Basic Concepts of Heat Transfer

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Content

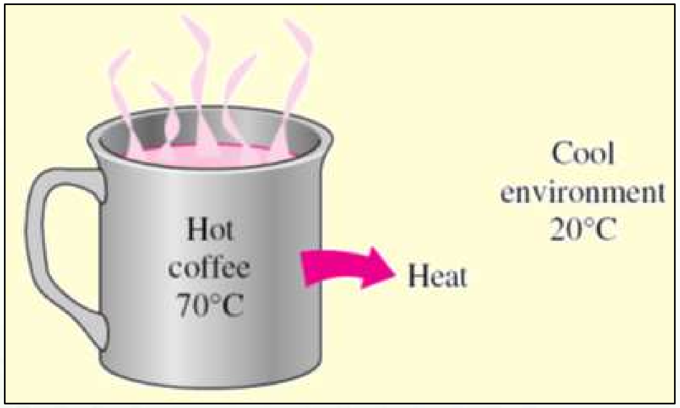
- Thermodynamics and heat transfer
- Thermal energy, heat transfer and other forms of energy transfer,
- General energy balances and surface energy balances,
- The basic mechanisms of heat transfer, which are conduction, convection, and radiation, and Fourier's law of heat conduction, Newton's law of cooling, and the Stefan-Boltzmann law of radiation,
- The mechanisms of heat transfer that occur simultaneously in practice,

Thermodynamics and Heat Transfer

- The science of thermodynamics deals 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.
- The science of heat transfer deals with the **determination of the rates** of energy that can be transferred from one system to another as a result of temperature difference.
- Thermodynamics deals with equilibrium states and changes from one **equilibrium state** to another. Heat transfer, on the other hand, deals with systems that lack thermal equilibrium, and thus it is a **nonequilibrium** phenomenon.

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.

Objectives of Heat Transfer Science

- To extend thermodynamics analysis through the study of the modes of heat transfer.
- Development of relations to calculate heat transfer rates.

What is heat transfer?

- Heat transfer is energy in transit due to a temperature difference.

How is heat transferred?

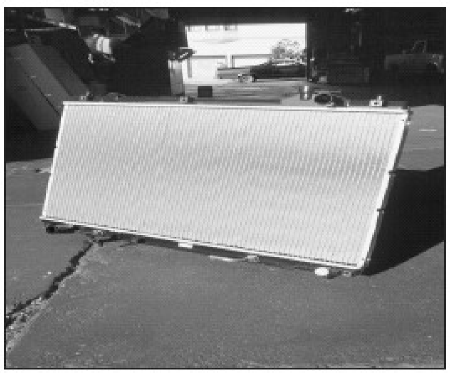
- Heat can be transferred through three modes: Conduction, Convection and Radiation

Application 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, electrical, magnetic, chemical, and nuclear.
- Their sum constitutes the total energy E (or e on a unit mass basis) of a system.
- The sum of all microscopic forms of energy is called the internal energy of a system.

Heat and Other Forms of Energy

- Internal energy may be viewed as the sum of the kinetic and potential energies of the molecules.
- The internal energy associated with the bonds within the nucleus of the atom itself is called nuclear energy.
- The internal energy associated with the atomic bonds in a molecule is called chemical (or bond) energy.
- The internal energy associated with the phase of a system is called latent heat.
- The kinetic energy of the molecules is called sensible heat.

- DO NOT confuse or interchange the meanings of Thermal Energy, Temperature and Heat Transfer

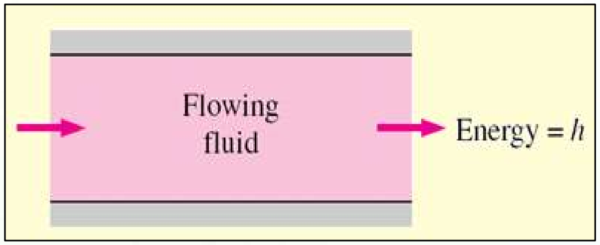
Quantity	Meaning	Symbol	Units
Thermal Energy+	Energy associated with microscopic behavior of matter	U or u	J or J/kg
Temperature	A means of indirectly assessing the amount of thermal energy stored in matter	T	K or °C
Heat Transfer	Thermal energy transport due to temperature gradients		
Heat	Amount of thermal energy transferred over a time interval $\Delta t > 0$	Q	J
Heat Rate	Thermal energy transfer per unit time	q	W

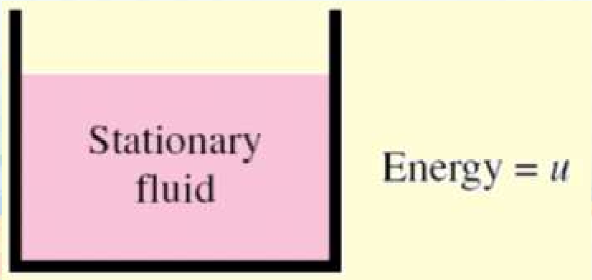
Internal Energy and Enthalpy

- In the analysis of systems that involve fluid flow, we frequently encounter the combination of properties u and P υ.

- The combination is defined as enthalpy ($h = u + P\upsilon$).

- The term $P\upsilon$ represents the flow energy of the fluid (also called the flow work).



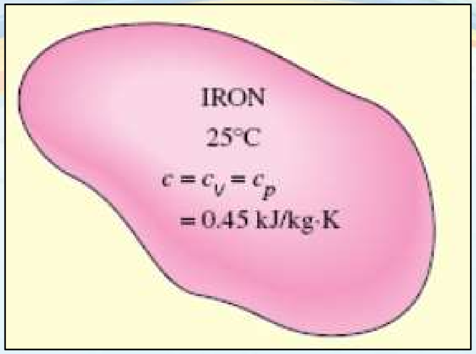


Specific Heats of Gases, Liquids, and Solids

- Specific heat is defined as the energy required to raise the temperature of a unit mass of a substance by one degree.
- Two kinds of specific heats:
  - specific heat at constant volume c_v, and
  - specific heat at constant pressure c_p.
- The specific heat of a substance, in general, depends on two independent properties such as temperature and pressure.
- For an ideal gas, however, they depend on temperature only.

