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Thermal Properties

Modern Construction Materials – Lecture 11
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Thermal Properties

- The response of a material to the application of heat is characterised by its thermal properties.

- The critical thermal properties of a material that affect its utilisation are the heat capacity, thermal expansion and thermal conductivity.

Heat Capacity

- Heat capacity is the amount of heat energy required to raise the temperature of a material by one degree.
- It is indicative of the ability of the material to absorb heat from its external surroundings.
- *Specific heat* (c_p) is the heat capacity per unit mass; its units: [J/kg-K], [cal/g-K]

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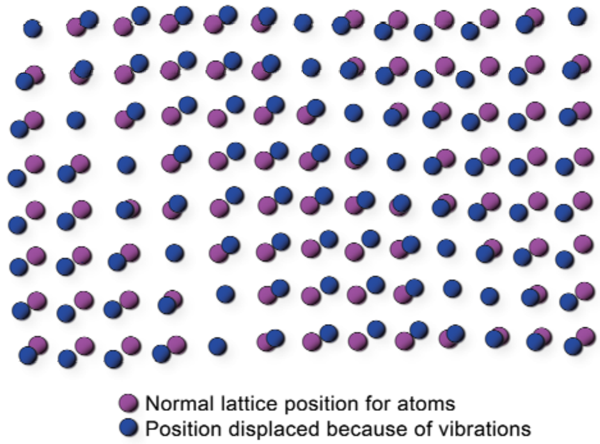
Vibrational Heat Capacity

In most solids, the principal mode of absorption of thermal energy is by the increase in the vibrational energy of the atoms.



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Thermal Expansion

- Most solids expand when they are heated and contract when cooled.
- The relative change in length with temperature can be expressed as:

$$\frac{\Delta l}{l_0} = \varepsilon_{th} = \alpha_l \Delta T$$

where l_0 and Δl are the initial length and the length change for a temperature change of ΔT, respectively; ε_{th} is the thermal strain; and α_l is the *linear coefficient of expansion*.

Thermal Expansion

Volumetric changes due to temperature can be represented as:

$$\frac{\Delta V}{V_0} = \alpha_v \Delta T$$

where α_v is the *volume coefficient of thermal expansion*. When the thermal expansion is isotropic, $\alpha_v = 3\alpha_l$.

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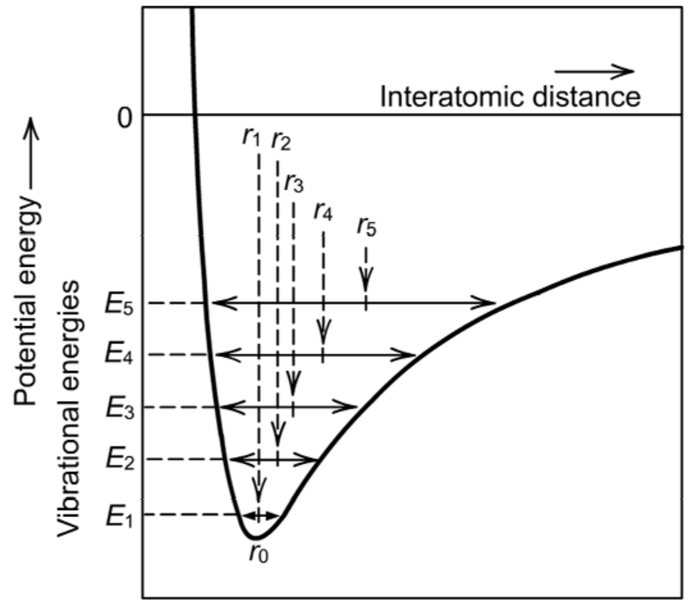
Thermal Expansion



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Thermal Expansion

- Thermal expansion arises from an increase in the interatomic spacing when the potential energy increases.
- In the potential energy versus interatomic spacing well, the minimum energy corresponds to 0° K, where the interatomic spacing is r_0. As the temperature increases, the vibrational energy increases and the average vibrational amplitude corresponds to the well width at the corresponding energy level.
- The average interatomic distance increases with the temperature since the well is asymmetric.

