

Objective 9: Energy and heat 2: predict heat and work in a chemical reaction and chemical heat transfer. Apply using Hess' law.

Quiz Practice problems:

Key ideas:

Two types of heat:

Physical heat transfer = when a hot object touches a cold object: $q = m s \Delta T$

Chemical heat transfer = a chemical reaction releases heat (exothermic) to its surroundings or absorbs heat (endothermic) from its surroundings: $q = \Delta H$. Calculate ΔH using Hess' law.

A chemical reaction involves energy.

Hess' law: $\Delta H_{\text{reaction}} = \sum n\Delta H_f(\text{products}) - \sum n\Delta H_f(\text{reactants})$ where n = coefficient in moles in balanced chemical equation and ΔH_f = change in enthalpy of formation.

A formation reaction is a reaction in which a substance is formed from elements in the standard state.

Example: formation reaction of liquid water is $2 \text{H}_2(\text{g}) + \text{O}_2(\text{g}) \rightarrow 2 \text{H}_2\text{O}(\text{l})$

ΔH_f of an element in its standard state = 0 kJ/mole.

ΔH_f of a substance tells us how stable or reactive the substance is.

Example: ΔH_f of $\text{H}_2(\text{g}) = 0$ kJ/mole, ΔH_f of $\text{H}_2\text{O}(\text{l}) = -285$ kJ/mole.

-285 kJ is a lower energy than 0 kJ so $\text{H}_2\text{O}(\text{l})$ is more stable or less reactive than $\text{H}_2(\text{g})$.

Skills: Use table of thermodynamic quantities to look up $\Delta H_{\text{formation}}$.

Apply Hess' law to calculate $\Delta H_{\text{reaction}}$.

Use heat equations, e.g., calculate the amount of water that is heated by a chemical reaction.

- Compare ΔH_f of $\text{Cl}_2(\text{g})$ to $\text{Cl}^-(\text{aq})$. Does chlorine exist as element or ion?
- Compare ΔH_f of $\text{H}_2\text{O}(\text{l})$ to $\text{H}_2\text{O}(\text{g})$. Does water exist as a liquid or gas at room temperature?
- Look up ΔH_f of $\text{CO}_2(\text{g})$. Is $\text{CO}_2(\text{g})$ stable or reactive?

Answers:

a. ΔH_f of $\text{Cl}_2(\text{g}) = 0$ kJ/mole

ΔH_f of $\text{Cl}^-(\text{aq}) = -167$ kJ/mole

Cl^- is lower in energy than Cl_2 so chlorine exists as an ion.

b. Compare ΔH_f of $\text{H}_2\text{O}(\text{l}) = -285.8$ kJ/mole

ΔH_f of $\text{H}_2\text{O}(\text{g}) = -241.8$ kJ/mole

$\text{H}_2\text{O}(\text{l})$ is lower in energy than $\text{H}_2\text{O}(\text{g})$ so water exists as a liquid or gas at room temperature.

c. ΔH_f of $\text{CO}_2(\text{g}) = -393.3$ kJ/mole

$\text{CO}_2(\text{g})$ is stable.

NOTE: lower ΔH_f means lower energy, less reactive, more stable.

Higher ΔH_f means higher energy, more reactive, less stable.

2. a. Is heat absorbed or released when water vaporizes to steam? Calculate ΔH_{rxn} for $\text{H}_2\text{O}(\text{l}) \rightarrow \text{H}_2\text{O}(\text{g})$ to confirm your answer. How is q related to ΔH_{rxn} ?

(Answer: ΔH_f for $\text{H}_2\text{O}(\text{l}) = -285$ kJ/mole, ΔH_f for $\text{H}_2\text{O}(\text{g}) = -241$ kJ/mole.

Apply Hess' law, $\Delta H_{\text{rxn}} = [1 \times \Delta H_f \text{ for } \text{H}_2\text{O}(\text{g})] - [1 \times \Delta H_f \text{ for } \text{H}_2\text{O}(\text{l})] = [-241 \text{ kJ/mole}] - [-285 \text{ kJ/mole}] = 44 \text{ kJ/mole}$)

b. Is heat absorbed or released when steam condenses to water? Calculate ΔH_{rxn} for $\text{H}_2\text{O}(\text{g}) \rightarrow \text{H}_2\text{O}(\text{l})$ to confirm your answer.

c. Is the same amount of heat involved in each phase change?

d. When 100°C steam comes in contact with a 25°C object, the 100°C steam condenses to 100°C $\text{H}_2\text{O}(\text{l})$ and then the $\text{H}_2\text{O}(\text{l})$ cools until T_f (thermal equilibrium) is reached.