Specific Heats

- At low pressures all real gases approach ideal gas behavior, and therefore their specific heats depend on temperature only.
- A substance whose specific volume (or density) does not change with temperature or pressure is called an incompressible substance.
- The constant-volume and constant-pressure specific heats are identical for incompressible substances.
- The specific heats of incompressible substances depend on temperature only.



Energy Transfer

- Energy can be transferred to or from a given mass by two mechanisms: 1) heat transfer 2) work
- The amount of heat transferred during a process is denoted by Q.
- The amount of heat transferred per unit time is called heat transfer rate, and is denoted by $\dot{Q}$.
- The total amount of heat transfer Q during a time interval Δt can be determined from $Q = \int_0^{\Delta t} \dot{Q} dt \quad (J)$
- 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 $\dot{q} = \frac{\dot{Q}}{A} \quad (W/m^2)$

The First Law of Thermodynamics

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

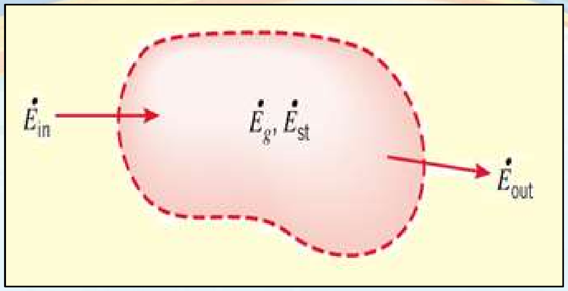
(Total energy entering the system) - (Total energy leaving the system) = (Change in the total energy of the system)

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

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

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

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



- 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 this case can be expressed as

$$\underbrace{Q_{in} - Q_{out}}_{\text{Net heat transfer}} + \underbrace{E_{gen}}_{\text{Heat generation}} = \underbrace{\Delta E_{thermal,system}}_{\text{Change in thermal energy of the system}} \quad \text{(J)}$$

Energy Balance

Closed systems

Stationary closed system, no work:

$$Q = mc_v \Delta T \qquad \text{(J)}$$

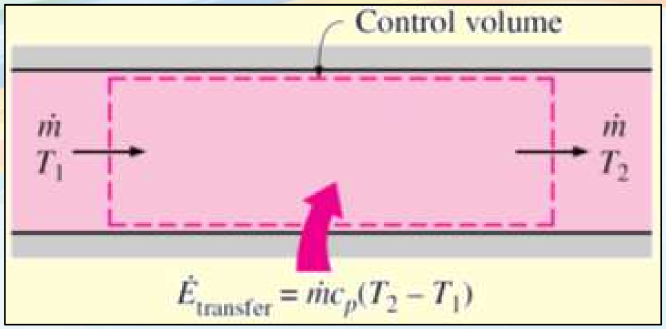
Steady-Flow Systems

- For system with one inlet and one exit:

$$\dot{m}_{in} = \dot{m}_{out} = \dot{m} \qquad \text{(kg/s)}$$

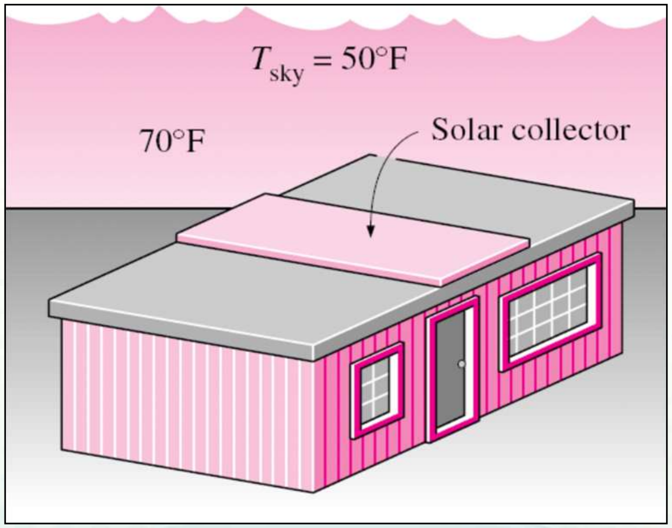
- When kinetic and potential energies are negligible, and there is no work interaction

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



Heat Transfer Mechanisms

- Heat can be transferred in three basic modes:
  - conduction,
  - convection,
  - radiation.

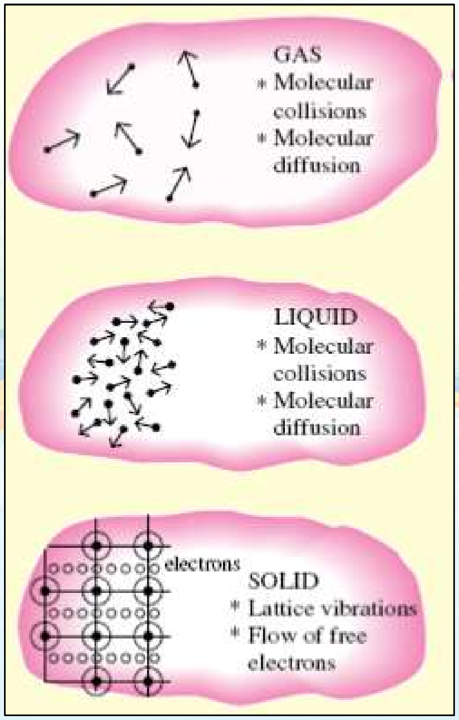


- All modes of heat transfer require the existence of a temperature difference.
- All modes are from the high-temperature medium to a lower-temperature one.

