Physical Properties of Material

The Challenger Accident

Challenger, launched at 11:38 am EST after a freezing Florida night, exploded 73 seconds after liftoff due to the failure of an O-ring seal on the right solid rocket booster killing 7 passengers. Redesign of the seal and modification of the space shuttle took almost 3 years. The replacement Endeavor resumed flight Sept. 29, 1988.

A material undergoes transition under the influence of temperature and pressure, and these changes are physical in nature, because their molecules remain intact. During our school days, we were asked to distinguish physical and chemical changes. At that stage, we began to think in more details than what our senses have detected. Having the ability to distinguish physical properties from chemical properties is indeed a good beginning in the study of materials.

The Challenger disaster is due to a human failure to recognize the limitation of the property of o-ring material.

Effects of Temperature on Substances

Phase Transition at Constant Pressure

Temperature

Vapor

Boiling point
Heat of vaporization

Liquid

Melting point
Heat of fussion

Solid

When temperature rises, a typical substance changes from solid to liquid and then to vapor, at a constant pressure. Some substance has several crystal forms in the solid state. The glassy state is also considered a solid. Transitions from one solid to another solid form, from solid to liquid, from liquid to vapor, from vapor to solid etc. are called phase transitions.

Phase transitions from solid to liquid, and from liquid to vapor absorb heat. The temperature of a system usually does not
change as long as two phases are present. The (phase) transition temperature from solid to liquid is called the melting point whereas the temperature at which the vapor pressure of a liquid equals 1 atm (101.3 kPa) is called the boiling point. Thus, the measured boiling point depends on the atmosphere pressure. For compounds that decompose at high temperature, boiling point can be either specified at lower pressure or be replaced by the decomposition temperature. Thus, conditions as well as the value of boiling point listed in literature must be taken into account for application considerations. Boiling points of mixtures change with composition. The boiling points of some common mixtures are listed in handbooks, and boiling points can be used to assess the composition of a mixture or the purity of a compound.

However, a glassy material becomes soft in a wide range of temperatures. The temperature at which the material becomes soft (behave molten like) is called glassy temperature, but it may be a range of temperatures. Behavior of a substance as the temperature changes must be carefully considered in its applications. Behavior of a mixture as temperature rises is different from its components. There is no theoretical way to predict the behavior of a mixture from its components, even if its exact composition is known. Addition of one or more materials usually changes the melting or glassy temperature of a substance. Thus, we often employ a blend (mixture) of materials whose behavior is acceptable within the desirable range of temperatures. Antifreeze for automobile radiator and deicing liquid for airplanes are examples of this application.

The behavior of mixtures as temperature and pressure change often requires a phase diagram to represent, and there are several models of two-component systems. A phase diagram of a many-component system requires a lengthy study.

**Combined Effect of Temperature and Pressure on the Behavior of Material**

When the temperature remains constant, the pressure also affects the behavior of a material. The volume of a gas changes as the pressure changes even if temperature remains the same. When temperature is close to the melting point of a substance, a liquid may solidify or a solid may melt as the pressure changes. A diagram showing the temperature and pressure combined effect on a system is called a phase diagram.

One-component phase diagrams for water and carbon dioxide are given here.

At pressure below 5.1 atm, solid and gas carbon dioxide coexist, but the vapor pressure depends on the temperature. The variation of vapor pressure is represented by a line, which separates the Dry ice phase from the CO₂ Gas phase. The vapor pressure of dry ice at 194.6 K (-78.5°C) the pressure is 1 atm, and at 216.7 K (-56.4°C) the pressure is 5.11 atm. The line separates the conditions for the formation of solid and vapor. A similar curve borders between liquid and gas CO₂, whereas a line separates dry ice from the liquid phase. At 216.7 K, vapor pressures of solid and liquid CO₂ are the same, 5.11 atm. At, 5.11 atm and 216.7 K, all three phases coexist, and the condition is called the triple point.
Chemical energy Use FIND to search for "tin disease" after

**Thermal expansion coefficient**

| Linear thermal expansion coefficient per K at room temperature of some substances |
|-----------------------------|-------------------|
| Aluminum                    | 24                |
| Copper                      | 17                |
| Diamond                     | 1                 |
| Glass                       | 11                |
| Pyrex glass                 | 3                 |
| Rubber, hard                | 80                |

A substance expands on heating. For a rod, the lengthening of a unit length per degree Kelvin is the linear thermal expansion coefficient. This factor affects the substance performance in machines or structural assemblies. Thermal expansion causes tight fitted parts to break and moving part to jam, in any machine. The problem is serious if different material is used. When a large body of glass is subject to local heating or cooling, it breaks up due to expansion or shrinkage. Thermal expansion also causes distortion, and some thermometers are made of two strips of different metals. Thermal properties must be considered in any engineering constructions such as railroad, bridges, pipelines, and buildings, especially in areas where temperatures go to extreme values.

