General Physics II at EPFL

(2018-2019 SS, Wed 17:15-19:00 and Thu 08:15-10:00, Exercise Thu 10:15-12:00)

Thermodynamic (4th week)

Energy, Heat, and Work

Energy

A unit of energy more related to thermal energy:

1 calorie (cal) = energy needed to increase the temperature of 1 g of water by 1 Celsius degree

1 cal = 4.186 J = 4.186 Nm

Temperature T in Kelvin: a measure of the average kinetic energy of individual molecules

Internal Energy E_{int}: total energy contained by a thermodynamic system

= thermal energy + potential energy

Thermal energy is kinetic energy due to translation, rotation and vibration, directly link to the temperature.

Internal energy of an ideal gas: no potential energy, i.e. internal energy is equal to the thermal energy. Thermal energy is only due to the translational kinetic energies of all the gas molecules.

$$E_{\text{int}} = E_{\text{kin}} = N\frac{m\langle v^2\rangle}{2} = \frac{3}{2}NkT = \frac{3}{2}nRT$$

where N is the number of molecules and n number of moles of the gas.

Flow of energy

Work (W): flow of energy out from the system in mechanics not related to temperature

Heat (Q): flow of energy into the system due to the difference in temperature

They can be transferred from one to the other**. They do not define the state, i.e. not state variables**.

Sensible heat

For Sensible heat, heat into the system, Q, changes the temperature of the system by ΔT:

$$Q = m \times c \times \Delta T$$

where m is the mass of the material in the system and c is a quantity characteristic to the material called "specific heat". The unit of c is given by $\text{J}/(\text{kg}\cdot \text{C}^\circ)$ or $\text{kcal}/(\text{kg}\cdot \text{C}^\circ)$. From the definition of the calorie, c for the water at 15°C and a constant pressure of 1 atm is $1\ \text{kcal}/\text{kg}\cdot \text{C}^\circ$.

Example:

We consider a system of Iron container of 20 kg, holding 20 kg of water. The specific heat for the iron is $0.11\ \text{kcal}/(\text{kg}\cdot \text{C}^\circ)$. Now we calculate the heat needed to increase the temperature of the system from 10°C to 90°C. For iron

$$Q_{\text{iron}} = m\cdot c_{\text{iron}}\cdot \Delta T = 20\text{kg}\cdot 0.11\text{kcal}\cdot \left(\text{kg}\cdot \text{C}^\circ\right)^{-1}\cdot (90-10)\text{C}^\circ = 176\text{kcal}$$

and for water

$$Q_{\text{water}} = m\cdot c_{\text{water}}\cdot \Delta T = 20\text{kg}\cdot 1\text{kcal}\cdot \left(\text{kg}\cdot \text{C}^\circ\right)^{-1}\cdot (90-10)\text{C}^\circ = 1600\text{kcal}$$

The total heat required is thus

$$Q_{\text{total}} = Q_{\text{iron}} + Q_{\text{water}} = 1776\text{kcal}$$

When the system cools down from 90°C to 10°C, the heat out from the system is 1776kcal. Note that water is a good heat reservoir being a material with one of the highest value of c.

