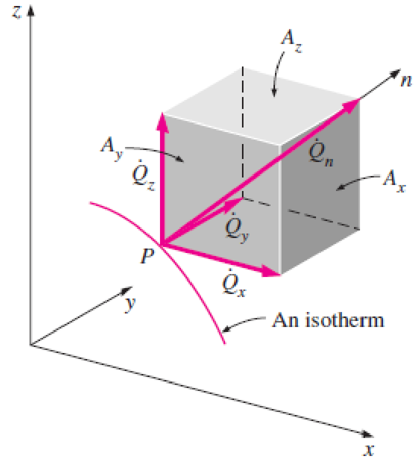
$$\dot{Q}_n = -kA\frac{\partial T}{\partial n} \qquad (W)$$

In a rectangular coordinates system,

$$\vec{\dot{Q}}_n = \dot{Q}_x \vec{i} + \dot{Q}_y \vec{j} + \dot{Q}_z \vec{k}$$

where $\vec{i}$, $\vec{j}$, and $\vec{k}$ are the unit vectors,

$\dot{Q}_x$, $\dot{Q}_y$, and $\dot{Q}_z$ are the magnitudes of the heat transfer rates in the ***x*-, *y*-,** *and* ***z*-directions**, which again can be determined from ***Fourier's law*** as:



$$\dot{Q}_x = -kA_x \frac{\partial T}{\partial x}, \quad \dot{Q}_y = -kA_y \frac{\partial T}{\partial y}, \quad and \quad \dot{Q}_z = -kA_z \frac{\partial T}{\partial z},$$

Here $\boldsymbol{A_x}$, $\boldsymbol{A_y}$ and $\boldsymbol{A_z}$ are heat conduction areas normal to the *x*-, *y*-, and *z*-directions, respectively. Most engineering materials are *isotropic* in nature, and thus they have the same properties in all directions.

Heat Generation

A medium through which heat is conducted may involve the ***conversion of electrical, nuclear, or chemical energy*** into ***heat (or thermal) energy***. In heat conduction analysis, such conversion processes are characterized as ***heat generation*****.**

The rate of heat generation in a medium is usually specified ***per unit volume*** and is denoted by $\dot{g}$, whose unit is W/m^3.

In the special case of ***uniform heat generation***, as in the case of ***electric resistance heating*** throughout a homogeneous material:

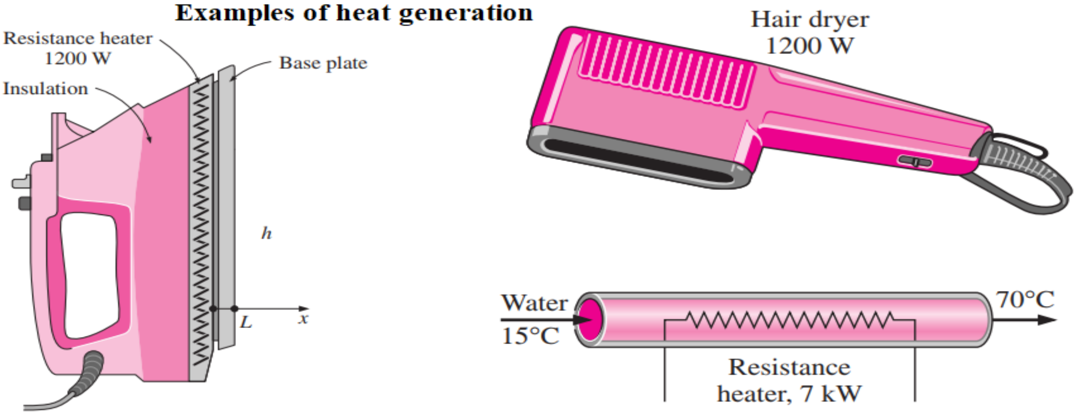
$$\dot{G} = \dot{g}V,$$

where $\dot{g}$: the constant rate of heat generation per unit volume (W/m^3).