Conduction

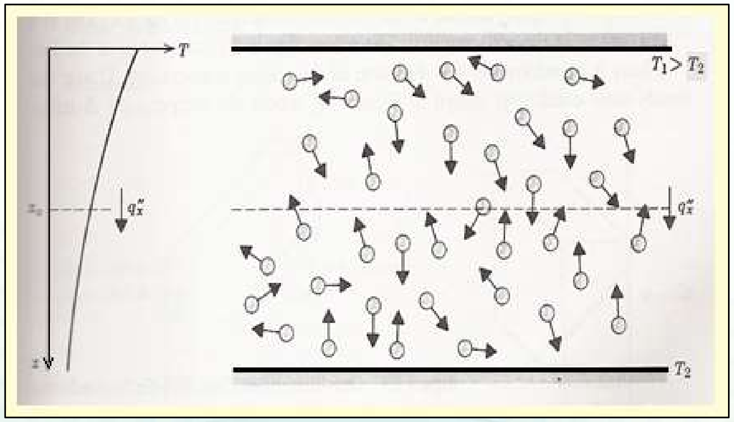
- Conduction is the transfer of energy from the more energetic particles of a substance to the adjacent less energetic ones as a result of interactions between the particles.

- Conduction can take place in solids, liquids, or gases
  - In gases and liquids conduction is due to the collisions and diffusion of the molecules during their random motion.
  - In **solids** conduction is due to the combination of vibrations of the molecules in a lattice and the energy transport by free electrons.



Physical mechanism: based on atomic and molecular activity

⇒ Conduction can be viewed as transfer of energy from the more energetic to less energetic particles of a substance due to interaction between particles (kinetic energy)



Consider a gas occupy the two surfaces shown in the drawing with no bulk motion at any point:

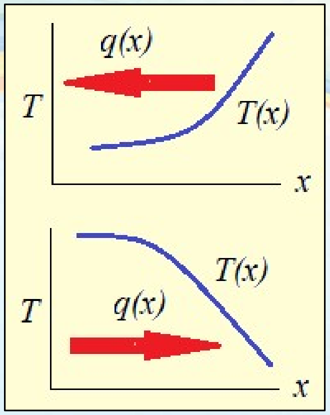
Energy* $\propto$ *T

$\therefore \uparrow T$ ⇒ Kinetic energy ⇒ Molecular energy

⇒ ↑ collisions of neighbouring molecules

⇒ Transfer of energy from more energetic to less energetic

energy is related to the random translation of motion of internal energy + vibrational motion of the molecules

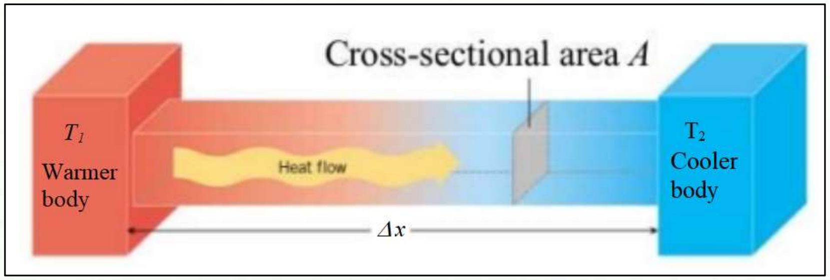


⇒ Thus, energy transfers in the direction of decreasing temperature

Rate equation for quantification of conduction – Fourier's law

Assumptions:

1. Homogeneous medium
2. One-dimensional heat flow



- Consider steady heat conduction through a large plate wall of thickness $\Delta x = L$ and cross-sectional area A.
  - Rate of heat conduction ∝ (Area) (Temperature difference)/(Thickness)

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

← **Fourier's law of heat conduction**

Remarks

⇒ Area (A) is perpendicular to the vector of heat flow; thickness (L) is parallel to the vector of heat flow.

⇒ First step in heat conduction problem: **evaluate** ***A*** **and** ***L*** **properly.**

⇒ In this course, we will use exclusively SI unit:

[W (J/s)] Or flux, $\dot{Q}/A$ [W/m^2]; A [m^2]; T [K]; L [m] ⇒ k [W/m K]

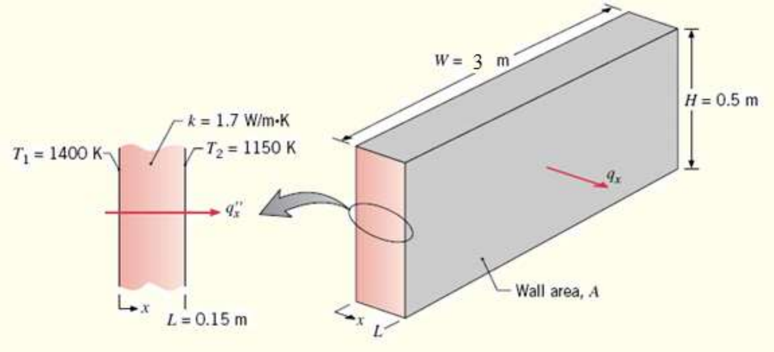
⇒ **Negative sign** is the sequence of fact that heat is transferred in the direction of decreasing temperature, i.e. $q(x)$ and $T(x)$ are opposite.

⇒ If k is constant and steady state exists, integration of Fourier's equation from T_1 to T_2 gives: $\dot{Q} = -kA\frac{T_2 - T_1}{L}$

Example:

The wall of an industrial furnace is constructed from 0.15 m thick fireclay brick having a thermal conductivity of 1.7 W/m.K. Measurements made during steady state operation reveal temperatures of 1400 and 1150 K at the inner and outer surfaces, respectively. What is the rate of heat loss through a wall which is 0.5 m by 3 m on a side?