Open, Closed and Isolated System

Closed system: can exchange energy but not matter with the surroundings

Isolated system: can exchange neither energy nor matter with the surroundings

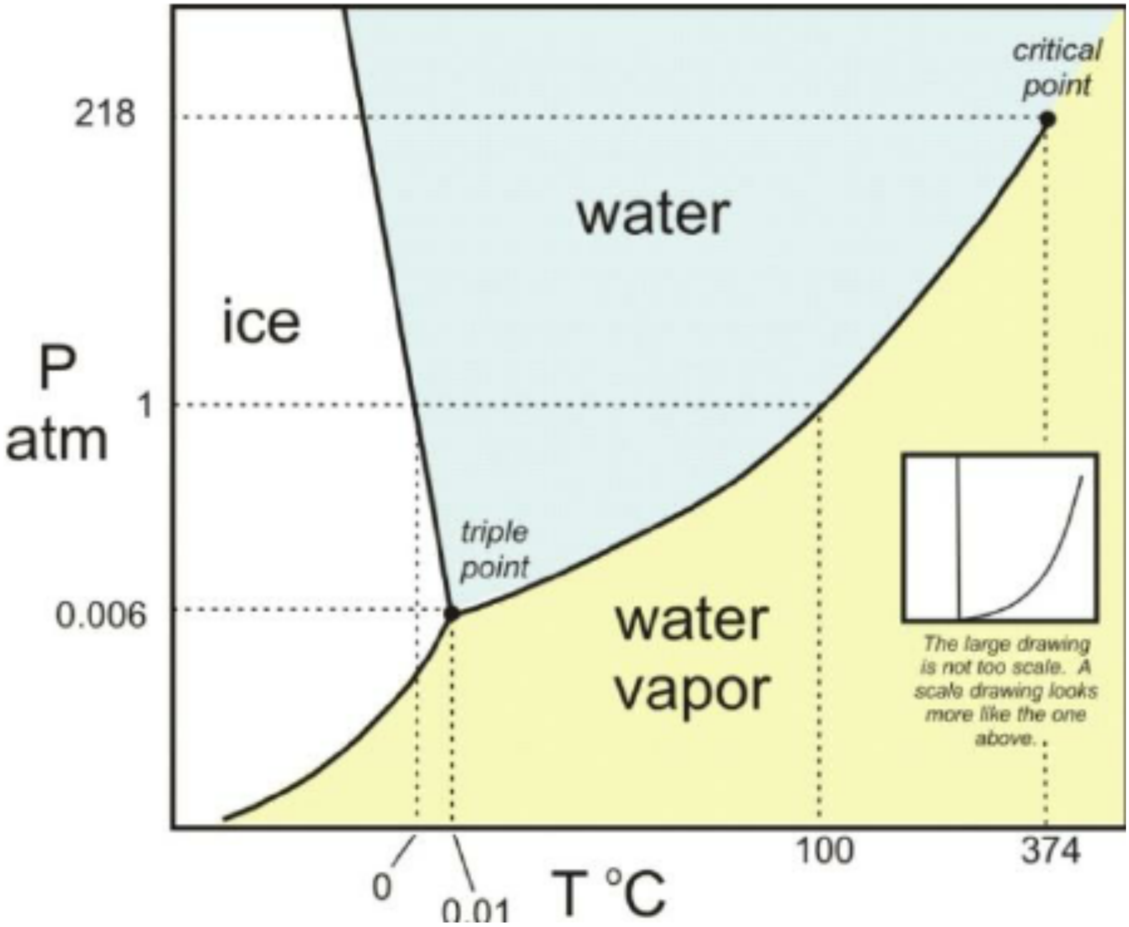
Open system: can exchange both energy and matter with surroundings

Phase of matter and transitions between them

As discussed in the first week, there are three phases of matter: solid, liquid and gas. Table below summarise the transitions mong the phases:

			TO	
		Solid	**Liquid**	**Gas**
FROM	**Solid**	-	Melting	Sublimation
	Liquid	Freezing	-	Vaporisation
	Gas	Deposition	Condensation	-

Figure below is called "phase diagram" where three phases are indicated as a function of pressure and temperature.



When you cross the solid black lines by changing the pressure or/and temperature, there is a phase transition, usually involving latent heat. At the triple point, the all three phases exist simultaneously. Above critical point, vapour can change to water or water to vapour smoothly without latent heat.

Latent Heat

Latent heat is heat that does not change the temperature. When the phase of matter changes, e.g. from solid to liquid, or from liquid to gas, heat to the system is needed. However, the temperature of the system remains constant, i.e. all the energy is used to transform the molecular structure and not to increase the kinetic energy of molecules:

Heat of fusion (melting) L_F: heat needed to change 1 kg of material from the solid to liquid phase.

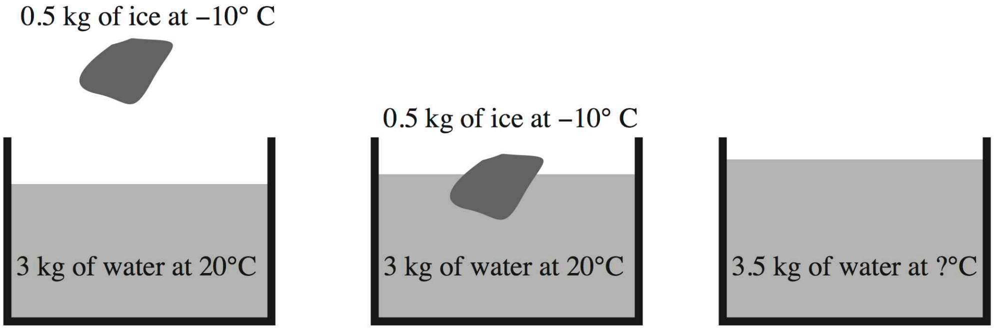
Heat of vaporization (boiling) L_V: heat needed to change 1 kg of material from the liquid to gas phase.

They are called latent heat. The total heat needed, Q, to melt m kg of material is then

$$Q = mL_\mathrm{F}$$

On the other hand, in order to solidify m kg of liquid, $Q = mL_\mathrm{F}$, must be taken out from the system at the melting temperature.

