Calorimetry

Select LEARNING OBJECTIVES:

- Be able to identify an isolated system which heat is not gained or lost to the environment.
- Be able to use the concepts from specific heat and phase transitions to determine quantities when two or more systems interact in an isolated condition (i.e. set up calorimetry equations).
- Identify and determine if a phase transition could occur during a calorimetry experiment.

TEXTBOOK CHAPTERS:

- Giancoli (Physics Principles with Applications 7th) :: 14-4
- Knight (College Physics : A strategic approach 3rd) :: 12.6
- BoxSand :: [Heat]

WARM UP: We know that gases can condense to liquids and liquids can evaporate into gases. Can you use this observation to identify any shortcomings of the ideal gas law?

$PV = Nk_BT$

↖ ONLY 1 V FOR A GIVEN P, N, T .... THUS IT MODELS AN IDEAL GAS ALL THE WAY DOWN TO ABS. ZERO.

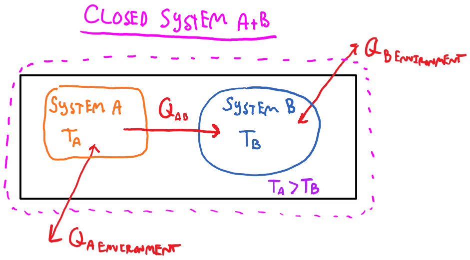
BUT WE KNOW GASES CONDENSE INTO A LIQUID.

.... VAN DER WAALS EQN PREDICT PHASE CHANGES (MULTIPLE SOLUTIONS TO V)

So far we have looked at how the temperature of a substance changes when thermal energy is added or removed ($\Delta E^{th} = m c \Delta T$). We also explored the additional energy needed to carry a substance through a phase transition ($\Delta E^{th} = +/- m L_{v/f}$) . We can now combine what we have learned and apply those results to systems with multiple substances which are not at equilibrium interacting with each other. The study of such systems is often referred to as calorimetry.

When parts of a system are at different temperatures (i.e. not in thermal equilibrium), thermal energy will be transferred between the parts within the system via heat until equilibrium is reached. Recall equilibrium is when the average translational kinetic energy is the same, thus the temperature is the same. While considering a system that is evolving from a non-equilibrium state to an equilibrium state it is important to identify what type of system is being observed (e.g. isolated, closed, or open). If the system is open or closed, energy is lost to the environment which means that we would also need to keep track of this energy as well as the energy transforming within the system. To avoid such an experimental nightmare we can ensure that our system is isolated from the environment so that no thermal energy is lost to the environment. Below is a helpful picture comparing the differences between a closed and an isolated system illustrating why isolated systems are desired for calorimetry experiments.

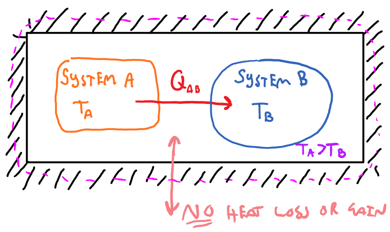
CLOSED SYSTEM A+B



w/ CLOSED SYSTEM

.... COMPLICATED....

ISOLATED SYSTEM A+B



w/ ISOLATED SYSTEM *ASSUME W=0

$Q_{lost_{sys A}} = Q_{gained_{sys B}}$

OR

$Q_A + Q_B = 0$

OR

$\Sigma Q = 0$ + w/ $W=0$ $\Sigma \Delta E^{TH} = 0$

EXAMPLE: If 200 cm³ of water is poured into a 150 g insulated glass cup, initially at 25 °C, what will the finial temperature be when in equilibrium? Assume the specific heat for this type of glass is 840 J/(kg K).

ASSUME VERY LITTLE OR NO $Q_{IN/OUT}$ ~ $Q_{LOST_w} = Q_{GAINED\,CUP}$

$T_F = ?$

$\Sigma Q = 0$

w/ $W=0$ $\Delta E^{TH} = Q = mc\Delta T$

$M_w = ?$

$Q_w + Q_{cup} = 0$

$\rho = \frac{M}{V}$

$M_w C_w \Delta T_w + M_{cup} C_{cup} \Delta T_{cup} = 0$

$M_w = \rho_w V_w$

$M_w = \left(1000 \frac{kg}{m^3}\right)\left(2 \times 10^{-4} m^3\right)$

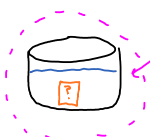
$M_w = 0.2 kg$

$(0.2kg)\left(4190 \frac{J}{kgK}\right)(T_F - 95)°C + (0.15kg)\left(840 \frac{J}{kgK}\right)(T_F - 25)°C = 0$

$838 T_F - 79610 + 126 T_F - 3150 = 0$

$T_F \approx 85.9°C$

PRACTICE: A 0.2 kg aluminum bowl contains 0.3 kg of water. The initial temperature of the bowl and water is 20 °C. An unknown metal of mass 0.532 kg is heated to a temperature of 90 °C and then added to the water. The equilibrium temperature is 30 °C. What is the specific heat of this unknown metal? c_{Al} = 900 J/(kg K)



NO $Q_{IN/OUT}$ ~ $Q_{LOST?} = Q_{GAINED\,w+Al}$

$\Sigma Q = 0$

$Q_{w_{20 \to 30}} + Q_{Al_{20 \to 30}} + Q_{?_{90 \to 30}} = 0$

$M_w C_w \Delta T_w + M_{Al} C_{Al} \Delta T_{Al} + M_? C_? \Delta T_? = 0$

$(0.3kg)\left(4190 \frac{J}{kgK}\right)(30-20)K + (0.2kg)\left(900 \frac{J}{kgK}\right)(30-20)K + (0.532kg)(C_?)(30-90)K = 0$

$C_? = 450 \frac{J}{kgK}$ ~ PROBABLY IRON OR STEEL

PRACTICE: 30 g of copper pellets are removed from a 300 °C oven and immediately dropped into 100 g of water at 20 °C in an insulated cup. What will the equilibrium temperature of the water be? The specific heat of copper and water are 385 J/(kg K) and 4190 J/(kg K) respectively.