Assumptions: 1. Steady state, 2. One dimensional through the wall, 3. Constant properties



⇒ Using Fouriers'law

$$\dot{Q}/A = k\frac{T_1 - T_2}{L} = 1.7\ \text{W/m.K}\ \frac{(1400-1150)\ \text{K}}{0.15\ \text{m}}$$

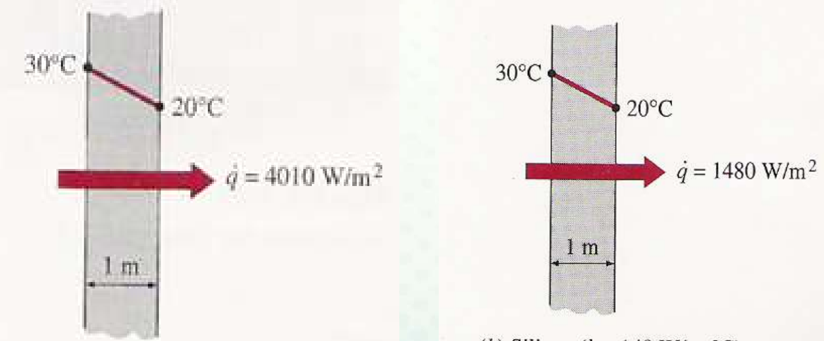
$= 2833\ \text{W/m}^2$ (Flux)

Heat transfer rate: $\dot{Q} = (\dot{Q}/A)A$ $= (0.5\ \text{m} \times 3\ \text{m})\ 2833\ \text{W/m}^2$

$= 4250\ \text{W}$

Thermal conductivity - k

⇒ It is a property of materials, which is a measure of the ability of the material to conduct heat



(*a*) Copper ($k = 401$ W/m·°C)

(*b*) Silicon ($k = 148$ W/m·°C)

⇒ k depends on microscopic structure of the substance;

⇒ Generally: $k_{solids} > k_{liq} > k_{gas}$

Why?

?

Table 1-1 | Thermal conductivity of various materials at 0°C.

Material	Thermal conductivity k W/m·°C	Thermal conductivity k Btu/h·ft·°F
Metals:		
Silver (pure)	410	237
Copper (pure)	385	223
Aluminum (pure)	202	117
Nickel (pure)	93	54
Iron (pure)	73	42
Carbon steel, 1% C	43	25
Lead (pure)	35	20.3
Chrome-nickel steel (18% Cr, 8% Ni)	16.3	9.4
Nonmetallic solids:		
Diamond	2300	1329
Quartz, parallel to axis	41.6	24
Magnesite	4.15	2.4
Marble	2.08–2.94	1.2–1.7
Sandstone	1.83	1.06
Glass, window	0.78	0.45
Maple or oak	0.17	0.096
Hard rubber	0.15	0.087
Polyvinyl chloride	0.09	0.052
Styrofoam	0.033	0.019
Sawdust	0.059	0.034
Glass wool	0.038	0.022
Ice	2.22	1.28
Liquids:		
Mercury	8.21	4.74
Water	0.556	0.327
Ammonia	0.540	0.312
Lubricating oil, SAE 50	0.147	0.085
Freon 12, CCl_2F_2	0.073	0.042
Gases:		
Hydrogen	0.175	0.101
Helium	0.141	0.081
Air	0.024	0.0139
Water vapor (saturated)	0.0206	0.0119
Carbon dioxide	0.0146	0.00844

Thermal Conductivity

- The thermal conductivity of a material is a measure of the ability of the material to conduct heat.
- High value for thermal conductivity

  → good heat conductor

- Low value

  → poor heat conductor or insulator.

Effect of temperature on k (gases)

- As previously mentioned, conduction depends merely on the molecular motion:

$$\uparrow T \Rightarrow \uparrow \text{energy}$$

$\Rightarrow$ faster transport of energy

$$\therefore k = f(T)$$

$\Rightarrow$ Based on kinetic theory for gases:

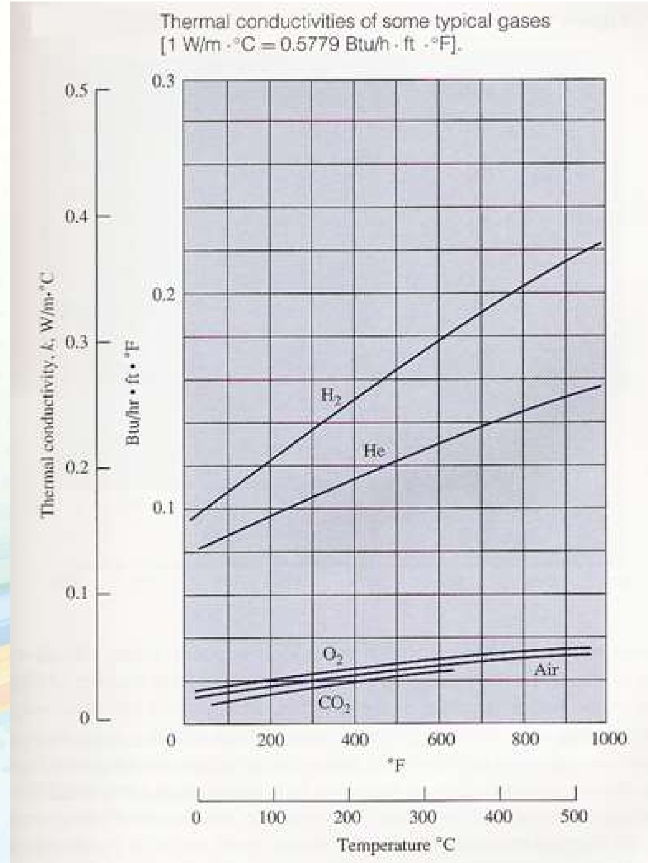
$$k \propto \sqrt{T}$$

For most gases, at low to moderate *P*;

