Investigation

Investigate the amount of heat evolved when magnesium reacts with dilute acids.

Planning

What I am going to do

I am going to find out how much heat is given out when magnesium reacts with a variety of dilute acids. In order to make comparisons between the acids, I shall use my results to work out how much heat would be given out if 1 mole of magnesium reacted with an excess of each acid.

The acids I shall use are hydrochloric acid, sulphuric acid, nitric acid and ethanoic acid.

What I already know

Magnesium reacts with most dilute acids to give a magnesium salt and hydrogen. For example:

$$Mg + 2HCl \rightarrow MgCl_2 + H_2$$

$$Mg + H_2SO_4 \rightarrow MgSO_4 + H_2$$

I discovered from an A' level text book (A-level Chemistry by Ramsden) that nitric acid doesn't usually give hydrogen, but may do with magnesium if the acid is cold and dilute. The book didn't say how dilute the acid had to be. Other products may include oxides of nitrogen.

I know that some acids are weak and some are strong. A strong acid is one which ionises fully in solution to give hydrogen ions and, for example, chloride ions or sulphate ions. Sulphuric acid, hydrochloric acid and nitric acid are all strong acids. Ethanoic acid is a weak acids. That means that its solution contains a high proportion of molecules that haven't split into ions.

For all the reactions which give off hydrogen, the same ionic equation applies - whether the acid is strong or weak:

$$Mg_{(s)} + 2H^+_{(aq)} \rightarrow Mg^{2+}_{(aq)} + H_{2(g)}$$

The key factors to vary, control or take into account

The amount of heat given out will depend on the mass of magnesium I use - the more magnesium I use, the more of the above reaction happens. But because I am going to work out the amount of heat evolved per mole of magnesium, I don't need to take exactly the same mass for each experiment. I do, though, need to weigh the magnesium accurately for each experiment.

I am going to use an excess of each acid, so their exact concentrations don't matter. The amount of heat given off will depend only on the amount of magnesium used. I shall use the normal dilute acids found in the lab. I do need to know exactly what volume of acid I am using for each experiment. If I don't know this I can't work out how much heat has been evolved.

I am going to measure the temperature rise of the reaction mixture. Because the temperature has gone up, heat will be lost to the surroundings. I shall have to take steps to keep this heat loss as low as possible.

Preliminary work

I needed to find out what sort of amounts of magnesium and acid to use in my experiments. If I use a small amount of magnesium, it will be more difficult to weigh it accurately and it will only give a small temperature rise which will be difficult to measure accurately. If I use a lot of magnesium, the temperature rise will be so great that there will be major heat losses to the surroundings.

I also need to choose a sensible volume of acid to use. It has to be enough to react with all the magnesium, but not so much that a lot of spray escapes from the reaction.

I started by using a strip of magnesium ribbon which weighed about 0.1 g, and 50 cm^3 of acid (measured roughly with a measuring cylinder). All the magnesium dissolved, and it gave a sensible temperature rise of about 9°C, but it took a very long time using ethanoic acid. That increases the possibility of heat losses to the surroundings. This preliminary experiment showed that my quantities were sensible, but that I needed to speed up the reaction. I tried different forms of magnesium. Magnesium turnings also took quite a long time, but magnesium powder reacted quite quickly with the ethanoic acid, and didn't produce too much spray with the strong acids.

I decided to use about 0.1 to 0.15 g of magnesium powder for my experiments. I weighed this in a weighing bottle, but found that when I tipped it into the acid, not all of it came out. So I would need to reweigh the bottle again to see how much I had actually added.

Producing precise and reliable evidence

Because of the small mass of magnesium used, I shall weigh it on a 3 decimal place balance.

I shall measure the 50 cm^3 of acid using a pipette for greater accuracy. I had hoped to use a 50 cm^3 pipette, but in fact had to measure out 2 x 25 cm^3.

I shall use a thermometer reading to 0.2°C to measure the temperature rise to make this as accurate as possible.

To try to cut down on heat losses, I shall do the reaction in a polystyrene cup.

