A METHOD OF PRODUCING A SYNTHETIC DIAMOND

TECHNICAL FIELD

Aspects and embodiments relate to a method of producing a synthetic diamond. In particular, certain embodiments relate to a method of using carbon dioxide from direct air capture (DAC) and renewable energy to produce a synthetic diamond.

BACKGROUND

Carbon dioxide in the atmosphere accounts for a large proportion of the "enhanced greenhouse effect." Carbon dioxide concentrations in the atmosphere are increasing, due at least in part to the burning of fossil fuels. The increasing level of carbon dioxide in the atmosphere is a significant contributor to climate change.

The process of mining a diamond typically requires the burning of large quantities of fossil fuels and therefore the release of large volumes of carbon dioxide into the atmosphere. In particular, fossil-fuel-powered vehicles are used to transport the rock in which diamonds are found in a mine to the surface and then to a factory for processing. Very little diamond by weight or volume is found in the rock by comparison to the overall weight or volume of the rock, and the diamond that is yielded from the rock must be further cut and polished to produce a gem. Thus, the vehicles must carry a significant amount of weight and volume of rock to the factory in comparison to the finished gem which is yielded after processing at the factory. The processing of the rock at the factory is also typically energy-intensive, since the rock has to be crushed to release the diamonds. The burning of fossil fuels in mining, transporting and processing diamonds therefore releases an appreciable volume of carbon dioxide into the atmosphere. For example, the Ekati mine in Canada releases 65 kg (143 lb) of carbon dioxide per carat. (BHP Billiton 2008: Ekati mine emissions 195,179 metric tons of CO_2 equivalent, production 3,000,000 carats of rough diamonds.)

An object of at least certain embodiments is to address one or more of these problems.

SUMMARY

According to a first aspect of the invention, there is provided a method of producing a synthetic diamond, the method comprising:

a) capturing carbon dioxide from the atmosphere;

b) conducting electrolysis of water to provide hydrogen;

c) reacting the carbon dioxide obtained from step (a) with the hydrogen obtained from step (b) to produce methane; and

d) using the hydrogen obtained from step (b) and the methane obtained from step c) to produce a synthetic diamond by chemical vapour deposition.

In some aspects, the method of producing a synthetic diamond comprises:

(a) capturing carbon dioxide from the atmosphere;

(b) performing electrolysis of water to provide hydrogen;

(c-1) electrochemically reacting the carbon dioxide obtained from step (a) with water to produce methane; and

(d) using the hydrogen obtained from step (b) and the methane obtained from step (c-1) to produce a synthetic diamond by chemical vapour deposition (CVD).

[Step (a) - Capture of Carbon Dioxide (CO_2) from Air]

In accordance with certain aspects, step (a) may comprise capturing carbon dioxide using a nanotube gas separator.

Step (a) may comprise capturing carbon dioxide using a recyclable carbon dioxide sorbent or a polymer membrane gas separator.

Step (a) may comprise capturing carbon dioxide using an amine scrubber. Various amines are suitable for carbon dioxide capture. The amine scrubber may be monoethanolamine.

Step (a) may comprise capturing carbon dioxide using an amine-based sorbent material. Various amine-based sorbent materials are suitable for carbon dioxide capture. Capturing carbon dioxide can be performed using an amine-based sorbent material can be accomplished at 25°C or below. Capturing carbon dioxide using an amine-based sorbent material can be accomplished at a temperature below 25°C.

Once carbon dioxide has been captured using a sorbent material, the captured carbon dioxide can be desorbed from the sorbent material by applying heat to the sorbent.

Step (a) may comprise capturing carbon dioxide using a mineral or a zeolite, which binds reversibly to carbon dioxide. The mineral or zeolite may comprise calcium oxide, serpentinite or molecular sieves.

Step (a) may comprise capturing carbon dioxide using a caustic solution. The caustic solution may be calcium hydroxide solution, sodium hydroxide solution, potassium hydroxide solution, lithium hydroxide solution or soda lime.

Step (a) may comprise capturing carbon dioxide using activated carbon or lithium peroxide.

Step (a) may comprise capturing air. The air captured may be ambient air. Preferably, the carbon dioxide is not captured from flue gas.

Step (a) may comprise drying the air. A dessicant dryer may be used to dry the air. The air may be dried to a dew point of less than -70 °C. The air may be dried to a dew point of substantially -70 °C. Step (a) may comprise cooling the air to liquefy carbon dioxide in the airCooling the air to liquefy carbon dioxide in the air may comprise compressing the air and then expanding the air. The steps of compression and then expansion of the air may be repeated. The steps may be repeated three times. The steps may be repeated four times.

