

APPARATUS AND METHOD FOR PRODUCING GRAPHENE AND HYDROGEN

TECHNICAL FIELD

[0001] The following generally relates to graphene production by pyrolysis of hydrocarbons. More particularly, the present disclosure relates to apparatus and methods for producing graphene by pyrolysis of hydrocarbons, such as methane, in the presence of a catalyst, and isolating and recovering the hydrogen byproduct.

BACKGROUND

[0002] Graphene is an allotrope of carbon consisting of a single layer of atoms arranged in a two-dimensional lattice. Since its inception, graphene has been found to be useful in many areas including, but not limited to, water purification, medicine, construction, electronic chips, and quantum computers. Each of these uses generally requires a graphene material having specific properties which can change depending on, for example, the length and number of graphene layers forming the graphene material.

[0003] Some existing methods of forming graphene involve catalytic pyrolysis of hydrocarbons, such as methane or natural gas, into solid carbon and hydrogen. In such processes, the produced hydrogen is often an unused or undesired byproduct.

[0004] Industrial demand for both graphene and hydrogen continues to increase; thus, there exists an ongoing need to develop improved methods and apparatus for generating graphene and hydrogen.

SUMMARY

[0005] Provided herein are a method and apparatus for producing graphene by pyrolysis of hydrocarbons from a hydrocarbon feedstock and for recovering hydrogen gas which is a byproduct of the pyrolysis, and which may also be present in the hydrocarbon feedstock.

[0006] In one aspect, provided is an apparatus for graphene and hydrogen production, the apparatus comprising: an elongate reactor having: a first end and a second end, the first end being configured to receive a hydrocarbon feedstock; a channel defined therein for conveying a fluid between the first and second ends, wherein the fluid is a reaction mixture comprising the hydrocarbon feedstock; a terminal section attached to the second end, the terminal section being selectively permeable to hydrogen gas and impermeable to other components of the reaction mixture; and a hydrogen collection section attached to the second end to receive hydrogen gas from the terminal section, the hydrogen collection section being impermeable to hydrogen gas.

[0007] In an implementation, the reactor further comprises an inlet intermediate the first and second ends, the inlet being for addition of catalytic metal particles to the reaction mixture.

[0008] In another implementation, the reactor is made from iron.

[0009] In yet another implementation, the terminal section is made from stainless steel.

[0010] In yet another implementation, the reactor further comprises at least one heating element for heating the reaction mixture in the channel.

[0011] In yet another implementation, the reactor further comprises a sleeve provided there-around near the at least one heating element, the sleeve being made from a hydrogen impermeable material and defining a sealed space between the sleeve and the reactor.

[0012] In yet another implementation, the hydrogen impermeable material is a ceramic material.

[0013] In yet another implementation, the channel comprises catalytic packing in the form of metal beads.

[0014] In yet another implementation, the metal beads are ferrous.

[0015] In another aspect, provided is a method for producing graphene and hydrogen, the method comprising: introducing a hydrocarbon feed into a first region of a reactor; heating the first region to about 300°C or higher to decompose hydrocarbons therein to create a reaction mixture comprising nascent carbon; introducing the reaction mixture to a second region of the reactor; heating the second region to about 1000°C or higher and reacting the nascent carbon with catalytic metal particles to generate graphene fibers; and extracting hydrogen gas from the reaction mixture as the mixture exits the second region and contacts a terminal end of the reactor that is covered with a material permeable only to hydrogen gas.

[0016] In an implementation, the reaction mixture comprises entrained catalytic metal particles.

[0017] In another implementation, an inner surface of the second region is nucleated with metal particles before the hydrocarbon feed is introduced into the reactor.

BRIEF DESCRIPTION OF THE DRAWINGS

[0018] Embodiments will now be described with reference to the appended drawings wherein:

[0019] FIG. 1 is a cross-sectional view of an example embodiment of an apparatus for graphene and hydrogen production.

[0020] FIG. 2 is a cross-sectional view of another example embodiment of an apparatus for graphene and hydrogen production, the apparatus being further configured to control hydrogen content therein.

[0021] FIG. 3 illustrates a schematic illustration of a reactor and heating system for producing graphene and hydrogen.

