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Coal Refining

As a highly-industrialised world, we use a vast amount of energy each day. Current estimates put the average global rate of energy use at 1.25 x 10^{13} W or 12,500 GJ s^{-1}. Let's think about three areas in which energy consumption is very high: (1) electricity use, (2) heating buildings and (3) transportation. Typically, the source of the energy in each of these three areas is some sort of fuel, i.e., a chemical substance.

In order to satisfy the world's energy demands, these fuels are needed in huge quantities, and so fuels that can be obtained in bulk are the most commonly used. Such fuels include coal, hydrocarbons (from crude oil), natural gas and wood (biomass). There are problems with our reliance on these fuels; coal, natural gas and crude oil are non-renewable resources. Wood might be renewable, but trees take time to grow and our hunger for wood and land is leading to rapid and potentially irreversible deforestation, which has several negative environmental impacts.

Although there has been a big shift towards energy production from renewable sources, there has continued to be a steady increase in our use of coal, oil and gas. On the assumption that we will continue to use the resources until they are depleted, it makes sense to try to ensure we use them in the wisest possible way.

In this Factsheet, we will focus on coal and how we can get the most out of it. Most coal is burnt in power stations in order to generate electricity. However, coal has a number of disadvantages (from an energy production point-of-view) compared to natural gas and hydrocarbons:

1. Coal has a larger carbon footprint than other non-renewable resources:

Resource type	**CO_2 produced /cm^3 g^{-1}**	**CO_2 produced /cm^3 kJ^{-1}**
Coal (carbon, C)	2000	60
Natural gas (methane, CH_4)	1500	27
Hydrocarbon (octane, C_8H_{18})	1685	35

2. Although coal has a high energy density (one of its main attractions), it has a significantly lower specific energy than some other non-renewable resources:

Resource type	**Energy density /kJ dm^{-3}**	**Specific energy /kJ kg^{-1}**
Coal	38000 (approx.)	30000 (approx.)
Natural gas (methane, CH_4)	36	55500
Hydrocarbon (octane, C_8H_{18})	33700	47900

3. Coal tends to release larger quantities of harmful pollutants than other non-renewable resources for the amount of energy generated:

Resource type	**SO_2 /kg GWh^{-1}**	**NO_x / kg GWh^{-1}**	**Particulates**
Coal	8.8	2.1	Significant
Natural gas (methane, CH_4)	Negligible	1.1	Negligible
Hydrocarbon (octane, C_8H_{18})	Negligible	-	Moderate

It could also be argued that coal has many other disadvantages compared to natural gas and liquid hydrocarbon production from crude oil. Coal mining is arguably more hazardous and creates more obvious impact on the environment (e.g., open pit mining, spoil heaps, etc.) than oil refining and gas drilling. Coal is bulky and needs to be transported by vehicles (ships, trains and lorries) which is costly, slow and polluting. In contrast, natural gas can be transported rapidly and cleanly from gas fields by pipeline.

Based on these data, it appears more environmentally sound and energy-efficient to use natural gas and liquid hydrocarbons as our principal non-renewable sources of energy.

Current estimates of global fuel reserves suggest about 120 years of coal usage remains, whilst only 50 years of crude oil and natural gas usage remains. The ideal situation would be to develop a way to convert more abundant coal into other, more useful and less polluting fuels. In recent years, coal refining has developed to the extent that coal can now be converted into both gas and liquid fuels.

Coal Gasification

In the process of coal gasification, coal is converted into the equivalent chemical form of natural gas, methane. The overall process is a multistep one and first involves the reaction of carbon with steam and oxygen at very high temperatures.

Many different reactions can occur during this stage, such as:

$C(s) + O_2(g) \rightarrow CO_2(g)$ $2C(s) + O_2(g) \rightarrow 2CO(g)$

$C(s) + CO_2(g) \rightarrow 2CO(g)$ $C(s) + H_2O(g) \rightarrow H_2(g) + CO(g)$

$C(s) + 2H_2(g) \rightarrow CH_4(g)$

The key reaction is **$C(s) + H_2O(g) \rightarrow H_2(g) + CO(g)$**

The overall product of this first stage, a mixture of CO and H_2 (with some CO_2 and CH_4), is called **syngas** (synthesis gas), and is vital to the production of synthetic natural gas (SNG) and liquid hydrocarbons (see coal liquefaction).