The features explained above can be combined. For instance, carbon dioxide may be captured using an amine-containing sorbent material at a temperature below 25°C, followed by desorbing the captured carbon dixoide by applying heat to the sorbent material.

[Step (b) - Production of Hydrogen]

Step (b) may comprise conducting electrolysis of water using at least one solid oxide electrolysis cell (SOEC). the, or each, SOEC may be a solid oxide fuel cell that is arranged to use a solid oxide or ceramic electrolyte to produce oxygen and hydrogen gas. When at least one SOEC is used for the electrolysis of water in step (b), the electrolysis may be conducted at a temperature of between 350 and 1000 °C. The electrolysis may be conducted at a temperature of between 500 and 850 °C.

Step (b) may comprise conducting electrolysis of water using at least one polymer electrolyte membrane (PEM) cell. The PEM cell may be arranged to use a solid polymer electrolyte (SPE) to produce hydrogen. When at least one PEM cell is used for the electrolysis of water in step (b), the electrolysis may be conducted at a temperature below 150 °C. The electrolysis may be conducted at a temperature of 100 °C or below. The electrolysis may be conducted at a temperature between 50 and 100 °C.

Step (b) may comprise conducting electrolysis of water using at least one alkaline electrolysis cell (AEC). The alkaline electrolysis cell (AEC) may comprise two electrodes arranged to operate in a liquid alkaline electrolyte solution. The liquid alkaline electrolyte solution may comprise potassium hydroxide, sodium hydroxide or potassium carbonate. When at least one AEC is used for the electrolysis of water in step (b), the electrolysis may be conducted at a temperature of between 50 °C and 300 °C. The electrolysis may be conducted at a temperature between 150 °C and 250 °C.

The water may comprise rainwater, potable water, or water recycled from elsewhere in the diamond-production method and combinations of these. Step (b) may comprise filtering the water. Step (b) may comprise conducting reverse osmosis on the water. The reverse osmosis may be conducted so as to substantially purify the water. Step (b) may comprise distilling the water. Step (b) may comprise de-ionising the water.

The majority of hydrogen produced globally is from the cracking of methane. This is not an environmentally friendly way to generate hydrogen as the methane comes from natural gas sources. Electrolysis of water is the most environmentally-friendly method of producing hydrogen, particularly when the energy used for this process is renewable energy (as discussed further below).

[Step (c) - Production of Methane]

A benefit of the present process is that a number of methane-production (methanation) methods can be used in step (c). These methane-production methods can, for instance, include thermochemical processes and biological processes and combinations of these processesStep (c) can be employed in conjunction with an electrochemical processes for producing methane from water and carbon dioxide, which is discussed in relation to step (c-1) below.

Step (c) may comprise reacting the carbon dioxide with the hydrogen according to the Sabatier reaction; in other words, according to the Sabatier process, which is a thermochemical process. The Sabatier process involves the reaction of hydrogen with carbon dioxide to produce methane and water, which is described by the following exothermic reaction:

$$CO_2 + 4\ H_2 \rightarrow CH_4 + 2\ H_2O + \text{energy}$$

The reaction of step (c) may be carried out at a temperature between 100 °C and 800 °C. The reaction may be carried out at a temperature between 150 °C and 600 °C. The reaction may be carried out at a temperature between 250 °C and 450 °C. The reaction may be carried out at a temperature of substantially 250 °C.

The reaction of step (c) may be carried out at atmospheric pressure. The reaction of step (c) may be carried out at a pressure above atmospheric pressure. The reaction of step (c) may be carried out at a pressure of 0.7 barg.

At least a portion of the water produced from the Sabatier process may be recycled or otherwise used in the electrolysis process of step (b). In certain instances at least a portion of the water produced from the Sabatier process may be used alone or in combination with rainwater or any other source of water in the electrolysis process. This allows for an additional savings of resources.

The reaction of step (c) may be carried out in the presence of a catalyst. The catalyst may be a nickel-based catalyst, a ruthenium-based catalyst, a rhenium-based catalyst, a rhodium-based catalyst or a cobalt-based catalyst. The catalyst may comprise a mixture of a nickel-based catalyst and a ruthenium-based catalyst. In accordance with various aspects, the catalyst may be supported or unsupported. The catalyst may be supported on a support comprising an oxide. The catalyst may be supported on a support comprising TiO_2, SiO_2, MgO or Al_2O_3.