**Heat and Electric Conductance**

<table>
<thead>
<tr>
<th>Electric resistance of some elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>Al</td>
</tr>
<tr>
<td>Au</td>
</tr>
<tr>
<td>W</td>
</tr>
<tr>
<td>Ge</td>
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<tr>
<td>Si</td>
</tr>
</tbody>
</table>
Transmissions of energy and electric charge across a body of material give rise to heat and electric conductance respectively. The rate of flow across a unit-area section when the temperature or electric potential difference applied to the wire of unit length is called the thermal or electric conductance coefficient. Metals are usually good conductors of both, and their conductance coefficients are high. Insulation material for heat and electricity should have low conductance, whereas metals have high conductance.

The reciprocal of electric conductance is called electric resistance; thus, the higher the conductance, the lower the resistance. Electric resistance for some familiar materials are given in the table here. Note the large range of $10^{15}$ among these substances. Aluminium and copper are very good conductors, and their resistances are very low, in the order of $10^{-8}$, almost 100 times smaller than that of tungsten, W. Germanium, Ge, and silicon, Si, are typical semiconductors, whereas sulfur and phosphorous are insulation material.

### Magnetic Properties

A magnetic field strength is measured in Tesla (T) and gauss (G, $1 \text{T} = 10,000 \text{ G}$). The Earth magnetic field is 0.5 G. When a material is placed into a magnetic field $H$, a magnetic field of different intensity $B$ is produced inside the material. The ratio $B/H$ is called the magnetic susceptibility. The higher the magnetic susceptibility, the easier the material is magnetized. Most substances are diamagnetic. The magnetic fields ($B$) within the bodies of these substances when they are placed in a magnetic field ($H$) are less than that of an empty space (vacuum); thus their magnetic susceptibilities ($B/H$ ratio) are less than 1. When a body of paramagnetic substance is placed in a magnetic field, the intensity of the field within the body is slightly larger than that of the applied field. The magnetic susceptibilities of paramagnetic substances are slightly greater than 1.

Iron, cobalt and nickel are some ferromagnetic substances, there are some other alloys and oxides that behave this way. They possess a spontaneous magnetic moment. A magnetic field is present in these materials even in the absence of an external magnetic field. However, ferromagnetism is temperature dependent, and above the so called Curie temperatures of the substances, magnetism vanishes. The Curie temperature or Curie point of a substance is unique. The Curie points for Fe, Co, and Ni are 1043, 1400, and 630 K respectively.

Ferromagnetism are due to the presence of magnetic domains in the substance, and when these domains line up parallel to each other, they give a net magnetic field. If the domains line up antiparallel to each other at the Curie point, the substance is said to be antiferromagnetic. The magnetic susceptibility reaches a maximum at Curie temperature for antiferromagnetic material. For example, FeO, MnO, CoO, NiO, FeF$_2$, FeCl$_2$, a-Mn, Cr$_2$O$_3$ etc. are some of the antiferromagnetic substances.

Ferromagnetic substances play important roles in recording tapes and disks for audio, video, and computer signals. Furthermore, ferromagnetic materials are used in permanent magnets, which are used in motors, antenna, and speakers. Recent development in strong magnets enables communication equipment and computers to be miniaturized.
Density

The mass per unit volume (cm\(^3\) = mL, m\(^3\) etc.) of is called density, an intensive property. Often, specific gravity is given. Specific gravity is the ratio of density of a substance compared to that of water. As a ratio, it has no units. Since density of water is 1.00 g/mL, specific gravity is the density in g/mL. Other units to use are kg/L or 10\(^3\) kg m\(^{-3}\). Specific gravity for a few common substances are given here: Au, 19.3; mercury, 13.6; alcohol, 0.7893; benzene, 0.8786. Do you know which element has the highest density?

Dielectric Constant

The dielectric constant \(\varepsilon\) of a medium is its ability to reduce the force \(F\) of attraction of charged \((q_1\) and \(q_2\)\) particles separated at distance \(r\), compared to vacuum. It is usually defined by the equation, \(F = q_1 q_2 / (\varepsilon r)\). A substance with large dielectric constant placed between two plates to which an electric voltage has been applied will result in a weak electric field within it. Water, due to its polar nature, has a rather large dielectric constant, 80.4. At the atomic scale, water molecules weaken the attraction between Na\(^+\) and Cl\(^-\) ions, resulting in dissolving it. Dielectric constants for some familiar substances are: H\(_2\)O, 80.4; methanol, 33.6; benzene, 2.3; H\(_2\) at 20 K, 1.23.