So the heat lost by steam = (moles steam)(ΔH_{rxn} for $\text{H}_2\text{O}(\text{l}) \rightarrow \text{H}_2\text{O}(\text{g})$) + (mass of water)(specific heat of water)(ΔT)

When 100°C $\text{H}_2\text{O}(\text{l})$ comes in contact with a 25°C object, hot $\text{H}_2\text{O}(\text{l})$ cools until T_f (thermal equilibrium) is reached.

So the heat lost by hot water = _____

Explain why being burned by steam is much worse than being burned by water.

Answers:

a. Heat is absorbed when water vaporizes to steam.

Use Hess' law to calculate ΔH_{rxn} for $\text{H}_2\text{O}(\text{l}) \rightarrow \text{H}_2\text{O}(\text{g})$.

$\Delta H_{\text{rxn}} = \sum (n \Delta H_f(\text{products})) - \sum (n \Delta H_f(\text{reactants}))$

$\Delta H_{\text{rxn}} = \Delta H_f \text{ for } \text{H}_2\text{O}(\text{g}) - \Delta H_f \text{ for } \text{H}_2\text{O}(\text{l})$

$= 1(-241.8 \text{ kJ/mole}) - 1(-285.8 \text{ kJ/mole})$

$= +44 \text{ kJ/mole}$

+ sign means endothermic – heat is absorbed. Water has to gain heat to evaporate.

$q = \Delta H_{\text{rxn}}$.

b. Heat is released when steam condenses to water.

ΔH_{rxn} for $\text{H}_2\text{O}(\text{g}) \rightarrow \text{H}_2\text{O}(\text{l}) = -44 \text{ kJ/mole}$.

- sign means exothermic – heat is released. Steam has to lose heat to condense to water.

This reaction is the reverse of $\text{H}_2\text{O}(\text{l}) \rightarrow \text{H}_2\text{O}(\text{g})$. $\Delta H_{\text{rxn}} = +44 \text{ kJ/mole}$.

Reverse reaction \Rightarrow Change sign of ΔH_{rxn} .

c. The same amount of heat is involved in each phase change. Heat is either gained (evaporation) or lost (condensation).

d. heat lost by hot water = (mass of water)(specific heat of water)(ΔT)

Steam loses more heat than hot water:

Steam loses heat when it condenses to water at 100°C . The hot water loses more heat. The total heat lost is the sum of these two terms:

heat lost by steam = (moles steam)(ΔH_{rxn} for $\text{H}_2\text{O}(\text{l}) \rightarrow \text{H}_2\text{O}(\text{g})$) + (mass of water)(specific heat of water)(ΔT)

Since steam loses more heat than hot water, it is much worse to be burned by steam than hot water.

3. In a combustion reaction, a fuel burns (reacts) with O_2 to form water and CO_2 (for a carbon based fuel).

Natural gas, CH_4 , is used in gas stoves: $\text{CH}_4(\text{g}) + \text{O}_2(\text{g}) \rightarrow \text{CO}_2(\text{g}) + \text{H}_2\text{O}(\text{g})$

a. Balance the equation:

(i) Balance C. 1 C on each side of the equation.

(ii) Balance H. 4 H on reactant side. 2 H on product side. What coefficient should you use for H_2O ?

(iii) Balance O. 2 O on reactant side. 4 O on product side (2 from CO_2 , 2 from 2 H_2O). What coefficient should you use for O_2 ?

(iv) Combustion reactions are oxidation-reduction reactions. Which reactant is oxidized? Determine the charge of the element in the reactant and product that is being oxidized.

b. Apply Hess' law to calculate ΔH_{rxn} . (Look up ΔH_f for $\text{CH}_4(\text{g})$ and $\text{H}_2\text{O}(\text{g})$. Answer: ΔH_{rxn} between -790 to -810 kJ/mole)

c. 0.1 moles of CH_4 is burned to heat up 1 liter of water at 25°C . Calculate the final temperature of the water.