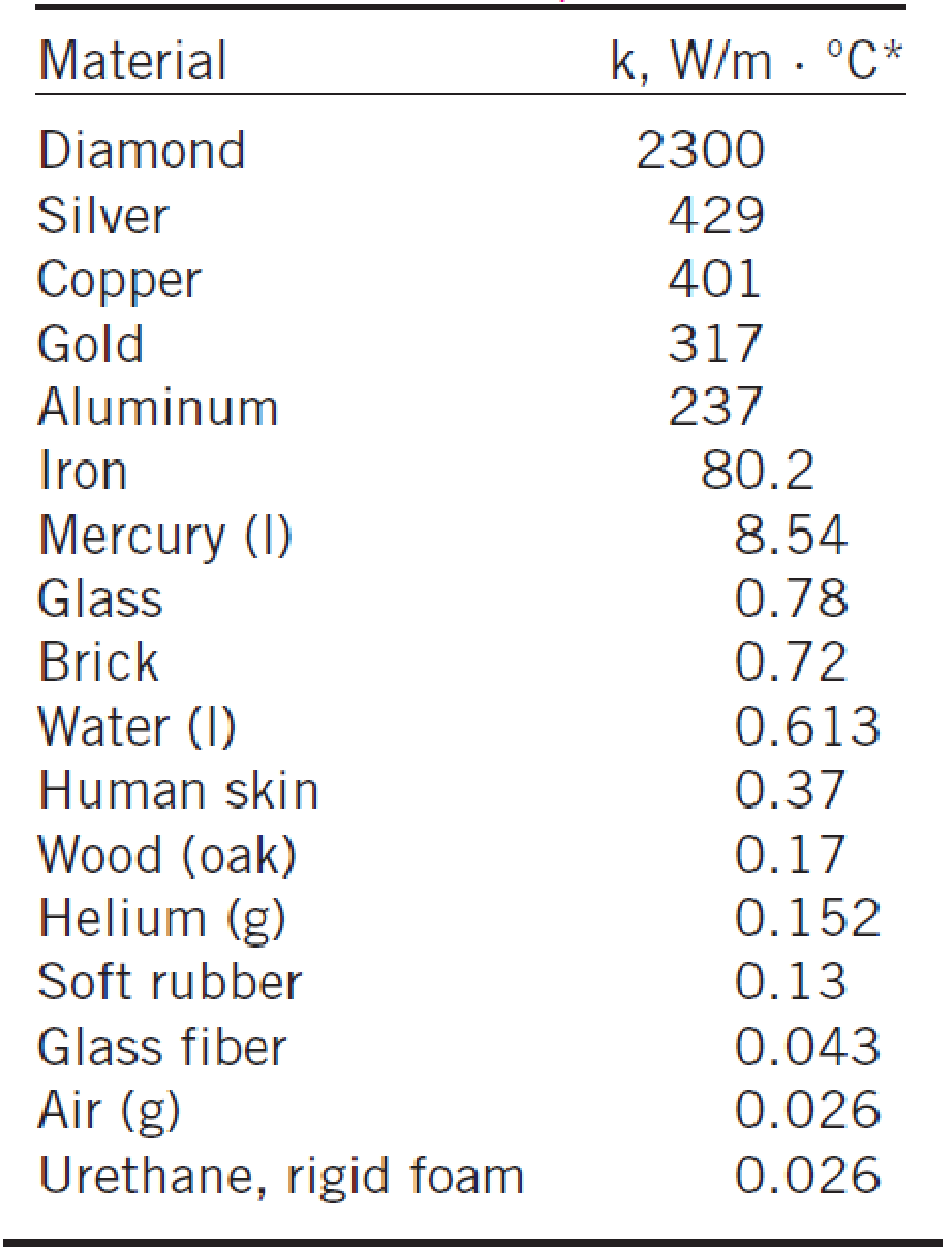
V : total volume (m^3)

$\dot{G}$: total heat generation (Watt)

Examples of heat generation



Thermal conductivity (k) 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)	0.613
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