Thermal Expansion

- **METALS:** Linear coefficients of expansion normally vary from $5\sim25\times10^{-6}$ / °C. Some alloys with better dimensional stability have been developed; e.g., there are iron-nickel and iron-cobalt alloys with α_l values in the order of 1×10^{-6} / °C.

- **CERAMICS:** Strongly bonded ceramics have relatively low α_l values, e.g., in the range of $0.5\sim15\times10^{-6}$ / °C. Fused silica glass has an expansion coefficient of 0.5×10^{-6} / °C due to the low atomic packing density, where interatomic expansion produces little macroscopic dimensional changes.

Thermal Expansion

- **POLYMERS:** Some polymeric materials have high expansion coefficients, in the range of $50\sim300\times10^{-6}$ / °C. The highest expansion is seen in linear and branched polymers. With increased cross-linking, the expansion coefficient decreases, and is lowest in thermosetting network polymers.

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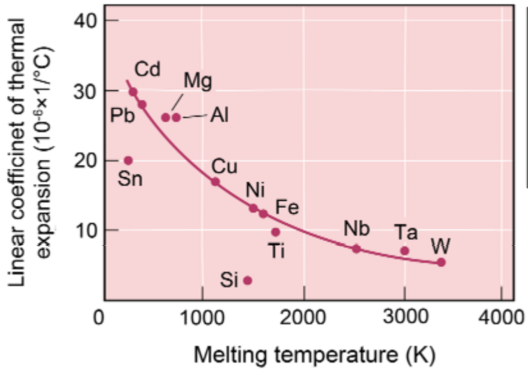
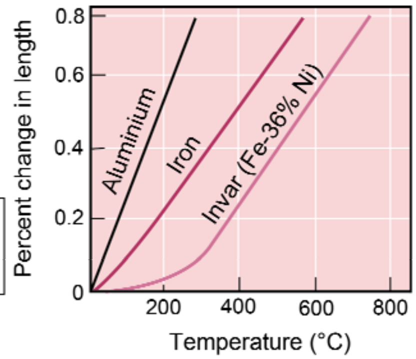
Thermal Expansion



Relation between thermal expansion and melting point (depends on bond type and strength)



Thermal expansion of some metals

Thermal Stresses

- When thermal expansion is restrained, *thermal stresses* develop in the material.
- In brittle materials, temperature gradients (e.g., temperature differences between the exterior and interior) can lead to cracking.
- Rapid cooling of brittle materials creates surface tensile stresses, which result in crack propagation, and even failure. This is called *thermal shock*.
- Common soda-lime glasses with α_l in the range of 9×10^{-6} / °C is more susceptible to thermal shock than borosilicate (or Pyrex) glass that has an α_l value of about 3×10^{-6} / °C.

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Thermal Conductivity

Thermal conduction is the phenomenon by which heat is transported from high- to low-temperature regions of a material. The ability of a material to transfer heat is called *thermal conductivity*.

Thermal Conductivity

- Thermal conductivity can be defined by the expression:

$$q = -k\frac{dT}{dx}$$

where q is the heat flux (or heat flow), per unit time per unit area; dT/dx is the temperature gradient; and k is the thermal conductivity.

The units for q and k are [W/m^2] and [W/m-K], respectively.

- Heat is transported in solids by both lattice vibration waves and free electrons.