(i) Fill in the blanks: Heat gained by _____ = - heat lost by _____

(ii) Should you use $q = \Delta H$ or $q = ms\Delta T$ for heat gained by _____? (Hint: if a chemical reaction occurs, $q = \Delta H$)

(iii) Should you use $q = \Delta H$ or $q = ms\Delta T$ for heat lost by _____?

(iv) Set up your calculation – it should look like:

$$m s \Delta T = - \text{moles of } \underline{\hspace{2cm}} \times \Delta H \text{ (in J/mole)}$$

$$\text{Remember } \Delta T = T_f - T_i$$

$$\text{Solve for } T_f. \text{ (Answer: } T_f \text{ is between } 40\text{--}45^\circ\text{C)}$$

Answers:

a. $\text{CH}_4(\text{g}) + 2 \text{O}_2(\text{g}) \rightarrow \text{CO}_2(\text{g}) + 2 \text{H}_2\text{O}(\text{g})$

b. $\Delta H_{\text{rxn}} = \sum (n \Delta H_f \text{ (products)}) - \sum (n \Delta H_f \text{ (reactants)})$

$$\begin{aligned} \Delta H_{\text{rxn}} &= [1 \Delta H_f (\text{CO}_2(\text{g})) + 2 \Delta H_f (\text{H}_2\text{O}(\text{g}))] - [1 \Delta H_f (\text{CH}_4(\text{g})) + 2 \Delta H_f (\text{O}_2(\text{g}))] \\ &= [2 (-393.5 \text{ kJ/mole}) + 2 (-241.8 \text{ kJ/mole})] - [1 (-74.8 \text{ kJ/mole}) + 2 (0)] \\ &= -802 \text{ kJ/mole} \end{aligned}$$

c. (i) Fill in the blanks: Heat gained by **water** = - heat lost by **CH_4 combustion reaction**

(ii) Use $q = ms\Delta T$ for heat gained by **water**

(iii) Use $q = \Delta H$ for heat lost by **CH_4 combustion reaction**

(iv) Set up your calculation – it should look like:

$$m s \Delta T = - \text{moles of } \underline{\hspace{2cm}} \times \Delta H \text{ (in J/mole)}$$

$$(1000 \text{ g water})(4.18 \text{ J/g } ^\circ\text{C})(T_f - 25^\circ\text{C}) = - (0.1 \text{ moles } \text{CH}_4)(-802 \text{ kJ/mole})(1000 \text{ J/1 kJ})$$

$$\text{Solve for } T_f = 44^\circ\text{C}$$

4. Butane, C_4H_{10} , is used in lighters and camping stoves.

a. Write a chemical equation that represents the combustion of butane.

b. Calculate ΔH_{rxn} .

c. Will burning 0.1 moles of butane heat up 1 liter of water at 25°C more or less or the same as burning 0.1 moles of natural gas? Calculate T_f to support your answer.

Answers:

a. $2 \text{C}_4\text{H}_{10}(\text{g}) + 13 \text{O}_2(\text{g}) \rightarrow 8 \text{CO}_2(\text{g}) + 10 \text{H}_2\text{O}(\text{g})$

$$\begin{aligned} \Delta H_{\text{rxn}} &= [8 \Delta H_f (\text{CO}_2(\text{g})) + 10 \Delta H_f (\text{H}_2\text{O}(\text{g}))] - [2 \Delta H_f (\text{C}_4\text{H}_{10}(\text{g})) + 13 \Delta H_f (\text{O}_2(\text{g}))] \\ &= [8 (-393.5 \text{ kJ/mole}) + 10 (-241.8 \text{ kJ/mole})] - [2 (-126.5 \text{ kJ/mole}) + 13 (0)] \\ &= -5313 \text{ kJ/2 moles of } \text{C}_4\text{H}_{10}(\text{g}) \text{ that burns} \\ &= -2656.5 \text{ kJ/mole of } \text{C}_4\text{H}_{10}(\text{g}) \end{aligned}$$

c. $m s \Delta T = - \text{moles of } \underline{\hspace{2cm}} \times \Delta H \text{ (in J/mole)}$

$$(1000 \text{ g water})(4.18 \text{ J/g } ^\circ\text{C})(T_f - 25^\circ\text{C}) = - (0.1 \text{ moles } \text{CH}_4)(-2656.5 \text{ kJ/mole})(1000 \text{ J/1 kJ})$$

$$\text{Solve for } T_f = 88.6^\circ\text{C}$$

Burning 0.1 moles of butane heat up 1 liter of water at 25°C more ($T_f = 88.6^\circ\text{C}$) than burning 0.1 moles of natural gas ($T_f = 44^\circ\text{C}$).