I shall repeat each experiment twice to check that my results are reliable. To check whether my results are consistent for each acid used, I shall work out the temperature rise per gram of magnesium after each experiment. If these don't agree then I shall go on repeating the experiment until there is good agreement.

Safety

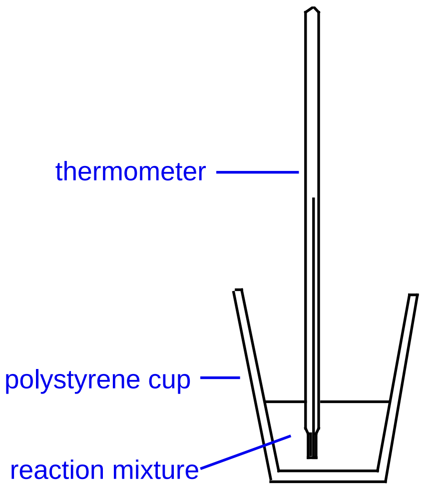
All the dilute acids are corrosive and so I must wear eye protection. If I get any on my skin, I must wash it off at once with plenty of water. Any spills on the bench must also be mopped up with lots of water.

I shall use a pipette filler to fill the pipette safely.

Because of the risk of poisonous oxides of nitrogen being given off, the nitric acid experiment should be done in a fume cupboard.

Doing the experiment

The apparatus I am going to use is shown on the right. In addition, I shall need a 3 decimal place balance, a weighing bottle, a pipette and pipette filler The thermometer should read to 0.2°C.



Measure 50 cm^3 of one of the acids into the polystyrene cup from a pipette. To get maximum accuracy, you should let the pipette drain naturally, and then touch the tip on the surface of the acid in the cup.

Weigh a weighing bottle to 3 decimal places and then add between 0.1 and 0.15 g of magnesium powder. Record the total weight.

Measure the steady temperature of the acid.

Tip the magnesium into the acid, making sure that none of it sticks to the thermometer above the level of the liquid. Stir the mixture continuously with the thermometer and measure the maximum temperature reached at the point the reaction stops.

Reweigh the weighing bottle plus any magnesium still stuck to it, and work out the mass of magnesium added to the acid.

Wash the cup and thermometer thoroughly with water, and then dry them with paper tissue.

Repeat the experiment with the same acid and a similar amount of magnesium. It doesn't matter if the two masses aren't exactly the same. After each experiment divide the temperature rise by the mass of magnesium to find the temperature rise per gram of magnesium. If the figures for the two experiments don't agree quite closely, repeat the experiment again until you get two figures which do agree.

Then repeat the whole experiment with the other three acids, remembering that the nitric acid experiment should be done in the fume cupboard.

My prediction

I predict that the heat given out per mole of magnesium will be the same for the strong acids hydrochloric acid and sulphuric acid, because in both cases the underlying ionic equation is the same:

$$Mg_{(s)} + 2H^+_{(aq)} \rightarrow Mg^{2+}_{(aq)} + H_{2(g)}$$

In both cases, the solid magnesium has turned into ions in solution, and the hydrogen ions have turned into hydrogen molecules. The overall energy change is going to be made up from contributions due to both of these changes. Since these are the same in both cases, the heat evolved ought to be the same.

With nitric acid, I would expect that the heat evolved would be the same if the reaction produces just hydrogen. If oxides of nitrogen are formed as well as or instead of hydrogen, the heat evolved will be different, because different bonds are being broken and made.

I expect that the weak acid will give out less heat than the strong ones. Weak acids are only slightly ionised in solution, and some energy will be used in breaking the acid into ions. That means that less heat energy will be left over to release to the surroundings.