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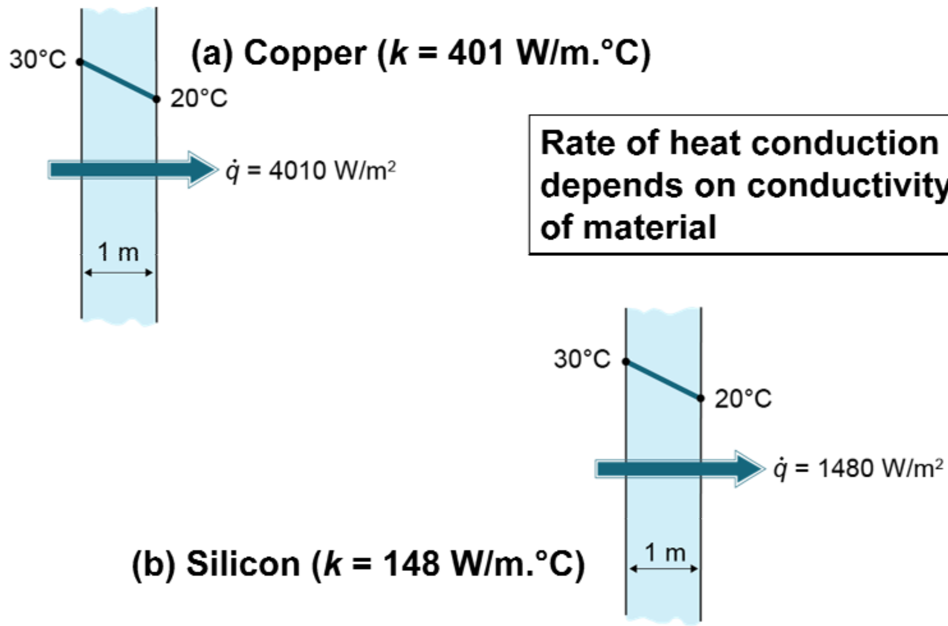
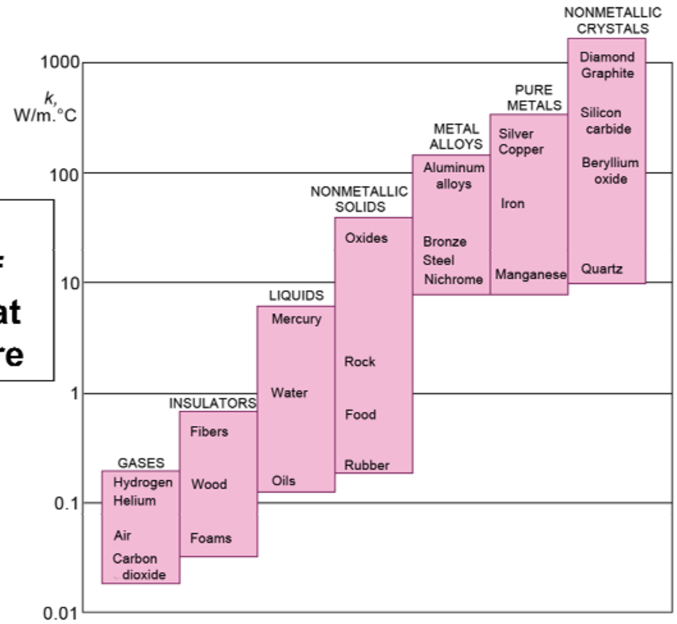
Thermal Conductivity



Rate of heat conduction depends on conductivity of material

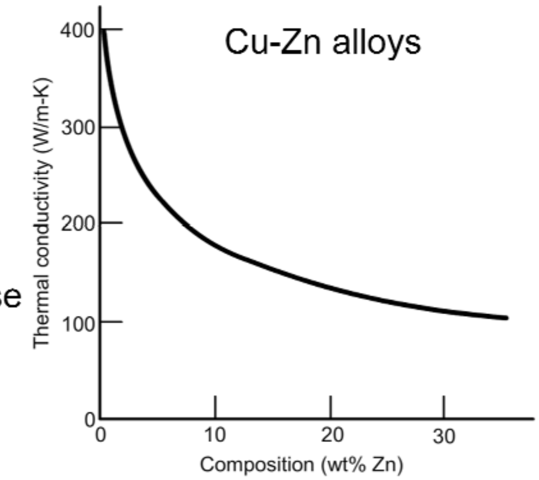
Thermal Conductivity

Thermal conductivities of some materials at room temperature



Thermal Conductivity

METALS: The thermal conductivities of common metals generally are in the range of 20~400W/m-K. Alloying metals with impurities tends to decrease the thermal conductivity; e.g., stainless steel, Cu-Zn alloys.



