Gas equilibria and Kp

OCR A H432 · Full A-level

Show your working where needed. Check the worked answers when you finish.

Name _____ Date _____

1. Write a Kp expression

$PCl_5(g) \rightleftharpoons PCl_3(g) + Cl_2(g)$. Write the equilibrium expression for Kp using partial pressures. Deduce its units when every partial pressure is in kPa.

2. Go from amounts to partial pressures

$N_2O_4(g) \rightleftharpoons 2NO_2(g)$. At equilibrium there are 0.600 mol of N_2O_4 and 0.400 mol of NO_2. Total pressure is 150 kPa.

Find both partial pressures and Kp.

3. Two ways to write the Haber equilibrium

At equilibrium $p(N_2)$ = 75.0 kPa, $p(H_2)$ = 145 kPa and $p(NH_3)$ = 90.0 kPa for $N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$.

Find Kp and its units for the equation shown and for the equation written to form one mole of NH_3.

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4. A vessel containing phosphorus chlorides

1.20 mol of $PCl_5(g)$ is present initially. At equilibrium for $PCl_5(g) \rightleftharpoons PCl_3(g) + Cl_2(g)$, 0.300 mol of PCl_5 has decomposed. Total pressure is 200 kPa.

Calculate Kp at this temperature.

5. Find a missing pressure

$CO(g) + H_2O(g) \rightleftharpoons CO_2(g) + H_2(g)$. Kp = 2.50. At equilibrium, p(CO) = 42.0 kPa, $p(H_2O)$ = 80.0 kPa and $p(H_2)$ = 70.0 kPa.

Find $p(CO_2)$.

6. Change pressure and temperature separately

$N_2O_4(g) \rightleftharpoons 2NO_2(g)$ is endothermic forwards. For each change, predict the equilibrium shift and what happens to Kp.

First consider compression at fixed temperature. Then consider heating the original mixture at fixed total pressure.

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7. Ammonium chloride at equilibrium

$NH_4Cl(s) \rightleftharpoons NH_3(g) + HCl(g)$. The only initial material in an evacuated vessel is solid NH_4Cl. Some solid remains at equilibrium and the total gas pressure is 72.0 kPa.

Write the Kp expression and calculate its value.

8. Find the total equilibrium pressure

$2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g)$. The equilibrium mole fractions of SO_2, O_2 and SO_3 are 0.250, 0.200 and 0.550 respectively. Kp is 0.242 kPa^{-1}.

Calculate the total pressure.

9. Extra challenge · Compress an equilibrium with an inert gas

$CaCO_3(s) \rightleftharpoons CaO(s) + CO_2(g)$. A vessel initially contains both solids and only Ar at 42.0 kPa. At fixed volume and temperature, the total equilibrium pressure is 80.0 kPa.

Calculate Kp. The vessel volume is then halved at the same temperature. Find the new total equilibrium pressure, assuming both solids remain.

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Worked answers

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1. Write a Kp expression

$Kp = p(PCl_3) \times p(Cl_2) \div p(PCl_5)$.

The pressure units give $kPa^2 \div kPa = kPa$.

2. Go from amounts to partial pressures

Total amount is 1.000 mol. Multiply each mole fraction by total pressure: $p(N_2O_4) = 90.0$ kPa and $p(NO_2) = 60.0$ kPa.

$Kp = p(NO_2)^2 \div p(N_2O_4) = 60.0^2 \div 90.0 = 40.0$ kPa.

3. Two ways to write the Haber equilibrium

For the equation shown, $Kp = p(NH_3)^2 \div [p(N_2) \times p(H_2)^3] = 90.0^2 \div (75.0 \times 145^3) = 3.54 \times 10^{-5}$ kPa^{-2}.

Halving all coefficients halves the powers in the expression. The new Kp is $\sqrt{(3.54258\ldots \times 10^{-5})} = 5.95 \times 10^{-3}$ kPa^{-1}. The physical equilibrium is unchanged.

4. A vessel containing phosphorus chlorides

The equilibrium amounts are 0.900 mol PCl_5 and 0.300 mol each of PCl_3 and Cl_2. Total amount is 1.50 mol.

Their partial pressures are 120 kPa, 40.0 kPa and 40.0 kPa. $Kp = 40.0 \times 40.0 \div 120 = 13.3$ kPa.

5. Find a missing pressure

Rearrange $Kp = [p(CO_2) \times p(H_2)] \div [p(CO) \times p(H_2O)]$.

$p(CO_2) = 2.50 \times 42.0 \times 80.0 \div 70.0 = 120$ kPa.

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Worked answers

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6. Change pressure and temperature separately

Compression shifts equilibrium towards N_2O_4 because this side has fewer gas molecules. With temperature held fixed, Kp remains constant.

Heating favours the endothermic direction, towards NO_2. Kp increases. Temperature determines the value of Kp for a given balanced equation.

7. Ammonium chloride at equilibrium

Omit the pure solid. $Kp = p(NH_3) \times p(HCl)$.

Equal amounts of both gases form, so each partial pressure is 36.0 kPa. $Kp = 36.0^2 = 1.30 \times 10^3$ kPa^2 to three significant figures.

8. Find the total equilibrium pressure

Let total pressure be P. $Kp = p(SO_3)^2 \div [p(SO_2)^2 \times p(O_2)] = (0.550P)^2 \div [(0.250P)^2 \times (0.200P)]$.

One factor of P remains in the denominator, so $P = 0.550^2 \div (0.250^2 \times 0.200 \times 0.242) = 1.00 \times 10^2$ kPa.

9. Extra challenge · Compress an equilibrium with an inert gas

The argon partial pressure remains 42.0 kPa initially. Thus $p(CO_2)$ at equilibrium is 80.0 − 42.0 = 38.0 kPa. Neither pure solid appears in the expression, so $Kp = p(CO_2) = 38.0$ kPa.

Compression initially doubles both gas pressures. At constant temperature Kp stays 38.0 kPa, so some CO_2 is removed by the reverse reaction. The Ar partial pressure stays at 84.0 kPa, and the new total is 84.0 + 38.0 = 122.0 kPa.

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