Obtaining evidence

Results with hydrochloric acid

Concentration of acid used is approximately 1 mol dm^{-3}..
Volume of acid used = 50.0 cm^3

	Expt 1	**Expt 2**	**Expt 3**
Mass of weighing bottle plus Mg (g)	10.807	10.806	10.820
Mass of weighing bottle afterwards (g)	10.684	10.689	10.687
Mass of Mg used (g)	0.123	0.117	0.133
Initial temperature (°C)	17.4	17.5	17.4
Maximum temperature (°C)	27.5	27.4	28.4
Temperature rise (°C)	10.1	9.9	11.0
Accuracy check - temperature rise per gram of Mg (°C/g)	82.1	(84.6)	82.7

Results with sulphuric acid

Concentration of acid used is approximately 0.5 mol dm^{-3}..
Volume of acid used = 50.0 cm^3

	Expt 1	Expt 2
Mass of weighing bottle + Mg (g)	10.810	10.800
Mass of weighing bottle afterwards (g)	10.687	10.685
Mass of Mg used (g)	0.123	0.115
Initial temperature (°C)	17.4	17.3
Maximum temperature (°C)	27.5	26.7
Temperature rise (°C)	10.1	9.4
Accuracy check - temperature rise per gram of Mg (°C/g)	82.1	81.7

Results with nitric acid

Concentration of acid used is approximately 1 mol dm^{-3}..
Volume of acid used = 50.0 cm^3

	Expt 1	Expt 2	Expt 3
Mass of weighing bottle + Mg (g)	10.817	10.787	10.773
Mass of weighing bottle afterwards (g)	10.688	10.685	10.684
Mass of Mg used (g)	0.129	0.102	0.089
Initial temperature (°C)	17.4	17.4	18.1
Maximum temperature (°C)	32.9	29.1	28.2
Temperature rise (°C)	15.5	11.7	10.1
Accuracy check - temperature rise per gram of Mg (°C/g)	(120.2)	114.7	113.5

Results with ethanoic acid

Concentration of acid used is approximately 1 mol dm^{-3}..
Volume of acid used = 50.0 cm^3

	Expt 1	**Expt 2**	**Expt 3**
Mass of weighing bottle + Mg (g)	10.882	10.830	10.806
Mass of weighing bottle afterwards (g)	10.686	10.685	10.686
Mass of Mg used (g)	0.196	0.145	0.120
Initial temperature (°C)	18.2	18.4	18.4
Maximum temperature (°C)	34.1	30.1	28.1
Temperature rise (°C)	15.9	11.7	9.7
Accuracy check - temperature rise per gram of Mg (°C/g)	81.1	80.7	80.8

Analysing my evidence and drawing conclusions

Calculating the heat evolved per mole of magnesium

The heat given out by the reaction is used to heat up the liquid in the polystyrene cup. The heat evolved is given by the expression:

Heat evolved = mass x specific heat x temperature rise

Because the solutions used are dilute, I shall assume that the density and the specific heat are the same as water.

The density of the solution is 1 g cm^{-3}.

The specific heat of the solution is 4.18 J g^{-1} K^{-1}.
That means that in each experiment, the heat evolved is given by

50.0 x 4.18 x temperature rise joules

To find out how much heat is given out per mole of magnesium, I need to divide this by the mass of magnesium to find the heat given out per gram, and then multiply by the mass of 1 mole (24.3 g). That gives an answer in joules. To convert this into kJ, divide by 1000.

$$\text{Heat evolved per mole of magnesium} = \frac{50 \times 4.18 \times \text{temperature rise} \times 24.3}{\text{mass of Mg} \times 1000} \text{ kJ}$$

Results from hydrochloric acid

	mass Mg (g)	temp rise (°C)	heat evolved per mole Mg (kJ/mol)	average value (kJ/mol)
Expt 1	0.123	10.1	417	419
Expt 3	0.133	11.0	420	

The results from Experiment 2 are not being included in the average because the accuracy check showed them to give a rather high value.

Results from sulphuric acid

	mass Mg (g)	temp rise (°C)	heat evolved per mole Mg (kJ/mol)	average value (kJ/mol)
Expt 1	0.123	10.1	417	416
Expt 2	0.115	9.4	415	

Results from nitric acid

	mass Mg (g)	temp rise (°C)	heat evolved per mole Mg (kJ/mol)	average value (kJ/mol)
Expt 2	0.102	11.7	583	580
Expt 3	0.089	10.1	576	