Thermal Conductivity

POLYMERS: Thermal conductivities of most polymers are in the order of 0.3 W/m-K. In these materials, heat transfer is realised by the vibration and rotation of the chain molecules. A polymer with a higher degree of crystallinity and more ordered structure will have higher conductivity than an equivalent amorphous material. Many polymers are good thermal insulators.

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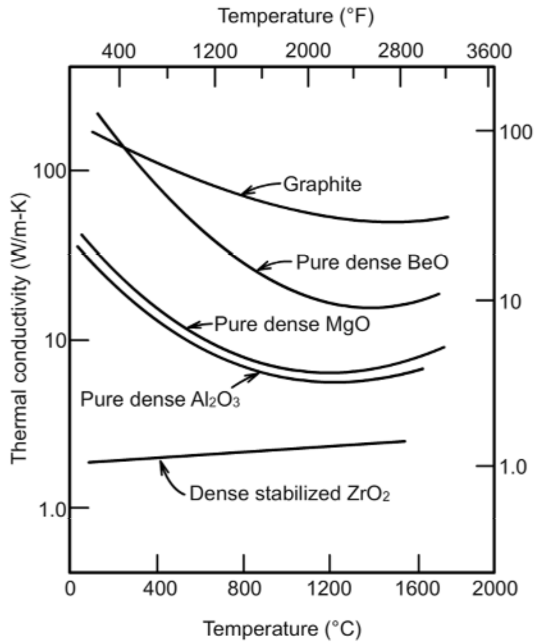
Thermal Conductivity

CERAMICS: The thermal conductivities of several ceramics, at room temperature, is in the range of 2~50 W/m-K. Glass and other amorphous ceramics have lower conductivity than crystalline ceramics.

The porosity of ceramics influences conductivity significantly since the thermal conductivity of air (in the pores) is only about 0.02 W/m-K.

The thermal conductivity of many ceramics decreases as the temperature increases, at least at lower temperatures, due to the higher scattering of the lattice vibrations. At higher temperatures, the conductivity may increase due to radiant heat transfer.

Thermal Conductivity



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Thermal Properties

Material	c_p (J/kg-K)[a]	α_l $[(°C)^{-1} \times 10^{-6}]$[b]	k (W/m-K)[c]
		Metals	
Aluminum	900	23.6	247
Copper	386	16.5	398
Gold	130	13.8	315
Iron	448	11.8	80.4
Nickel	443	13.3	89.9
Silver	235	19.0	428
Tungsten	142	4.5	178
1025 Steel	486	12.5	51.9
316 Stainless steel	502	16.0	16.3[d]
Brass (70Cu–30Zn)	375	20.0	120
		Ceramics	
Alumina (Al_2O_3)	775	8.8	30.1
Beryllia (BeO)	1050[d]	9.0[d]	220[e]
Magnesia (MgO)	940	13.5[d]	37.7[e]
Spinel ($MgAl_2O_4$)	790	7.6[d]	15.0[e]
Fused silica (SiO_2)	740	0.5[d]	2.0[e]
Soda–lime glass	840	9.0[d]	1.7[e]
		Polymers	
Polyethylene	2100	60–220	0.38
Polypropylene	1880	80–100	0.12
Polystyrene	1360	50–85	0.13
Polytetrafluoroethylene (Teflon)	1050	135–150	0.25
Phenol-formaldehyde (Bakelite)	1650	68	0.15
Nylon 6,6	1670	80–90	0.24
Polyisoprene	—	220	0.14

c_p : specific heat

α_l : coefficient of linear expansion

k : thermal conductivity

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References

- *Materials Science and Engineering: An Introduction*, W.D. Callister, John Wiley, 1994.

- *The Science and Design of Engineering Materials*, J.P. Schaffer, A. Saxena, S.D. Antolovich, T.H. Sanders and S.B. Warner, Irwin, 1995.