STEAM?

NO $Q_{IN/OUT}$ ⟶ $\Sigma Q = 0$

$Q_{Cu_{300 \to T_F}} + Q_{w_{20 \to T_F}} + Q_{w_V} + Q_{V_{100 \to T_F}} = 0$

1ST CHECK TO SEE IF THE Cu WILL PROVIDE ENOUGH HEAT TO EVAPORATE SOME WATER....

$Q_{w_{20 \to 100}} = M_w C_w \Delta T_w$

$= (0.1)(4190)(100-20)\ J$

$= 33520\ J$

IT TAKES 33520 J TO BRING THE WATER UP TO THE BEGINNING OF A PHASE CHANGE

$Q_{Cu_{300 \to 100}} = M_{Cu} C_{Cu} \Delta T$

$= (0.03)(385)(100-300)\ J$

$= -2310\ J$

THE COPPER WILL TRANSFER 2310 J OF THERMAL ENERGY TO THE WATER

SINCE 2310 J < 33520 J, THE WATER WILL NOT GO THROUGH A PHASE CHANGE

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$\therefore$

$$Q_{Cu_{300\to T_F}} + Q_{w_{20\to T_F}} = 0$$

$$M_{Cu} C_{Cu} \Delta T_{Cu} + M_w C_w \Delta T_w = 0$$

$$(0.03\ kg)(385\ \tfrac{J}{kg\,K})(T_f - 300\ ^\circ C) + (0.1\ kg)(4190\ \tfrac{J}{kg\,K})(T_f - 20^\circ C) = 0$$

$$T_f = 27.5\ ^\circ C$$

PRACTICE: 1 kg of water at 20 °C is in an insulated container of negligible mass and heat capacity. 8.1 kg of aluminum is added to the water at 301 °C. What is the final temperature of the system once equilibrium is reached?

STEAM?

$$\Sigma Q = 0$$

$$Q_{Al} + Q_w + Q_{vw} + Q_s = 0$$

1ST CHECK TO SEE IF THE Al WILL PROVIDE ENOUGH HEAT TO BRING THE WATER UP TO A PHASE TRANSITION

$$Q_{w_{20\to 100}} = M_w C_w \Delta T_w$$
$$= (1)(4190)(100-20)\ J$$
$$= 335200\ J$$

IT TAKES 33520 J TO BRING THE WATER UP TO THE BEGINNING OF A PHASE CHANGE

$$Q_{Al_{301\to 100}} = M_{Al} C_{Al} \Delta T_{Al}$$
$$= (8.1)(900)(100-301)\ J$$
$$= 1465290\ J$$

THE Al WILL TRANSFER 1465290 J OF THERMAL ENERGY TO THE WATER

SINCE 1465290 J > 335200 J, THE WATER WILL GO THROUGH A PHASE TRANSITION INTO STEAM

2ND NOW CHECK IF ALL THE WATER WILL BE CONVERTED TO STEAM OR JUST SOME OF IT...

$$Q_{vw} = M_w L_{vw}$$
$$= (1\ kg)(22.6\times10^5\ \tfrac{J}{kg})$$
$$= 2260000\ J$$

HOW MUCH ENERGY IS NEEDED TO CONVERT ALL OF THE WATER TO STEAM

$$Q_{Al} = Q_{Al_{301\to 100}} - Q_{w_{20\to 100}}$$
$$= 1465290\ J - 335200\ J$$
$$= 1130090\ J$$

HOW MUCH ENERGY THE Al HAS LEFT ON ITS WAY DOWN TO 100 °C AFTER THE WATER BEGINS ITS PHASE TRANSITION

SINCE 2260000 J > 1130090 J

ONLY SOME OF THE WATER WILL BE CONVERTED TO STEAM

$\therefore$ THE FINAL TEMP IS @ THE PHASE TRANSITION OF W → STEAM

$$T_F = 100\ ^\circ C$$

... HOW MUCH WATER WILL BE LEFT?

$$\frac{1130090\ J}{2260000\ J} = 0.50$$

THE Al PROVIDED ENOUGH ENERGY TO THE WATER TO GET IT $\frac{1}{2}$ WAY THROUGH

THE PHASE TRANSITION,

THUS ... $1\,kg - (0.5)(1\,kg) = 0.5\,kg$ OF WATER LEFT

Questions for discussion:

1. Explain why burns caused by steam at 100 °C on skin are often more severe than burns caused by water at 100 °C.

(2) Evaporation involves some of the molecules escaping the intermolecular bonds within a liquid. Use your knowledge of the kinetic theory of gases, latent heat, and thermal energy to explain why water cools down as it evaporates.

(3) Discuss the validity of this statement: When heat is added to a system the temperature increases.