The reaction of step (c) may be a biological process. For example, step (c) can be performed using methanogens. Methanogens are microorganisms that produce methane as a metabolic by-product in anoxic conditions. In some aspects, the methanogens are archaea, which are less sensitive to the environment they operate in. When the reaction of step (c) is performed using methanogens, the reaction may comprise reacting the carbon dioxide with the hydrogen according to the following reaction:

$$CO_2 + 4\ H_2 \rightarrow CH_4 + 2\ H_2O + \text{energy}$$

In other words, the reaction may be substantially the same as the Sabatier process, but may be a natural reaction. The methanogens may be archaea or other prokaryotes. Step (c) may be carried out using conceivably any species of methanogen. The methanogens create methane as part of their respiration process, where carbon dioxide is converted into methane under conditions that are generally low temperature (~50 °C) and low pressure (atmospheric pressure or slightly above). Step (c) may comprise purifying the methane produced.

[Step (c-1) - Production of Methane]

As explained above, step (c) can be conducted as step (c-1), which comprises the electrochemical formation of methane from carbon dioxide, captured in step (a), and water. Step (c-1) has the advantage that both input materials, carbon and dioxide and water, are abundant natural resources. The electrochemical reaction below shows the reactants and a range of possible products that can be obtained when an electric current is applied to conduct such a reaction:

$$CO_2 + H_2O + \text{electric energy} \rightarrow CH_4 + H_2 + CO + C_2H_4$$

The reaction of step (c-1) may be carried out at a temperature between 0°C and 100°C. The reaction may be carried out at a temperature between 10°C and 70°C. The reaction may be carried out at a temperature between 15°C and 40°C. The reaction may be carried out at a temperature of substantially 25°C.

The reaction of step (c-1) may be carried out above atmospheric pressure. The reaction may be carried out at a pressure of from 1 to 10 atm. The reaction may be carried out at a temperature below atmospheric pressure. The reaction may be carried out at atmospheric pressure.

The reaction of step (c-1) may be carried out by providing electric energy in the form of direct current. The voltage of the direct current may be 1.0-5.0 V. The voltage of the direct current may be 1.5-2.5 V. The voltage of the direct current may be 1.8-2.2 V.

The reaction of step (c-1) may be carried out in the gaseous phase. The gas flow rate through the reactor may be from 20 to 50 sccm.

The reaction of step (c-1) may be carried out in the presence of a catalyst. The catalyst, if used, may be a metal catalyst. The metal catalyst may be a nickel-based catalyst. The metal catalyst, such as the nickel catalyst, may be supported on a support material.

The water may comprise rainwater, potable water, or water recycled from elsewhere in the diamond-production method and combinations of these.

Step (c) may be be conducted using a combination of one or more thermochemical processes and biological processes. For instance, one or more thermochemical processes and biological processes of step (c) may be carried out in combination with the electrochemical process of step (c-1) in order to produce methane by different reactions. Where more than one process is used in combination, the processes can, for instance, be used in series or parallel or a mixture of series and parallel.

The methane produced by step (c) or step (c-1) may be purified using a pressure swing adsorption technique. Sep (c) or step (c-1) may comprise using molecular sieves to remove oxygen. Step (c) or step (c-1) may comprise using zeolites to remove at least one of carbon dioxide, nitrogen, and water. In a similar manner as discussed above with reference to the Sabatier process, according to at least one aspect at least a portion of the water produced as a result of the methanation process using the methanogens may be recycled or otherwise used in the electrolysis process of step (b).

The methane may be purified using cryogenics. Step (c) or step (c-1) may comprise using membranes to remove nitrogen and CO_2. Step (c) or step (c-1) may comprise using desiccant drying to remove water.

Step (c) or step (c-1) may comprise using an amine gas treater to remove sulphide impurities.

[Step (d) Production of Diamond using Chemical Vapor Deposition (CVD)]

Chemical vapour deposition (CVD) allows films of synthetic diamond to be grown over large areas of substrate with control over the properties of the diamond produced.

The CVD of step (d) may be carried out at a pressure of between 0.5 kPa and 100 kPa. The CVD step may be carried out at a pressure of between 1 kPa and 50 kPa. The CVD step may be carried out at a pressure of substantially 40 kPa.

The CVD of step (d) may be carried out at a temperature between 600 °C and 1200 °C. The CVD step may be carried out at a temperature between 700 °C and 1000 °C. The CVD step may be carried out at a temperature of substantially 950 °C. The ratio of hydrogen to methane used in step (d) may be substantially 5:1. The ratio of hydrogen to methane used in step (d) can be from 1:1 to 9:1, from 1:1 to 8:1 or from 5:1 to 8:1.

The CVD of step (d) may be carried out on a substrate. In accordance with certain aspects, the substrate may comprise diamond, silicon, tungsten, molybdenum, silicon carbide, silicon nitride, quartz glass or cemented carbide.