$$k = f(T) \text{ only}$$

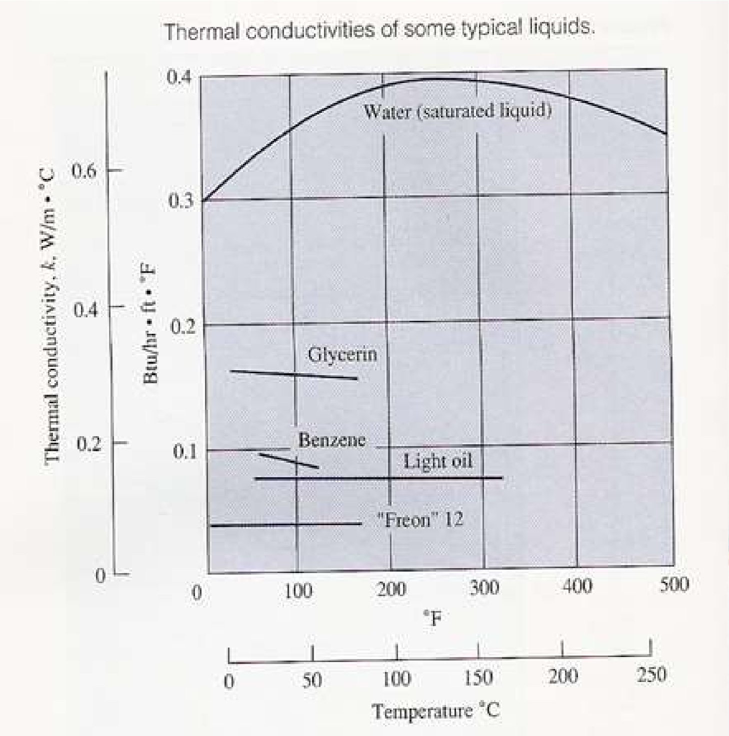
At high *P*, close to critical pressure:

$$k = f(T, P) \text{ is needed}$$



Effect of temperature on k (liquids)

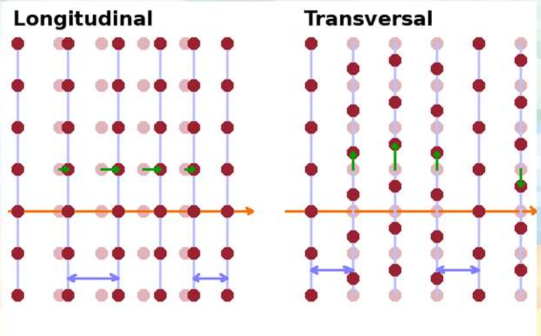
- For liquids: the mechanism of thermal energy conduction is similar to that of gases.
- However, situation is more complex since molecules are more closely spaced and molecular force fields exert a strong influence on the energy exchange in the collision process

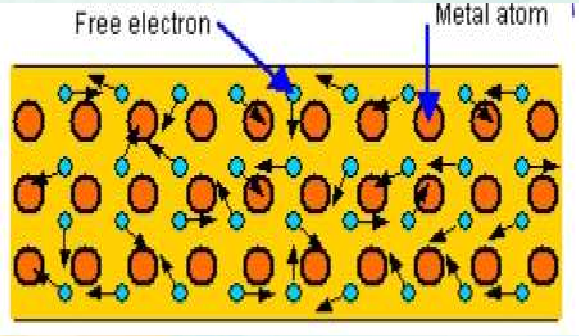


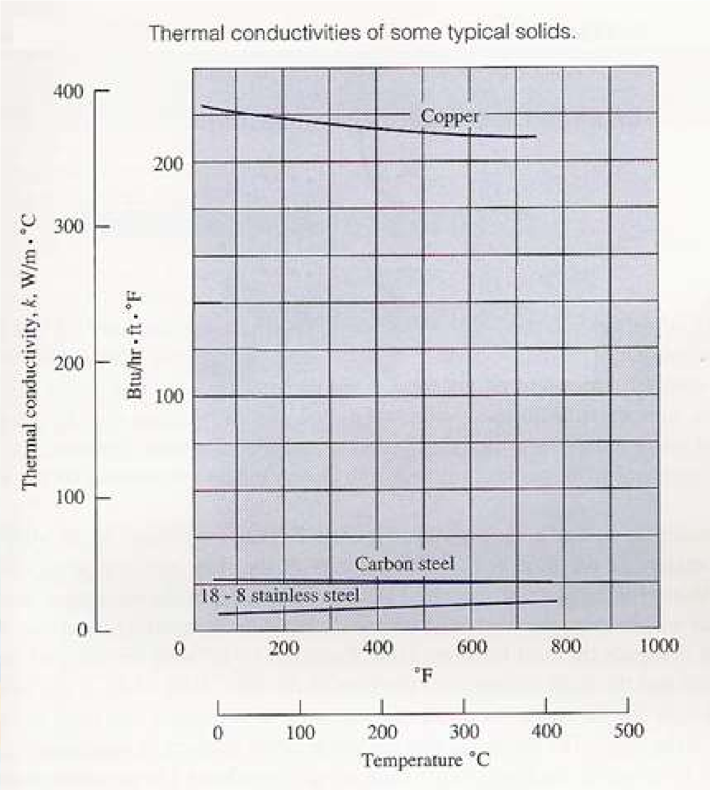
⇒ ***k* less dependent than gases**

Effect of temperature on k (solids)

- For solids: two modes for thermal conduction:
  1. Lattice vibration
  2. Transport by free electrons (electron gas)







Thermal insulators

- Materials of low *k* values can thus be used as insulators

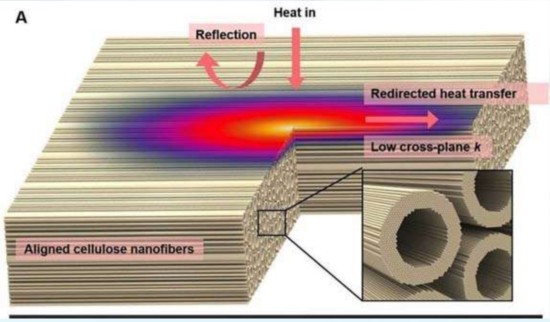
⇒ At high temperatures, energy transfer through insulating materials may involve several modes:

Effective thermal conductivities of cryogenic insulating materials for use in range 15°C to −195°C. Density range 30 to 80 kg/m^3.

Type of insulation	Effective k, mW/m·°C
1. Foams, powders, and fibers, unevacuated	7–36
2. Powders, evacuated	0.9–6
3. Glass fibers, evacuated	0.6–3
4. Opacified powders, evacuated	0.3–1
5. Multilayer insulations, evacuated	0.015–0.06

1. Conduction through the fibrous or porous solid material
2. Conduction through the air trapped in the void spaces, and
3. Radiation at relatively high temperature

- ***Super-insulators:*** special insulating materials used for storage and transport of cryogenic liquids, e.g. liquid H_2.
  - ✓ act at very low temperatures, about -250°C
  - ✓ Normally consist of multilayers of highly reflective materials



Thermal diffusivity

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

- The **thermal diffusivity** represents how fast heat diffuses through a material.
- Appears in the transient heat conduction analysis.
- A material that has a high thermal conductivity or a low heat capacity will have a large thermal diffusivity.
- The larger the thermal diffusivity, the faster the propagation of heat into the medium.