Heat capacity

The amount of energy required to raise the temperature of a substance by 1 K is the heat capacity. If the substance has a unit mass, the amount is referred to as specific heat capacity, or specific heat. For example, it takes 1 cal (4.184 J) to raise the temperature of 1 g water by 1 K. Thus, the specific heat for water is 1 cal g\(^{-1}\) K\(^{-1}\) (75 J mol\(^{-1}\) K\(^{-1}\)). Specific heat of water is large compared to most other substances, for example: Cu, 24.4 J mol\(^{-1}\) K\(^{-1}\). This large heat capacity of water affect the weather, making temperatures in areas close to large bodies of water more steadier than large dry land.

Refractive Index

Refractive index of some common substances

<table>
<thead>
<tr>
<th>Substance</th>
<th>Refractive Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>water</td>
<td>1.3</td>
</tr>
<tr>
<td>benzene</td>
<td>1.5011</td>
</tr>
<tr>
<td>ethanol</td>
<td>1.359</td>
</tr>
<tr>
<td>quartz</td>
<td>1.5*</td>
</tr>
<tr>
<td>NaCl solid</td>
<td>1.5</td>
</tr>
</tbody>
</table>

The ratio of light speed in vacuum to its speed in the medium is refractive index. Light travel slower in any medium than in vacuum. Thus, refractive index is always greater than unity (1), and light beam usually bents when entering from air to another medium. This value depends on the wavelength of the light used, and the property is important for material used in optics instrument such as eye glasses. The higher the refractive index, the thinner the glasses to achieve the same
power. The difference in refractive indexes between two liquid gives rise to the visible boundary between layers.

Difference in refractive indexes of lights of different wavelengths can be separated using a prism. Refractive indexes for some familiar substances are given in a box. It should also be kept in mind that index of refraction changes with dissolved substance and concentration.

**Solubility**

The amount of substance dissolved in 100 mL of solvent is called **solubility**. However, units for solubility might be specified in some other fashion. Solubility depends on temperature, and the variation can be used to separate components in a solid mixture. Sodium acetate trihydrate, CH$_3$COONa·3H$_2$O, when heated will melt in the sense that it dissolves in its water of crystallization. This liquid remains liquid till about -15 °C (258 K), and when crystallization does take place after triggered by cold hand, heat is released providing a source of heat. This property provides a winter hand warmer pack for skiers or winter travelers.

Washing and cleaning also involve solubility, and the formulation of an effective cleaning agent requires the knowledge of many substances. Substances can be classified according to polarity. Water, ammonia (NH$_3$), and methanol (CH$_3$OH) are polar, because their molecules have negative and positive sites, whereas methane (CH$_4$), gasoline, and motor oil are non-polar. Regarding solubility, a rule of thumb reads like dissolves like, which means that polar solvents dissolve polar substances and non-polar solvents dissolve non-polar substances. An organic compound with a polar group attached to non-polar chain will bring water molecules to a non-polar surface, and hence it can be used as a detergent or wetting agent. This rule of thumb has potential for both domestic and industrial applications.

**Optical activity**

The ability of certain substances to rotate the plane of polarized light as it passes through a crystal, liquid, or solution is generally referred to as the optical activity. Substances possessing this activity usually lack a center of symmetry (see crystal symmetry), and they have two isomers as mirror images of each other. The two isomers, called dextrorotatory (d, right hand) or laevorotory (l, left hand) isomers, rotate the polarized light in opposite directions. Thus, equi-molar or racemic mixture of the two appears optically inactive. For example, sugar, tartaric acid, and aminoacids are optically active compounds.

**Viscosity and Surface Tension**

**Viscosity** and **surface tension** are properties of liquid state. The former is a measure of its resistance to flow. Molasses, glycerin, oil, softened glass have high viscosity, and water, gasoline, ethanol have low viscosity. The SI units for viscosity is N·s/m$^2$, but the unit poise ($P$, a cgs unit) have been used for a long time, and is more common, and 1 P = 0.1 N·s m$^{-2}$. Viscosity usually decreases with increase in temperature, and softened glass has a viscosity more than 1014 N·s m$^{-2}$.

Surface tension results from intermolecular attraction, the higher of which, the higher surface tension. Energy required to stretch the surface by some defined unit is called **surface tension**, and whose unit is N·m/m$^2$ (= N/m). Like viscosity, surface tension decrease with increase temperature. Surface tension causes the dew and raindrops to be round, and the idea to manufacture perfect spheres in zero gravity zone is making use of surface tension. Soap reduces surface tension of water and soapy water forms bubbles when air is blown into it.
Activities:

Ask the class to give examples of physical properties.

Describe an application of a material based on any one of the physical properties.

Point out two physical properties that has not been mentioned here.

What substance has the highest dielectric constant?

What is a beam of polarized light?

Give a sketch of the molecular structure of an aminoacid.

Learning Guide

- Describe phase transitions
- Describe the phase diagram of water or carbon dioxide.
- What is dielectric constant? What is the dielectric constant for water and methanol? Why do ionic substances such as NaCl and CaCO₃ have higher solubility in water than in methanol?

Contributors

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