The CVD of step (d) may be carried out using a microwave plasma CVD machine.

[Other Features]

Step (a) may be performed before step (b). Step (b) may be performed before step (a) or substantially simultaneously with step (a).

The method may comprise an additional step, after step (d), of annealing the synthetic diamond. The step of annealing the synthetic diamond may be carried out in a High Pressure High Temperature (HPHT) press.

The method may comprise a step, after step (d), and, in embodiments in which the synthetic diamond is annealed, after the step of annealing the synthetic diamond, of cutting and/or polishing the diamond produced in step (d) to produce a gem-quality diamond.

The method may comprise the step of reacting oxygen produced from the electrolysis of the water in step (b) with carbon produced by the chemical vapour deposition in step (d) to produce carbon dioxide. The method may comprise reacting the carbon dioxide obtained from this step with the hydrogen obtained from step (b) to produce methane. The method may comprise adding the carbon dioxide to the carbon dioxide captured from the atmosphere prior to step (c).

The method may comprise separating water produced from the reaction of step (c) from the methane produced by that reaction. The separation of the water from the methane may be conducted by centrifugation, condensation or adsorption. The method may comprise electrolysing the water to provide hydrogen.

The method may comprise using energy from at least one renewable source to perform at least one of the steps. The method may comprise using energy from at least one renewable source to perform the electrolysis. The method may comprise using energy from at least one renewable source to perform each of the steps. As used herein, the term "renewable source" when used in reference to energy sources generally refers to one or more technologies that utilize replenishable energy sources such as energy from water, wind, and the sun. For example, the at least one renewable source may comprise wind power. The at least one renewable source may comprise solar power. The at least one renewable source may comprise wave power or tide power.

In accordance with embodiments in which the diamond produced in step (b) is cut and/or polished to produce a gem-quality diamond, in which energy from at least one renewable source is used to perform each of the steps, and in which the water in step (b) is rainwater, up to 230 times less carbon dioxide is released in the production of a gem-quality diamond than the production of such a diamond from mining. Approximately 40 times less carbon dioxide is released than in the production of a gem-quality diamond using the process which releases the next-least quantity of carbon dioxide. It is estimated that if the global demand for diamonds (124 million carats in 2011) were switched to diamonds produced using this method, carbon dioxide emissions would be reduced by nearly 8 million tonnes per year.

BRIEF DESCRIPTION OF THE DRAWINGS

Specific embodiments will now be described by way of example only, and with reference to the accompanying drawings in which:

Figure 1 is a flow diagram of an embodiment of the method of producing a synthetic diamond; and

Figure 2 shows, schematically, an apparatus for use with the method.

DETAILED DESCRIPTION

Overview

With reference to Figure 1, an example of the method for manufacturing diamonds will now be described in overview.

First, carbon dioxide 2 is captured from the atmosphere; that is, carbon dioxide 2 is captured from air 1. To capture carbon dioxide 2, the following process can be used. Air 1, which has carbon dioxide 2 in it, is compressed 3 and then dried 4. Carbon dioxide 2 is then separated 5 from the air 1 (although some air 1 will remain) and the separated carbon dioxide 2 and remaining air 1 are compressed and expanded to cool 6 the carbon dioxide 2. The carbon dioxide 2 and remaining air 1 are compressed and expanded 7, such that the carbon dioxide 2 liquefies. The remaining air 1 is evacuated.

Second, water is electrolysed to provide hydrogen 11. In one embodiment, the water is rainwater 8. To produce hydrogen 11 from the rainwater 8, the following process is used. Rainwater 8 is captured, filtered, distilled and de-ionised 9. The resulting filtered and de-ionised rainwater 8 is then electrolysed 10 to produce hydrogen 11 and oxygen 12.

Third, carbon dioxide 2 obtained from the first step is reacted with the hydrogen 11 obtained from the second step to produce methane 14 (methanation 13). The methanation 13 process is as follows. The hydrogen 11 and carbon dioxide 2 are reacted according to the Sabatier reaction, described by the following equation:

$$CO_2 + 4\ H_2 \rightarrow CH_4 + 2\ H_2O + \text{energy}$$

The products are methane 14 and water 8. As noted throughout this application, the reaction of carbon dioxide with hydrogen to form methane can also be conducted using a biological process, which can involve organisms known as methanogens. In further aspects, methanation can be conducted by carried out by reacting carbon dioxide with water to produce methane. In reference to Figure 1, methanation 13 may be carried out by reacting carbon dioxide 2 with water 8 rather than processing water 8 through stage 10 to produce hydrogen 11.

Fourth, the hydrogen 11 obtained from the second step and the methane 14 obtained from the third step are used to produce a synthetic diamond 16 using CVD 15.