5. You made hot packs and cold packs in lab. An ionic solid is dissolved in water.

a. If the dissolution of an ionic solid is endothermic, the solid is used in a _____ pack.

b. KNO_3 can be used in a cold pack. Write a chemical equation and calculate ΔH_{rxn} to confirm this answer.

c. Calculate the mass of KNO_3 that will lower the temperature of 50 g of water from 25°C to 0°C.

Answers:

a. cold pack. The chemical reaction gains heat and the water loses heat so the water temperature decreases.

b. $\text{KNO}_3(\text{s}) \rightarrow \text{K}^+(\text{aq}) + \text{NO}_3^-(\text{aq})$

$$\begin{aligned}\Delta H_{\text{rxn}} &= \sum (n \Delta H_f(\text{products})) - \sum (n \Delta H_f(\text{reactants})) \\ &= [1 (\Delta H_f(\text{products})) + 1 (\Delta H_f(\text{products}))] - [1 (\Delta H_f(\text{reactants}))] \\ &= [1(-251) + 1(-207)] - [1(-492.9)] \\ &= 34.9 \text{ kJ/mole} \Rightarrow \text{endothermic, so cold pack}\end{aligned}$$

c. - heat lost by water = heat gained by KNO_3 reaction

- $m s \Delta T = \text{moles of } \underline{\hspace{2cm}} \times \Delta H$ (in J/mole)

$$-(50)(4.18 \text{ J/g } ^\circ\text{C})(0 - 25^\circ\text{C}) = (\text{mass of } \text{KNO}_3)(1 \text{ mole } \text{KNO}_3/101 \text{ g } \text{KNO}_3)(34.9 \text{ kJ/mole}) (1000 \text{ J/1 kJ})$$

solve for mass of $\text{KNO}_3 = 15.1 \text{ g}$

6. Fuels are used to produce work. Work involves gases: $w = -p \Delta V$.

When a gas expands ($V_f > V_i$ so $\Delta V = V_f - V_i > 0$), the gas can do work on an object. In other words, the gas produces work so $w = -p \Delta V < 0$.

To compress a gas ($V_f < V_i$ so $\Delta V = V_f - V_i < 0$), some thing, e.g., you, have to do work on the gas. In other words, work is supplied to the gas so $w = -p \Delta V > 0$.

Is $\Delta V > 0$, < 0 , or $= 0$?

Is $w > 0$, < 0 , or $= 0$?

a. Explain how a car airbag inflating produces work.

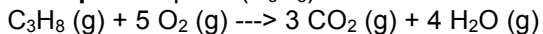
b. You have a 20 ml syringe. You move the plunger to the 10 ml mark. You plug the end of the syringe. You push on the plunger to move it to the 5 ml mark.

(i) Is work produced by the gas or is work supplied to the gas?

(ii) Is work > 0 or < 0 ? Give reasons.

c. Work is involved in a chemical reaction if a reactant or product is a gas.

Example: Propane (C_3H_8) is used as a fuel.



Compare the moles of gas reactants to the moles of gas products: 6 moles of gas reactants \rightarrow 7 moles of gas products

$$\Delta n = \text{moles of gas products} - \text{moles of gas reactants} = 7 - 6 = 1 \text{ mole}$$

According to ideal gas law, $PV = nRT$. So Δn is directly proportional to ΔV .

If $\Delta n > 0$, then $\Delta V > 0$.

Since $\Delta V > 0$, work must be < 0 (remember $w = -p\Delta V$).

When propane burns, work is produced.

(i) When natural gas (CH_4) burns, is work produced?

Write a balanced chemical equation for the combustion of CH_4 .

Compare the moles of gas reactants to the moles of gas products.

Determine Δn .

Determine ΔV .