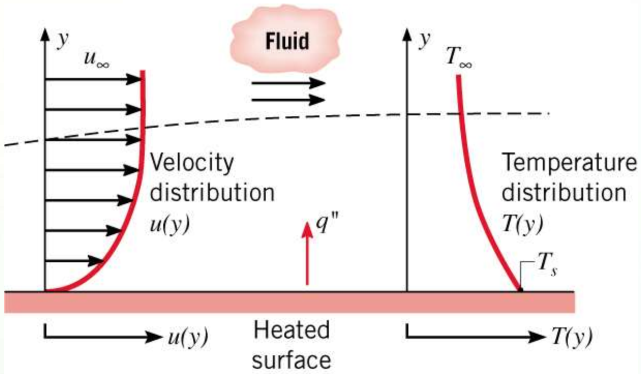
	K (W/m.K)	C_p (J/g.°C)
Copper	385	0.385
Iron	73	0.444

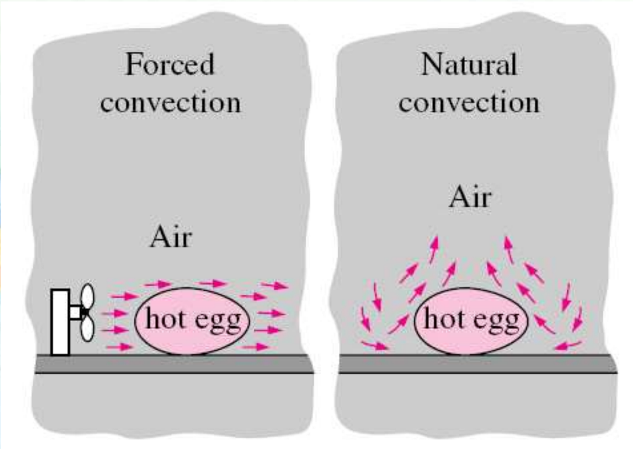
Convection

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 (L/V, S/L)





Convection

- The rate of *convective heat transfer* is expressed by **Newton's law of cooling** as

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

h is the convection heat transfer coefficient in **W/m²°C**.

- *h* depends on variables such as:
  - ✓ the surface geometry,
  - ✓ the nature of fluid motion,
  - ✓ the properties of the fluid,
  - ✓ the bulk fluid velocity.

TABLE 1–5

Typical values of convection heat transfer coefficient

Type of convection	h, W/m^2 · °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

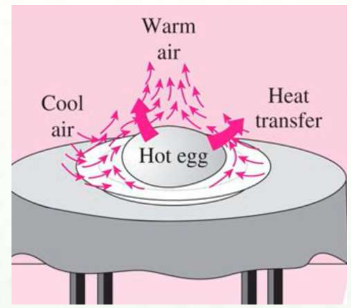
*Multiply by 0.176 to convert to Btu/h · ft^2 · °F.

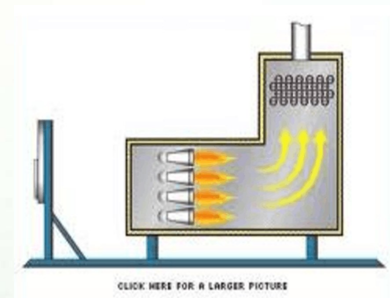
Natural and Forced Convection:

➢ The forces used to create convection currents in fluids are of two types:

- *Natural convection*: if the hot plate exposed to ambient air without external sources of motion,
- *Forced convection*: If the currents are set in motion by action of a mechanical device, such as a pump or agitator blower.
- *Boiling and Condensation*: grouped as convection.

⇒ energy is convicted by latent heat exchange or phase transition





Generally:

$h_{free} < h_{forced} < h_{boiling}$ & $h_{condensation}$

Example: Water at 300 K flows over both sides of a plate of 1 m × 2 m in area, maintained at 400 K. If the convective heat transfer coefficient is 200 W/m².K, calculate the heat transfer.

$$\dot{Q} = 2hA(T_s - T_\infty)$$

Why 2?

$$\therefore Q = (2)\ (200)\ (1)\ (2)\ (400 - 300)$$

$$Q = 80{,}000\ \text{W}$$

Approximate values of convection heat-transfer coefficients

Mode	h: W/m² · °C	h: Btu/h · ft² · °F
Free convection, $\Delta T = 30°C$		
Vertical plate 0.3 m [1 ft] high in air	4.5	0.79
Horizontal cylinder, 5-cm diameter, in air	6.5	1.14
Horizontal cylinder, 2-cm diameter, in water	890	157
Heat transfer across 1.5-cm vertical air gap with $\Delta T = 60°C$	2.64	0.46
Forced convection		
Airflow at 2 m/s over 0.2-m square plate	12	2.1
Airflow at 35 m/s over 0.75-m square plate	75	13.2
Air at 2 atm flowing in 2.5-cm-diameter tube at 10 m/s	65	11.4
Water at 0.5 kg/s flowing in 2.5-cm-diameter tube	3500	616
Airflow *across* 5-cm-diameter cylinder with velocity of 50 m/s	180	32
Boiling water		
In a pool or container	2500–35,000	440–6200
Flowing in a tube	5000–100,000	880–17,600
Condensation of water vapor, 1 atm		
Vertical surfaces	4000–11,300	700–2000
Outside horizontal tubes	9500–25,000	1700–4400

Radiation Heat Transfer

- Radiation is the energy emitted by a matter in the form of electromagnetic waves as a result of the changes in the electronic configurations of the atoms or molecules.
- In heat transfer studies we are interested in thermal radiation (radiation emitted by bodies because of their temperature).
- Although we will focus on radiation from solid surfaces, emissions may also occur from liquids and gases.
- Heat transfer by radiation does not require the presence of an intervening medium.
- Heat transfer through a vacuum is by radiation only since conduction or convection requires the presence of a material medium.