Direct Air Capture of Carbon Dioxide

With continued reference to Figure 1, and with additional reference to Figure 2, the process of capturing carbon dioxide 2 as described above in overview above will now be described in more detail. An example of an apparatus used for this process will also be described.

The step of producing a synthetic diamond 16 using CVD requires high-purity carbon dioxide 2. In one embodiment, the purity required is 99.9999%. The concentration of carbon dioxide in the atmosphere is around 400ppm. The process of capturing carbon dioxide 2 from the air 1 therefore requires the concentration of carbon dioxide 2 to be increased. Air 1, with carbon dioxide 2 in it, is drawn from a column Q-1 into a compressor C-1. The air 1 and carbon dioxide 2 are compressed 3 in the compressor C-1 (shown in Figure 2). In one example, the compressor C-1 is a high purity oil-free air compressor. The compressor C-1 increases the pressure of the air 1 and carbon dioxide 2 to a gauge pressure of around 12 barg.

Next, the air 1 and carbon dioxide 2 are dried 3. A desiccant dryer F-1 can be used. In this embodiment, the air 1 and carbon dioxide 2 are dried 3 to a dew point of -70°C.

Carbon dioxide 2 is then separated 5 from the air 1 (although some air 1 will remain), for example, using a nanotube gas separator. In this embodiment, the nanotube gas separator is a nanotube 13X zeolite adsorption stripper F-2. In this embodiment, the nanotube 13X zeolite adsorption stripper F-2 strips out the carbon dioxide 2 from at least 80% of the other air 1 components. The resulting gas stream is at ambient pressure and rich in carbon dioxide 2.

The gas stream of air 1 and carbon dioxide 2 is then passed through a series of turbo compressor-expanders C-2, C-3, C-4. Each turbo compressor-expander C-2, C-3, C-4 compresses the air 1 and carbon dioxide 2 to condense the carbon dioxide 2 and then expands the air 1 and carbon dioxide 2 to chill 6 them in a respective heat exchanger E-1, E-2, E-3. In this embodiment, there are three turbo compressor/expanders C-2, C-3, C-4, each with a heat exchanger E-1, E-2, E-3 through which the stream of air 1 and carbon dioxide 2 flows before it is again compressed and expanded. However, it is to be appreciated that more or fewer turbo compressor-expanders can be used. The turbo compressor-expanders C-2, C-3, C-4 are such as those used in automotive technology. According to various aspects, step (a) may comprise drying the air.

In reference to the turbo compressor-expander device discussed above, in accordance with some aspects, capturing carbon dioxide from the atmosphere may comprise cooling the air to liquefy carbon dioxide in the air. For example, cooling the air to liquefy carbon dioxide in the air may comprise compressing the air and then expanding the air, such as by using one or more of the turbo compressor-expander devices described above. According to a further aspect, the steps of compression and then expansion of the air may be repeated. In accordance with a further aspect, the steps may be repeated three times. According to an even further aspect, the steps may be repeated four times.

Next, liquid/gas separation 7 is used to separate carbon dioxide 2 from the stream of air 1 and carbon dioxide 2. The carbon dioxide 2 and remaining air 1 are compressed in a compressor C-5. Then, they are expanded in a tank V-1, such that the carbon dioxide 2 liquefies. In this embodiment, the carbon dioxide 2 is at a temperature of around -40 °C and a pressure of over 10 bar. The remaining air 1 is evacuated.

The liquid carbon dioxide 2 is warmed and returned into its gaseous form prior to being fed into a Sabatier reactor R-1 for methanation, as described further below.

Carbon dioxide can also be captured and prepared for methanation by other means. For instance, carbon dioxide can be captured on an amine-containing sorbent material at a temperature below 25°C, followed heating the sorbent material in order to release the captured carbon dioxide gas. In the context of Figure 1, this would process carbon dioxide 2 to methanation 13. In the context of Figure 2, this would process from column Q-1 to tank V-1 following different steps to those outlined in Figure 2 between column Q-1 and tank V-1.

Hydrogen Generation

With continued reference to Figures 1 and 2, the second step of electrolysing water 8 to provide hydrogen 11, will now be described in more detail. An example of the apparatus used in this step will also be described.