[0022] FIG. 4 illustrates a system for producing graphene and hydrogen.

[0023] FIG. 5 illustrates a system for producing graphene and hydrogen.

[0024] FIG. 6 illustrates a packed bed reactor for producing graphene and hydrogen.

[0025] FIG. 7 is a more detailed version of a process similar to that illustrated in FIG. 3,

[0026] FIG. 8 illustrates an example embodiment of a reactor vessel for catalytic pyrolysis of hydrocarbons into graphene and hydrogen.

[0027] FIG. 9 illustrates another example embodiment of a reactor vessel for catalytic pyrolysis of hydrocarbons into graphene and hydrogen.

[0028] FIG. 10 is a more detailed version of a process similar to that illustrated in FIG. 4.

[0029] FIG. 11 illustrates another example embodiment of a process for the catalytic conversion of a hydrocarbon feed into graphene and hydrogen.

DETAILED DESCRIPTION

[0030] One or more of the terms “front”, “back”, “rear”, “vertical”, “vertically”, “horizontal”, “horizontally”, “top”, “bottom”, “upwardly”, “downwardly”, “inwardly”, “outwardly”, “upper”, “lower”, “right” and “left” are used throughout this specification. It will be understood that these terms are not intended to be limiting. These terms are used for convenience and to aid in describing the features herein, for instance as illustrated in the accompanying drawings.

[0031] The following describes a method and apparatus for producing graphene by pyrolysis of hydrocarbons from a hydrocarbon feedstock and for recovering hydrogen gas which is a byproduct of the pyrolysis and may be present in the hydrocarbon feedstock. The production of graphene rather than graphite/carbon black may be encouraged by introduction of a catalyst in several ways as discussed below.

[0032] FIG. 1 illustrates an apparatus, or reactor 10, for the production of graphene and hydrogen. The reactor 10 comprises a tube 12 defining a continuous gas passage 3 between a first end, or inlet 1, and a second end, or outlet 11 of the tube 12. A feedstock 34 containing hydrocarbons, such as methane or natural gas, may flow through the inlet. A furnace 16 comprising a helical electrical resistance heating element 18 may be provided around the reactor 10 to heat a first reaction zone 13 within tube 12. Similarly, a second furnace 20 comprising a helical electrical resistance heating element 22 may be provided around the reactor 10 to heat a second reaction zone 15 within tube 12.

[0033] In alternative embodiments, there may be a plurality of tubes 12 and/or the tubes 12 may define a curved or straight continuous gas passage 3. Although two heating elements (18,22) and furnaces (16,20) are shown, the reactor 10 may comprise any number of heating elements/furnaces (collectively, "heating elements"). The heating elements can be of any suitable type such as, for example, standard, induction or flame heating elements.

[0034] The heating elements 18 and 22 may be heated to appropriate temperatures to create a desired temperature profile within the tube 12 to grow graphene fibers. For example, the elements 18 and 22 may be operated such that the tube 12 has a lower temperature (e.g., 300°C) in a zone 13 near the inlet 1 and a higher temperature in a zone 15 near the outlet 11 (e.g., 1000°C). The hydrocarbon feedstock 34 can be diluted with other gases, such as hydrogen. The flowrate of the feedstock 34 into the tube 12 may be adjusted as desired. It may be that a higher flowrate of the feedstock 34 into the tube 12 may yield longer and/or thinner graphene fibers 6. Various elements, primarily metals, may be combined with the gas stream 3 at zone 13, for example, in the form of organic or inorganic salts.

[0035] In one embodiment, iron pentacarbonyl vapors can be fed into or upstream of zone 13. As the gas flows through heated zone 13, the metal compound – an iron compound, in this example – can decompose to produce iron particles 36, the sizes of which are exaggerated in FIGS. 1 and 2 for ease of illustration. The metal catalytic compound, which may be iron, as mentioned, may be referred to hereinafter as "catalyst".