Radiation - Emission

- The maximum rate of radiation that can be emitted from a surface **(emissive power)** at a thermodynamic temperature T_s (in K or R) is given by the Stefan–Boltzmann law as

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

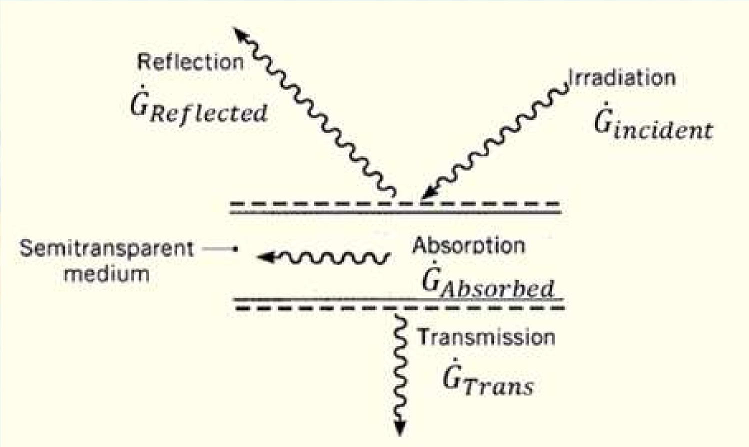
σ = 5.670*10^{-8} W/$m^2 \cdot K^4$ is the *Stefan–Boltzmann constant.*

- The **idealized surface** that emits radiation at this **maximum rate** is called a **blackbody**.

- The radiation heat flux emitted by all real surfaces is less than the radiation emitted by a blackbody at the same temperature, and is expressed as (ε is the **emissivity** of the surface)

$$\dot{Q}_{emit} = \varepsilon \sigma A_S T_S^4, \qquad 0 \le \varepsilon \le 1$$

- Emissivity depends strongly on the surface material and finish.
- Radiation may also be incident on a surface from its surroundings.
- The radiation may originate from a special source, such as the sun, or from other surfaces to which the surface of interest is exposed.
- Irrespective of the source, we designate the rate at which all such radiation is incident on a unit area of the surface as (irradiation, G′incident)

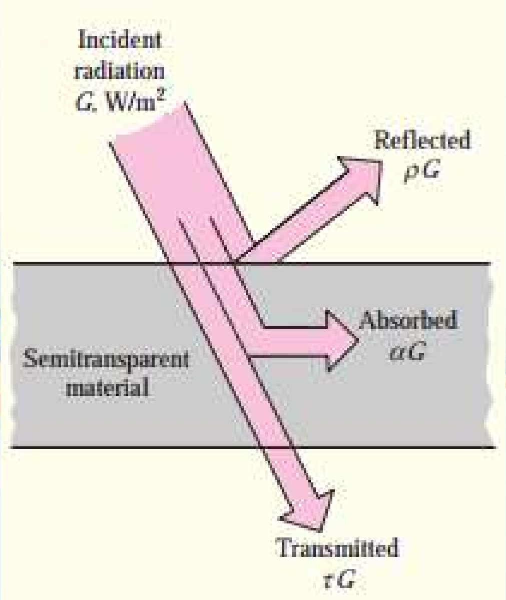


Radiation - Absorption

Receiving Properties

Targets receive radiation in one of three ways; absorption, reflection or transmission.

- ✓ Absorptivity, α, the fraction of incident radiation absorbed.
- ✓ Reflectivity, ρ, the fraction of incident radiation reflected.
- ✓ Transmissivity, τ, the fraction of incident radiation transmitted.



From Conservation of Energy: $\alpha + \rho + \tau = 1$

For opaque surfaces, $\tau = 0$, so that: $\alpha + \rho = 1$

- The rate at which a surface absorbs radiation is:

$$\dot{G}_{absorbed} = \alpha \dot{G}_{incident}$$

α: The absorptivity of the surface $0 \leq \alpha \leq 1$

- A special case that occurs frequently involves radiation exchange between a small surface at T_s and a much larger, isothermal surface that completely surrounds the smaller one.
- The *surroundings* could, for example, be the walls of a room or a furnace whose temperature T_{surr}..
- For such a condition, the irradiation may be approximated by emission from a blackbody at T_{surr}.

$\dot{G}_{incident}$: The rate at which radiation is incident on the surface $= \sigma A_S T_{surr}^4$

$$\rightarrow \quad \dot{Q}_{absorbed} = \alpha \sigma A_S T_{surr}^4 \qquad (W)$$

Radiation - Absorption

- Both ε and α depend on the temperature and the wavelength of the radiation.
- **Kirchhoff's law of radiation:** the emissivity and the absorptivity of a surface at a given temperature and wavelength are equal , $\varepsilon = \alpha$
- When a surface of emissivity ε and surface area A_s at temperature T_s is completely enclosed by a much larger (or black) surface at T_{surr} separated by a gas that does not intervene with radiation, *the net radiation heat rate between these two surfaces is given by*

Radiation - Absorption

$$\dot{Q}_{rad} = \dot{Q}_{emitted} - \dot{Q}_{absorbed}$$

$$\dot{Q}_{rad} = \epsilon\sigma A_S T_S^4 - \alpha\sigma A_S T_{surr}^4$$

But $\varepsilon = \alpha$:

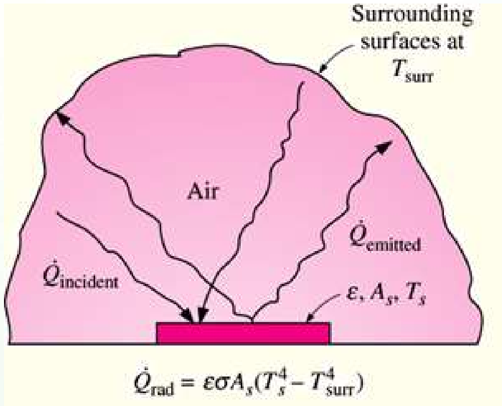
- The net radiation heat flux from the surface due to exchange with the surrounding is

$$\longrightarrow \dot{Q}_{rad} = \varepsilon\sigma A_S\left(T_S^4 - T_{surr}^4\right) \qquad (W)$$

or $\quad \dot{Q}_{rad} = h_r A_S(T_S - T_{surr})$

h_r: radiation heat transfer coefficient (W/m^2.K)

$$\longrightarrow h_r = \varepsilon\sigma(T_S + T_{surr})\left(T_S^2 + T_{surr}^2\right)$$