Rainwater 8 is collected via a rainwater 8 funnel Q-2 and stored in a tank 18. In a variation of this process, water could be collected in tank 18 from a source other than rainwater, such as potable water and/or water recycled from elsewhere in the overall diamond-production process. The water 8 is transferred via a metering pump 19 connected to the tank 18 into a strainer 20. The metering pump 19 operates at low pressure. In this embodiment, the pressure at

which the metering pump 19 operates is about 0.5 barg. The water 8 passes through the strainer 20 and is strained by the strainer 20. Next, the water 8 passes through a filter 21 which filters the water 8 relatively coarsely. From the filter 21, the water 8 enters a reverse osmosis purification unit 22, which further purifies the water 8 using reverse osmosis. Next, the water 8 is distilled in a still (not shown) and de-ionised in a de-ioniser 23. In an alternative process, water 8 can be purified by reverse osmosis.

From the de-ioniser 23, the water passes to an electrolyser X-1. The electrolyser X-1 is powered by renewable energy. For example, the electrolyser X-1 can be powered by wind, solar, wave, tide, or geothermal energy. The electrolyser X-1 splits the water 8 into hydrogen 11 and oxygen 12 via an electrolysis 10 process. In this embodiment, the resulting hydrogen 11 is at about 99.999% purity. The oxygen 12 is taken off into a waste gas oxidiser R-2, to be used in a waste gas recovery process, as will be described further below. The hydrogen 11 is taken into a hydrogen storage tank T-1.

The hydrogen storage tank T-1 is a specialist lab equipment tank that stores the hydrogen 11 input at 99.999% purity and returns the hydrogen 11 at 99.9999% purity. The tank T-1 is a container containing solid metal hydride. In this embodiment, the solid metal hydride is an AB5-type alloy. Pressure is regulated using let-down valves from the stored pressure, which in one example can be as high as 10 barg.

Electrolysis of water may be performed using at least one polymer electrolyte membrane (PEM) cell. According to a further aspect, the PEM cell may be arranged to use a solid polymer electrolyte (SPE) to produce hydrogen. According to various aspects, when at least one PEM cell is used for the electrolysis of water, the electrolysis may be conducted at a temperature below 150 °C. According to a further aspect, the electrolysis may be conducted at a temperature of 100 °C or below. According to an even further aspect, the electrolysis may be conducted at a temperature between 50 and 100 °C.

Methanation

As discussed above, the third step of the present method for the manufacture of a synthetic diamond involves the reaction of the carbon dioxide obtained from the first step with the hydrogen obtained from the second step to produce methane. This process, and the apparatus used for it, will now be described in more detail, with continued reference to Figures 1 and 2.

Carbon dioxide 2 obtained from the first step is stored, as described above, in a tank V-1. Hydrogen 11 from the second step is stored, as described above, in a hydrogen storage tank T-1. The carbon dioxide 2 and hydrogen 11 are drawn from these tanks V-1, T-1 into a Sabatier reactor R-1. In the Sabatier reactor R-1, the carbon dioxide 2 is reacted with the hydrogen 11 to produce methane 14 (methanation 13). The hydrogen 11 and carbon dioxide 2 are reacted according to the Sabatier reaction, described by the following equation:

$$CO_2 + 4\ H_2 \rightarrow CH_4 + 2\ H_2O + \text{energy}$$

The reaction may be carried out in the presence of a catalyst. In one embodiment, a Ruthenium catalyst is used. The reaction takes place at 250 °C and around 0.7 barg. Under these conditions, over 95% of the carbon dioxide 2 is converted, with substantially 100% selectivity of methane 14. That is, over 95% of the carbon dioxide 2 is converted exclusively to methane, without appreciable conversion of carbon dioxide 2 to any other product. The reaction of may be carried out at a temperature between 100 °C and 800 °C. The reaction may be carried out at a temperature between 150 °C and 600 °C. The reaction may be carried out at a temperature between 250 °C and 450 °C. The reaction may be carried out at a temperature of substantially 250 °C.

According to other aspects, the catalyst may be a nickel-based catalyst, a rhenium-based catalyst, a rhodium-based catalyst, or a cobalt-based catalyst. According to another aspect, the catalyst may comprise a mixture of a nickel-based catalyst and a ruthenium-based catalyst. In accordance with various aspects, the catalyst may be supported or unsupported. According to a further aspect, the catalyst may be supported on a support comprising an oxide. According to another aspect, the catalyst may be supported on a support comprising TiO_2, SiO_2, MgO or Al_2O_3.

The methanation reaction may be performed using methanogens. As discussed above, methanogens are microorganisms that produce methane as a metabolic by-product in anoxic or anaerobic conditions. When methanation is performed using methanogens, the reaction may comprise reacting the carbon dioxide with the hydrogen according to the following reaction:

$$CO_2 + 4\ H_2 \rightarrow CH_4 + 2\ H_2O + \text{energy}$$

In other words, the reaction may be substantially the same as the Sabatier process, but may be a natural reaction. The methanogens may be archaea or other prokaryotes. Methanation may be carried out using conceivably any species of methanogen. In accordance with various aspects, the methanogens create methane as part of their respiration process, where carbon dioxide is converted into methane under conditions that are generally low temperature (~50 °C) and low pressure (atmospheric pressure or slightly above).