Determine w .

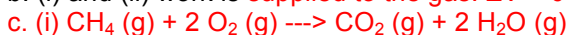
(ii) A fuel should produce work when used in car engine. Which fuel, propane or natural gas, works better in a car engine?

Give reasons.

Answers:

a. $\Delta V > 0$ when a car airbag inflates so $w = -p\Delta V < 0 \Rightarrow$ work is produced.

b. (i) and (ii) work is supplied to the gas. $\Delta V < 0$ so $w = -p\Delta V > 0 \Rightarrow$ work is supplied.



3 moles gas reactants \rightarrow 3 moles gas products

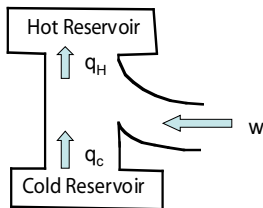
$$\Delta n = 3 \text{ moles gas products} - 3 \text{ moles gas reactants} = 0$$

$$\Delta V = 0$$

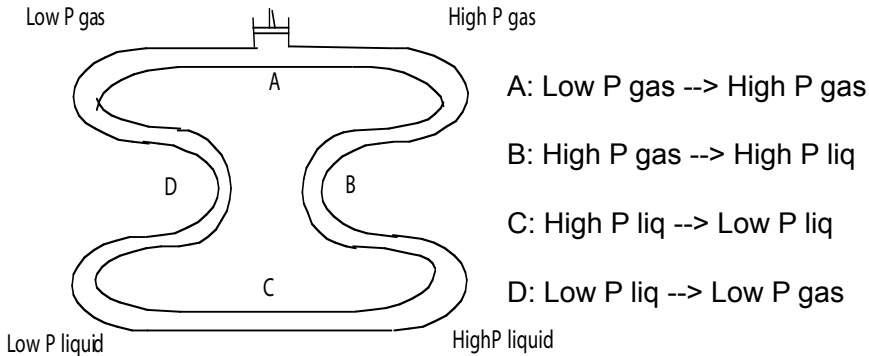
$$w = -p\Delta V = 0$$

(ii) Propane produces work whereas methane does not so propane works better as a fuel in a car engine.

7. a. A refrigerator is a heat engine in reverse.



- (i) Is work produced or supplied?
 (ii) What part of the refrigerator is the cold reservoir?
 (iii) How is work converted into heat ?
 b. A schematic diagram of a refrigerator is shown below.



- (i) Determine q and w for each step.
 (ii) Which step cools air inside the refrigerator?
 (iii) Would you want the refrigerant to have a high boiling point or low boiling point? Give reasons.
 (iv) Would you want the refrigerant to be compressible or incompressible? Give reasons.

Answers:

- a. (i) work is **supplied**
 (ii) The cold reservoir is the **inside of the refrigerator** that you want cold.
 (iii) **Work is supplied (to refrigerator compressor) to remove heat from the cold reservoir (the air inside the refrigerator). The work that is not used to remove heat is heat that leaves the reverse heat engine - heat that is wasted.**

b. (i)

Step	q	w
A	$= 0$	> 0 , work is supplied to compress gas
B	< 0 , condensation is exothermic	> 0 , $\Delta n < 0$, so $\Delta V < 0$ so $w > 0$
C	$= 0$	0 , no gases involved.
D	> 0 , evaporation is endothermic	< 0 , $\Delta n > 0$, so $\Delta V > 0$ so $w < 0$ ==> produced

(ii) Step D cools air in the fridge. Evaporation of refrigerant is endothermic (gains heat). The air inside the fridge loses heat.

(iii) You would want the refrigerant to have a low boiling point.

In Step D, you want the liquid refrigerant to evaporate by gaining heat from the air inside the fridge.

Example 1: refrigerant has a boiling point above room temperature and the air temperature is room temperature ==> the refrigerant will not evaporate because the air temperature is not high enough (not at b.p. of refrigerant).

Example 2: refrigerant has a boiling point below room temperature and the air temperature is room temperature ==> the refrigerant gains heat and evaporates because the air temperature is high enough (above the b.p. of refrigerant). The air loses heat and the air temperature drops. So low refrigerant boiling point lowers the temperature of the air inside the fridge.

(iv) You would want the refrigerant to be compressible for Step A and C.