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

Radiation - Absorption

For combined convection and radiation:

$$\dot{Q} = \dot{Q}_{conv} + \dot{Q}_{rad}$$

$$\dot{Q} = hA_S(T_S - T_\infty) + h_r A_S(T_S - T_{surr})$$

If :

$$T_{surr} = T_\infty$$

Then $\dot{Q} = h_{combined} A_S(T_S - T_\infty)$

$h_{combined}$: combined heat transfer coefficient

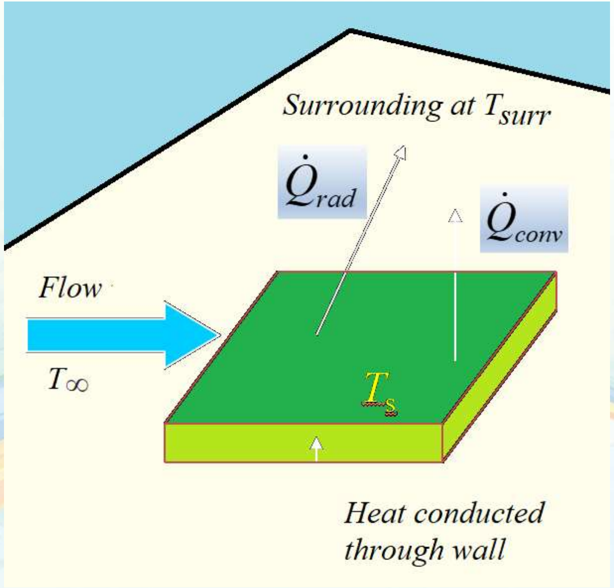
➢ It is possible that all three modes of heat transfer are present; in this case heat conducted through the wall is removed from the plate surface by a combination of convection and radiation.

Energy balance gives:

$$\dot{Q}_{cond} = \dot{Q}_{conv} + \dot{Q}_{rad}$$

Or,

$$-kA \left. \frac{dT}{dy} \right|_{y=0} = hA(T_s - T_\infty) + \varepsilon\sigma A(T_s^4 - T_{surr}^4)$$



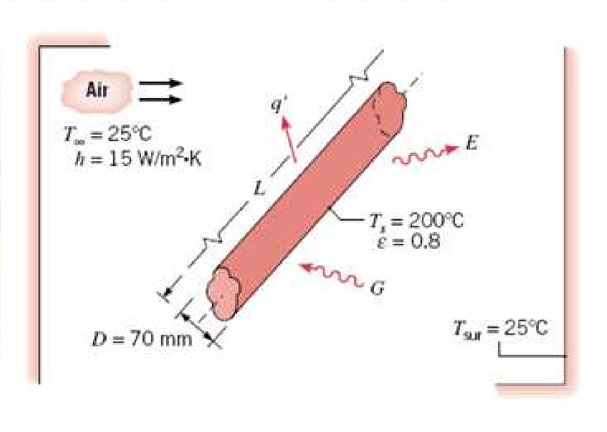
Example

An insulated steam pipe passes through a room in which the air and walls are at 25°C. The outside diameter of the pipe is 70 mm, and its surface temperature and emissivity are 200°C and 0.8, respectively. If the coefficient associated with free convection heat transfer from the surface to the air is 15 $W/m^2.K$, what is the rate of heat loss from the surface per unit length of pipe?

Assumptions:

1. Steady state conduction exist
2. Radiation exchange between the pipe and the room is between a small surface enclosed within a much larger surface

Schematic



Example Cont.

Analysis: Heat loss from the pipe is by convection to the room air and radiation exchange with the surface:

$$q = h(\pi DL)(T_s - T_\infty) + \varepsilon\sigma(\pi DL)(T_s^4 - T_{sur}^4)$$

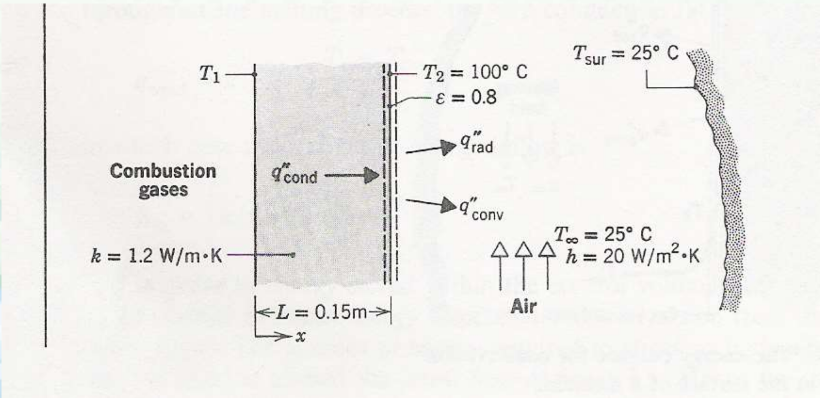
$$q / L = 15(\pi 0.07)(200 - 25) + 0.8(\pi 0.07)5.67 \times 10^{-8}(473^4 - 298^4)$$

= 577 + 421

= 998 W/m

Example

The hot combustion gases of a furnace are separated from the ambient air and its surrounding, which are at 25°C, by a brick wall 0.15 m thick. The brick has a thermal conductivity of 1.2 W/m.K and a thermal emissivity of 0.8. Under steady-state conditions and out surface temperature of 100°C is measured. Free convection heat transfer to the air adjoining this surface is characterized by a convection coefficient h = 20 W/m^2.K. What is the brick inner surface temperature?



Answer: T_1 = 352°C