As explained in the context of step (c-1) in the section above titled 'Summary', the present invention can also involve producing methane by the electrochemical reaction of water with carbon dioxide, instead of, or in addition to, the reaction of carbon dioxide with hydrogen obtained by the electrolysis of water.

In the context of Figures 1 and 2, for example, electrochemical methanation is conducted using carbon dioxide 2 that has been stored in tank V-1 and purified water. The water can, for example, be purified in accordance with the procedure detailed above in the subsection titled 'Hydrogen Generation' or by reverse osmosis.

The purified water and carbon dioxide may be fed to one or more electrochemical cells in the gaseous phase at a flow rate of 20-50 sccm. The electrochemical cell in this example is powered by direct current at 1.8-2.2 V and contains a catalyst comprising nickel.

Referring back to Figures 1 and 2, the methane 14 produced is then purified in a methane purification apparatus F-3. This apparatus F-3 purifies the methane 14 by removing any impurities, including the water 8 that is also a product of the Sabatier process or present as an unreacted input material for the electrochemical process. In this embodiment, the water 8 is collected via centrifugation, although condensation or an adsorption method can be used as alternatives. In this embodiment, the water 8 is added to (this is not shown) the water 8 that is electrolysed 10 in the electrolyser X-1 to be used for the creation of more hydrogen 11. The methane 14 is stored in a methane tank T-2, ready for use.

In the context of the electrochemical methanation process, hydrogen gas produced as a by-product can be fed to the CVD diamond manufacture step as a co-reagent. Hydrogen gas produced as a by-product of the electrochemical methanation process can also be fed to the thermochemical and/or biological methanation steps, if present, in order to react with carbon dioxide to produce methane.

The methane produced according to step (c) or step (c-1) may be purified using a pressure swing adsorption technique. Methanation may comprise using molecular sieves to remove oxygen. Methanation may comprise using zeolites to remove at least one of carbon dioxide, nitrogen, and water. In a similar manner as discussed above with reference to the Sabatier process, according to at least one aspect at least a portion of the water produced as a result of the methanation process using the methanogens may be recycled or otherwise used in the electrolysis process.

In accordance with certain aspects, the methane may be purified using cryogenics. According to one aspect, methanation may comprise using membranes to remove nitrogen and CO_2. According to another aspect, methanation may comprise using desiccant drying to remove water. According to some aspects, methanation may comprise using an amine gas treater to remove sulphide impurities.

CVD Diamond Manufacture

The fourth step of the present method for the manufacture of a synthetic diamond 16 comprises utilising the hydrogen 11 obtained from the second step and the methane 14 obtained from the third step, to produce a synthetic diamond 16 using a CVD process 15. This CVD process 15 in the context of the present embodiment, and the apparatus that is used to conduct the CVD process 15 will now be described, with continued reference to Figures 1 and 2.

In one embodiment, the aim is to produce gem quality diamonds suitable for the jewellery market. The hydrogen 11 and the methane 14 are drawn into a CVD diamond machine CVD-1 from their respective tanks T-1, T-2. In one embodiment, the CVD diamond machine is a microwave plasma CVD machine. The gas mixture fed into the CVD diamond machine CVD-1 is at a ratio of 5:1 hydrogen:methane. A microwave CVD process 15 is used to make a gem-quality single crystal diamond 16. In this embodiment, the CVD takes place at a pressure of 40 kPa (300Torr) and a temperature of around 950 °C. A power source of less than 50 kW produces a plasma zone on a diamond substrate. For example, the diamond substrate may comprise a diamond seed crystal that may then be used as the initial base for diamond crystal growth. Carbon drops out onto the lattice of the substrate to grow a diamond 16 that is ready for finishing.

In one embodiment, negatively-charged nitrogen inclusions are used to create green-coloured diamonds. In other embodiments, other dopants may be used to create other colours of diamonds.

In this embodiment, oxygen 12 is also purged from the CVD diamond machine CVD-1 to stop the formation of soot. This oxygen 12, along with carbon emissions from the machine, is sent to the waste gas oxidiser R-2. As discussed above, oxygen 12 from the electrolysis 10 process is also sent to the waste gas oxidiser R-2. In the waste gas oxidiser R-2, oxidation 17 of the carbon occurs, producing further carbon dioxide 2. According to one example, this carbon dioxide is added to the column Q-1 to increase the concentration of carbon dioxide 2 in the carbon dioxide 2 capture process. Remaining gases are made safe before emission to the atmosphere. According to another example, the carbon dioxide is reacted with the hydrogen obtained from the electrolysis process to produce methane.