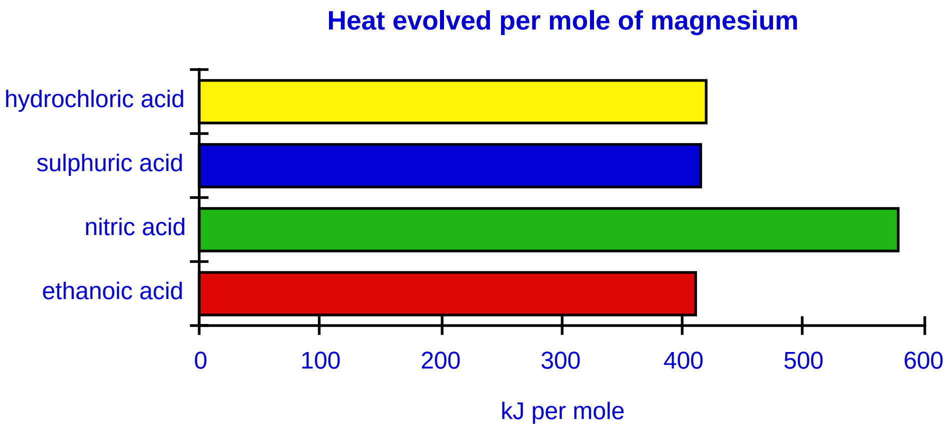
The results from Experiment 1 are not being included in the average because the accuracy check showed them to give an abnormally high value.

Results from ethanoic acid

	mass Mg (g)	temp rise (°C)	heat evolved per mole Mg (kJ/mol)	average value (kJ/mol)
Expt 1	0.196	15.9	412	411
Expt 2	0.145	11.7	410	
Expt 3	0.120	9.7	411	

All three values are included in the average. The reason for doing 3 experiments even though the first two were in good agreement was that I was surprised at the high value produced in the accuracy check.

Showing these values on a bar chart



Conclusion

The hydrochloric acid and sulphuric acid results

The average values in these two cases (419 and 416 kJ per mole) were in very good agreement - certainly to within experimental error. This was exactly in line with my prediction. Both of these are strong acids which means that they are fully ionised in solution. The reaction taking place in each case was simply between the magnesium and the hydrogen ions:

$$Mg_{(s)} + 2H^{+}{}_{(aq)} \rightarrow Mg^{2+}{}_{(aq)} + H_{2(g)}$$

The hydrogen ions were in excess, so that the amount of heat given off was controlled by the amount of magnesium present. The same amount of heat was evolved per mole of magnesium, because the reaction was the same in both cases.

The nitric acid case

The nitric acid produced far more heat than all the other acids. My prediction was that the value would be the same as for hydrochloric acid and sulphuric acid provided the product was hydrogen, but that if oxides of nitrogen were produced instead (or as well), the amount of heat would be different. The conclusion must be that the products contained significant amounts of oxides of nitrogen - although I didn't see or smell anything different because the reaction was done in a powerful fume cupboard.

The amount of heat given off is different because a different reaction is occurring. In the case of the hydrochloric acid or sulphuric acid, you can think of the reaction as being in two parts:

$$Mg_{(s)} \rightarrow Mg^{2+}{}_{(aq)} + 2e^{-}$$

$$2H^{+}{}_{(aq)} + 2e^{-} \rightarrow H_{2(g)}$$

The magnesium reaction is still happening with nitric acid, but the other half of the reaction is now perhaps:

$$NO_3^-{}_{(aq)} + 2H^+{}_{(aq)} + e^- \rightarrow H_2O + NO_2$$

or $$NO_3^-{}_{(aq)} + 4H^+{}_{(aq)} + 3e^- \rightarrow 2H_2O + NO$$

I found these equations in an A' level text book (A-level Chemistry by Ramsden), together with three other possible reactions.

Different bonds are being broken and made from when hydrogen ions form hydrogen gas. Because a lot of heat is being given out, the new bonds being made must be a lot stronger than the ones being broken.

The ethanoic acid case

The results show that the ethanoic acid gave out slightly less heat than the hydrochloric acid and sulphuric acid. The difference could easily be accounted for by experimental error. The ethanoic acid value (411) is only about 2% less than the hydrochloric acid value (419) and that could easily be accounted for by the errors in reading the thermometer or weighing the magnesium.