Example:



We consider a system of 0.5 kg of ice at $-10^\circ\mathrm{C}$ put into 3 kg of water at $20^\circ\mathrm{C}$. Specific heat of ice is $0.5\ \mathrm{kcal}\big/\left(\mathrm{kg}\cdot \mathrm{C}^\circ\right)$ and heat of fusion, $79.7\mathrm{kcal/kg}$. For the ice to melt, first the temperature must raise to $0^\circ\mathrm{C}$ requiring heat of

$$Q_\mathrm{ice} = m\cdot c_\mathrm{ice}\cdot \Delta T = 0.5\mathrm{kg}\cdot 0.5\mathrm{kcal}\cdot \left(\mathrm{kg}\cdot \mathrm{C}^\circ\right)^{-1}\cdot (0+10)\mathrm{C}^\circ = 2.5\mathrm{kcal}$$

plus latent heat of

$$Q_\mathrm{melting} = mL_\mathrm{F} = 0.5\mathrm{kg}\cdot 79.7\mathrm{kcal}\cdot \mathrm{kg}^{-1} = 39.85\mathrm{kcal}$$

thus the total heat needed is

$$Q_\mathrm{total} = Q_\mathrm{ice} + Q_\mathrm{melting} = 42.35\mathrm{kcal}$$

which has to come from the 3 kg of water at $20^\circ\mathrm{C}$. This will cool down the temperature of the water to $T_\text{water-3kg}$, which can be derived from

$$-Q_\mathrm{total} = m\cdot c_\mathrm{water}\cdot \Delta T = 3\mathrm{kg}\cdot 1\mathrm{kcal}\cdot \left(\mathrm{kg}\cdot \mathrm{C}^\circ\right)^{-1}\cdot (T_\text{water-3kg} - 20)\mathrm{C}^\circ = -42.35\mathrm{kcal}$$

leading to

$$T_\text{water-3kg}\mathrm{C}^\circ = -\frac{42.35\mathrm{kcal}}{3\mathrm{kcal}\cdot \mathrm{C}^{\circ-1}} + 20\mathrm{C}^\circ = 5.88\mathrm{C}^\circ$$

Now we are putting 3kg of water at $5.88\mathrm{C}^\circ$ and 0.5 kg of water at $0^\circ\mathrm{C}$ together. If we denote the final temperature of 3.5 kg of water to be $T_\text{water-3.5kg}$, the heat needed for the 0.5 kg of water is

$$Q_\mathrm{0.5kg} = m\cdot c_\mathrm{water}\cdot \Delta T = 0.5\mathrm{kg}\cdot 1\mathrm{kcal}\cdot \left(\mathrm{kg}\cdot \mathrm{C}^\circ\right)^{-1}\cdot (T_\text{water-3.5kg} - 0)\mathrm{C}^\circ$$

and heat of 3kg of water is

$$Q_{3\text{kg}} = m \cdot c_{\text{water}} \cdot \Delta T = 3\text{kg} \cdot 1\text{kcal} \cdot \left(\text{kg} \cdot \text{C}^{\circ}\right)^{-1} \cdot (T_{\text{water-3.5kg}} - 5.88)\text{C}^{\circ}$$

Since they are mixed each other,

$$Q_{0.5\text{kg}} + Q_{0.5\text{kg}} = 0$$

leading to

$$0.5\text{kcal} \cdot T_{\text{water-3.5kg}} + 3\text{kcal} \cdot T_{\text{water-3.5kg}} - 3\text{kca} \cdot 5.88 = 0$$

thus

$$T_{\text{water-3.5kg}} = \frac{3 \times 5.88}{0.5 + 3} = 5.04$$

i.e. the temperature of the water becomes 5.04C°.

Evaporation and boiling

At the boiling point, liquid changes to gas everywhere leading to the formation of gas bubble in the liquid. On the other hand, the change from liquid to gas occurs at the boundary surface between the two even below the boiling temperature, called evaporation: molecule with higher kinetic energy escaping from the liquid phase to the gas phase. Thus the average kinetic energy of the molecules remaining in the liquid decreases, thus the temperature of the liquid drops.

Work

When the volume changes, work is done. Consider a cylindrical container with a movable piston, which is gas tight but no friction with the wall. We change the volume in a quasistatical way, i.e. at any instance of the state change, the state in an equilibrium state, i.e. T and P are uniform in the gas. The gas pressure pushes the piston generating a force, $F = PA$ where A is the area of the piston. The work done to move the piston by an infinitesimal amount dl, the work done is given by

$$dW = Fdl = PAdl = PdV$$

where $dV = Adl$ is the infinitesimal change of the volume. Note that when the piston is pushed up, this is the work done by the gas. When the volume changes from V_{a} to V_{b}, the work done is given by

$$W = \int_{V_{\text{a}}}^{V_{\text{b}}} PdV$$