In accordance with one or more aspects, the CVD process may be carried out at a pressure of between 0.5 kPa and 100 kPa. According to a further aspect the CVD step may be carried out at a pressure of between 1 kPa and 50 kPa. According to an even further aspect, the CVD step may be carried out at a pressure of substantially 40 kPa.

According to various aspects, the CVD process may be carried out at a temperature between 600 °C and 1200 °C. According to a further aspect, the CVD step may be carried out at a temperature between 700 °C and 1000 °C. According to another aspect, the CVD step may be carried out at a temperature of substantially 950 °C. According to certain aspects, the ratio of hydrogen to methane used in the CVD process may be substantially 5:1.

According to at least one aspect, the CVD process may be carried out on a substrate. In accordance with certain aspects, the substrate may comprise diamond, silicon, tungsten, molybdenum, silicon carbide, silicon nitride, quartz glass or cemented carbide.

In accordance with one or more aspects, the CVD process may be carried out using a microwave plasma CVD machine.

Diamond Processing

In a final step (not shown) the diamond 16 is processed to gem quality by cutting and polishing.

In accordance with some aspects, after CVD processing, the synthetic diamond may be annealed. According to one example, the step of annealing the synthetic diamond may be carried out in a High Pressure High Temperature (HPHT) press.

In accordance with at least one aspect, the synthetic diamond may be cut and polished after the annealing step is performed to produce a gem-quality diamond.

According to at least one aspect, one or more of the processes discussed herein may include using energy from at least one renewable source. For example, electrolysis may comprise using energy from at least one renewable source. Thus, one or more technologies that utilize replenishable energy sources such as energy from water, wind, and the sun may be used to perform at least one of the processes discussed herein (i.e., carbon dioxide capture, electrolysis, methanation, CVD diamond formation). For example, according to various aspects, the at least one renewable source may comprise wind power, solar power, wave power, tide power, and/or geothermal power. According to a further aspect, renewable energy may be used to perform each of the processes discussed herein.

Having thus described several aspects of at least one example, it is to be appreciated that various alterations, modifications, and improvements will readily occur to those skilled in the art. For instance, examples disclosed herein may also be used in other contexts. Such alterations, modifications, and improvements are intended to be part of this disclosure, and are intended to be within the scope of the examples discussed herein. Accordingly, the foregoing description and drawings are by way of example only.

CLAIMS

1. A method of producing a synthetic diamond, the method comprising:

(a) capturing carbon dioxide from the atmosphere;

(b) performing electrolysis of water to provide hydrogen;

(c) reacting the carbon dioxide obtained from step (a) with the hydrogen obtained from step (b) to produce methane; and

(d) using the hydrogen obtained from step (b) and the methane obtained from step (c) to produce a synthetic diamond by chemical vapour deposition (CVD).

2. The method of claim 1, wherein the reaction of step (c) is a biological process.

3. The method of claim 1 or claim 2, wherein the reaction of step (c) is performed using methanogens.

4. The method of claim 3, wherein the methanogens are prokaryotes.

5. The method of claim 4, wherein the prokaryotes are archaea.

6. The method of any of claims 3 to 5, wherein the methanogens produce methane by respiration, and wherein the carbon dioxide obtained from step (a) is converted into methane at a temperature of around 50˚C and at a pressure of around atmospheric pressure.

7. The method of any of claims 3 to 6, wherein at least a portion of the water produced in step (c) is recycled in, or otherwise used in, the electrolysis process of step (b).

8. The method of any preceding claim, wherein step (c) comprises reacting the carbon dioxide obtained with the hydrogen according to the Sabatier reaction.

9. The method of any preceding claim, wherein step (c) further comprises purifying the methane produced at step (c).

10. The method of any preceding claim, wherein step (a) comprises capturing carbon dioxide using a nanotube gas separator or an amine-containing sorbent-material.

11. The method of any preceding claim, wherein step (b) comprises performing the electrolysis of water using at least one polymer electrolyte membrane (PEM) cell.

12. The method of any preceding claim, wherein the CVD is carried out on a substrate comprising diamond.

13. The method of any preceding claim, wherein the method further comprises using energy from at least one renewable source to perform at least one of the steps (a)-(d).

14. The method of any preceding claim, wherein the water comprises rainwater.

15. The method of any preceding claim, wherein the method further comprises: an additional step, after step (d), of annealing the synthetic diamond; and/or an additional step of at least one of cutting and/or polishing the diamond produced in step (d) to produce a gem-quality diamond.