My results don't give me enough evidence to reliably support my prediction that the heat given out by a weak acid will be less than that for a strong acid. I thought that the heat would be less because some of it would be used to split the weak acid molecules into ions. What my results show is that very little heat must be needed to split ethanoic acid into its ions.

While I was trying to find a reason for the ethanoic acid result, I found figures for the heat evolved when acids are neutralised (Chemistry Data Book by Stark and Wallace). These showed that the heat evolved when sodium hydroxide neutralises hydrochloric acid is 57.1 kJ per mole, and when it neutralises ethanoic acid it is 55.2 kJ per mole. Again, this is only slightly less - this time, just over 3% less. That gives me confidence that my unexpected ethanoic acid result is probably about right.

Evaluating my investigation

Evaluating my experiment

I was pleased at how consistent my results were for any particular acid. There were two results which I decided not to use when taking averages. These were Experiment 2 with hydrochloric acid and Experiment 1 with nitric acid, both of which gave rather high values on my accuracy check. The hydrochloric acid value was probably just within the experimental error due to reading the thermometer, but the first nitric acid value was about 5% higher than the other values. I think the errors might have to do with the balance I was using. I did the experiment over two days, using a different balance on each day. On the first day, the third decimal place on the balance drifted around quite a lot (perhaps because of draughts). Added to the errors in reading the thermometer, that could produce a result this far out.

I was confident that my results were good until I tried to find out the accepted value for the heat given out when magnesium reacts with a strong acid like hydrochloric acid. I asked my teacher how to find this and she showed me a table in the Nuffield Advanced Science Book of

Data. That gave a value of -466.9 kJ per mole (the minus sign shows that heat is evolved). That is far higher than my figures show. My figures are about 50 kJ less than this.

I think this must arise from large heat losses during the experiments. Because each experiment had a similar temperature rise, took a similar amount of time and used identical apparatus, the heat losses in each experiment would have been very similar. That's why I got consistency between my results.

There was a lot of fizzing in each experiment and lots of steamy spray was given off. This would have carried off heat. There would also have been normal heat losses due to convection and radiation from the top of the mixture anyway.

I also haven't allowed for the heat absorbed by the polystyrene cup (although that is likely to be small, because the cups don't weigh very much), or the heat absorbed by the thermometer.

The nitric acid experiment wasn't done under the same conditions as the other ones, because it was done in a fume cupboard. The strong draught will have carried away more heat than in the other cases. To be fair, I should perhaps have done all the experiments in the fume cupboard using the minimum possible air flow.

Improving my experiment

To try to cut down heat losses from the top of the cup, I could use a plastic lid to the cup (like a take-away coffee cup) with a hole punched through it to take the thermometer. I would fit the lid on as quickly as possible after adding the magnesium. The hole would be loose enough so that gases would still escape, but the spray would be mainly trapped and heat losses due to convection and radiation would be lessened.

Errors due to reading the thermometer, the balance and the pipette are very small compared with those due to heat losses. I could improve the temperature reading by using a thermometer calibrated to 0.1°C rather than 0.2°C. I can't do much about the weighing because I am already using the most accurate balance. I should, though, take more care to keep it out of draughts. The volumes I am adding using a pipette are about as accurate as I can make them. I could weigh the liquid added rather than measure its volume, but the errors in measuring the volume using a pipette are already extremely small.

My results for each acid are already very consistent, so I am not likely to gain much by simply repeating each experiment. The main problem is trying to reduce the heat losses.

Extending my experiment

I don't have enough results to be sure about the heat given out when weak acids react with magnesium, and so I should repeat the experiment using a selection of other weak acids like citric acid, ascorbic acid (vitamin C) or phosphoric acid. In each case, I would use the acid of a similar concentration to the ones I have already used, although the exact concentration doesn't matter as long as the acid is in excess. I would either have to do the experiments exactly as I did the first time in order to get fair comparisons, or redo all the experiments taking into account the changes I have suggested.

It might be a good idea to try to find a very weak acid to see whether the amount of heat given off is very different, but the reaction is likely to be very slow and that leaves more room for major heat losses.