Following the production of syngas, the ratio of hydrogen-to-carbon monoxide is manipulated using the **water-gas shift reaction**. By reacting the carbon monoxide content of syngas with steam, hydrogen is produced and thereby increases the hydrogen-to-carbon monoxide ratio.

$$CO(g) + H_2O(g) \rightleftharpoons CO_2(g) + H_2(g)$$

With a hydrogen-to-carbon monoxide ratio of 3:1, syngas will react to form methane.

$$3H_2(g) + CO(g) \rightarrow CH_4(g) + H_2O(g)$$

Methane produced this way is called **synthetic natural gas** (SNG) and it can be extracted, compressed and used in the same manner as methane from natural gas. Most SNG produced is currently used for electricity generation. The principal benefits of using SNG rather than coal, being reduced CO_2 and SO_2 emissions, as well as easier transportation (via pipelines).

Coal Liquefaction

Neither coal nor natural gas is a convenient form of energy for modern transportation. Most vehicles on the roads today use mixtures of liquid hydrocarbons (gasoline or diesel) as their principal fuel. These hydrocarbon mixtures have very high energy density and specific energy, making them ideal for situations when mass and, in particular, volume are important considerations—you would not want to have to transport tonnes or cubic metres of fuel on your car when going on a short journey!

In the process of coal liquefaction, solid coal is transformed into various liquid hydrocarbons with carbon chain lengths appropriate for use as a liquid fuel (C6-20). The liquefaction process can be carried out via direct (from coal) or indirect methods (via a gas phase).

Direct coal liquefaction typically involves the hydrogenation of the carbon content of coal using high temperatures and pressures as well as a catalyst (such as the iron-containing 'red mud' produced during alumina purification). The general process that occurs can be summarised as:

$nC(s) + (n + 1)H_2(g) \rightarrow C_nH_{2n+2}(l)$

e.g., $6C(s) + 7H_2(g) \rightarrow C_6H_{14}(l)$

An alternative direct approach involves heating coal to high temperatures in the absence of oxygen. This initiates pyrolytic events that result in the production of coal tar containing short chain liquid hydrocarbons.

Indirect coal liquefaction first starts with the production of syngas as previously described. The hydrogen-to-carbon monoxide ratio of the syngas is modified as required and then converted to liquid hydrocarbons via the **Fischer-Tropsch process**.

Typical conditions for the Fischer-Tropsch process are a moderate temperature such as 300-400 °C and a catalyst based on cobalt, iron or ruthenium. Industrially, the pressures used vary significantly but may be up to 100 atmospheres.

The overall process can be summarised as:

$(2n + 1)H_2(g) + nCO(g) \rightarrow C_nH_{2n+2}(l) + nH_2O(g)$

e.g., $17H_2(g) + 8CO(g) \rightarrow C_8H_{18}(l) + 8H_2O(g)$

The processes of coal gasification and liquefaction look very attractive. Natural gas and liquid hydrocarbons have many advantages over direct use of coal in energy generation, particularly environmental ones concerning harmful emissions. However, both gasification and liquefaction processes are energy-intensive in their own right and this is a major disadvantage. Typically, coal liquefaction is only profitable when global oil prices are so high that it is very expensive to create liquid hydrocarbons via oil refining.

As technology improves and more efficient catalysts are discovered, the overall cost may decrease, making these processes continuously viable and thus extend our reserves of hydrocarbons ("oil") and gas for additional decades and help reduce the production of carbon dioxide and other harmful gases.

Of course, eventually global reserves of coal will be depleted alongside crude oil and natural gas, which is why global efforts should focus on development of efficient, cost-effective, renewable energy sources.

Questions

1. Suggest one advantage and one disadvantage of converting coal into synthetic natural gas.
2. State an equation for the production of syngas from coal (carbon).
3. State an equation for the formation of methane from syngas.
4. State an equation for the formation of decane (10 carbons) from syngas.

Answers:

1. Advantages: SNG less polluting/less CO_2/less SO_2/less NO_x/less particulates than coal
   SNG easier to transport than coal/can be piped
   SNG has higher specific energy than coal
   Reserves of natural gas will run out before coal

   Disadvantages: Production of SNG is very expensive/energy intensive
   SNG has a lower energy density than coal
2. $C(s) + H_2O(g) \rightarrow CO(g) + H_2(g)$
3. $CO(g) + 3H_2(g) \rightarrow CH_4(g) + H_2O(g)$
4. $21H_2O(g) + 10CO(g) \rightarrow C_{10}H_{22}(l) + 10H_2O(g)$

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