[0036] Iron particles 36 may be entrained in the gas stream and carried through the tube 12 toward the outlet 11. Within heated zone 15, methane from the natural gas can be decomposed. The resulting nascent carbon may react with the iron particles 36 to produce microscopic graphene filaments 6. Deposition of additional nascent carbon may thicken the graphene filaments 6 by layering thereon additional individual filaments. The graphene filaments 6 may be collected in any suitable manner once the reaction is complete. For

example, a suitable tool, such as a ring or set of rings configured for insertion into the tube 12 to scrape, or knock the graphene off inner walls of the tube 12, may be used.

[0037] The reactor 10 may comprise an end section 7 that is made of a material that is permeable to hydrogen gas and substantially or completely impermeable to other gases in the tube 12, such as methane or inert gases. The end section 7 may be attached (e.g., threadedly or by welding) to the outlet 11 of the tube 12. During pyrolysis of the hydrocarbon feedstock, hydrogen may pass through the end section 7 (see arrows 19) into a hydrogen collection section 2 which may be made from a material being impermeable to hydrogen or resistant to passage of hydrogen therethrough, such as a ceramic material or iron. The hydrogen 5 may then exit the collection section 2 through an outlet 4 defined therein, and may be further processed or stored (not shown).

[0038] It may be that under certain conditions, such as high heat and/or pressure, the tube 12, which is made from iron in this example embodiment, may permit some hydrogen to pass therethrough. Thus, optionally, the apparatus 10 may include an impermeable (to hydrogen) sleeve 8 provided around the tube 12 and heater 20 to collect any hydrogen that may pass through the tube 12. The sleeve 8 may be made from or include a hydrogen impermeable material such as, for example, a ceramic material or iron. Any number of such sleeves 8 may be installed as needed.

[0039] Turning to FIG. 2, the apparatus 10 may further comprise one or more hydrogen collecting lines 35 made from a hydrogen permeable material such as, for example, 304 Stainless Steel. The lines 35 can be used to remove hydrogen from within the tube 12 and may provide some degree of control over the hydrogen content within the reactor 10, which may be beneficial to the pyrolysis reaction. Such lines 35 may also increase turbulence within the tube 12. It may be that increased turbulence increases uniformity of graphene distribution on the tube 12 walls. Alone or in combination with the lines 35, other objects or modifications to the tube 12 may be used to increase turbulence therein. In some embodiments, plasma and/or microwave heating may be used alone or in combination with the aforementioned heaters. In some embodiments, the tube 12 may be made from a ceramic material or another material impermeable to hydrogen gas. In some embodiments, a device for collecting graphene such as a fabric or mesh filter may be installed within the tube 12. In some embodiments, the tube 12 is a tubular iron reactor, and the graphene fibers 6 may grow upon an interior wall of the tube 12 and primarily within region 15. The primary location of graphene fiber 6 growth may vary depending on factors such as tube 12 dimensions and temperature profile therein.

[0040] Various metal particles may be obtained from suitable precursor compounds and used as nuclei for graphene filament formation. Iron particles, for example, may be formed by evaporating a ferric nitrate solution on a suitable surface and decomposing the resulting iron oxide residue. Nucleation effectiveness can be dependent at least in part on the metal particle size, and thus metal particle size (degree of coalescence of the elemental metal) may be adjusted depending on, for example, desired graphene filament growth rate and properties. As understood by a person skilled in the art, dissociation rate and particle forming kinetics are dependent on temperature and may change depending on the metal precursor used. Generally, one or more variables such as, for example, the temperature profile across the tube 12, dimensions and configuration of the tube 12, location of entry of metal precursor, type of metal nuclei and gas stream flow rate may be tailored to achieve a desired type of graphene.

[0041] In some embodiments, fibers may be grown on the interior surface of the tube 12, having deposited thereon metal nuclei. Prior to initiation of pyrolysis, the interior wall may be nucleated by in-situ decomposition of a metal precursor compound, such as an iron carbonyl compound. In an implementation, the metal precursor may be iron pentacarbonyl, $\text{Fe}(\text{CO})_5$, which may be injected into a stream of ambient temperature inert gas (e.g. argon), whereupon the iron carbonyl vaporizes. The inert gas stream may carry the vapors into the reactor and the flow rate of the stream may be controlled to achieve a desired dispersion of iron particles within the tube 12.

[0042] As discussed below, in some aspects, the catalyst may react with a stream (102) which may primarily consist of methane gas which may contain small amounts of other hydrocarbon gases, for example, ethane, propane or other gases often found in trace amounts in oil field production gases. Added to or included in the oil field gases may be H_2S , mercaptans, and/or other sulfur containing compounds. It may be that such sulfur gases may be important in forming various types of graphite and graphene.

[0043] In some embodiments, e.g., as shown in FIG.3 which depicts a reactor system 100, the catalyst may be provided as a gas suspension that is mixed with a feed stream 102 (which may be referred to as "methane gas" or "methane gas stream") which may primarily consist of methane gas preheated to 500 degrees centigrade at a heater (110). Feed stream 102 may be at ambient temperature prior to pre-heating at the heater 110. More than one pre-heater may be included. Part of the methane gas stream (i.e., feed stream 102) may first be diverted through a catalyst solution 118 to bubble through the liquid and leave carrying the suspended catalyst. A diffuser 116 may be used for bubbling the liquid through the liquid catalyst solution 118 in another vessel 108. The combined stream 106

then may enter an open reactor 114 where it may be heated to between 950 to 1100 degrees centigrade depending on the catalyst used. A pre-heater 110 (which may be, e.g., a resistance, induction, plasma, microwave, or flame powered heater) may create a pre-heated reactor feed 112 which enters the open reactor 114. Nanotubes of graphene, along with hydrogen, methane, and reaction by products may be produced in such reactor 114, and more generally as an output 120 of reactor system 100 depicted in FIG 3. Which, as indicated above, may optionally include the liquid catalyst recycle in addition to the pre-heater 110.

[0044] Alternatively, the catalyst may also be distributed throughout the reactor 114, alone or in combination with the feature of a liquid catalyst solution 118. This may be done by installing a metal grating, or similar to as would be done with ratch rings in a distillation column of various sizes and shape. If this approach is used the reactor may open quickly so that most or all of the catalyst matrix may be easily and/or quickly ejected and replaced with fresh catalyst. In this example embodiment, larger stripes of graphite or graphene may be produced. The operating temperature may be between 950 to 1050 degrees centigrade.

[0045] The catalyst may also be introduced by wetting the walls of the reactor 114 with catalyst solution. The reactor 114 may operate at 950 to 1150 degrees centigrade with the gas feed being preheated to 500 degrees centigrade before entering the reactor. This approach may produce graphite and graphene of a mixture of sizes from 8 cm in length to 3 to 6 microns in length.

[0046] As shown in FIG. 4, the reactor system 100 may be part of a system for the production of graphene and hydrogen 300. This system 300 may comprise a filtration system 306 that receives the output 120 of the reactor system 100. The filtration system 306 may include one or more filters that become progressively finer toward the outlet thereof (e.g., a coarse filter 304 and a fine filter 308). The filtration system 306 may optionally be closed and periodically opened to remove graphene therefrom by, e.g., shaking or vibration, and may produce an outlet stream of gas which may contain trace amounts of graphene (312) which optionally may be further filtered using an electrostatic filter 314, which may be emptied by e.g., shaking or vibration periodically. The substantially or completely graphene free gas 316 may then be conveyed to a heat exchanger 320 to be cooled, producing cooled outlet gas 322 which may comprise hydrogen and methane. The outlet gas may then be conveyed into a filtration system such as a pressure swing absorption (PSA) system 324, producing hydrogen 326 which may be conveyed to storage 330. The PSA system 324 may also produce a recycled hydrocarbon feed 328 to be conveyed back to the reactor system 100. Optionally, the incoming feed 102 may be heated by the heat exchanger 320 to create

a preheated stream 112 which may combine with the recycled stream 328 to produce a combined, recycled preheated stream 113. Optionally, the recycled preheated stream 113 may be further preheated within reactor system 100.

[0047] As indicated, a number of filters may be used to do the separation of graphene and hydrocarbon/hydrogen gas starting with a coarse filter, a finer filter, followed with yet another finer filter and so on until all carbon solid material has been removed. Each coarse filter may stop a portion of the fine carbon material and the final filter may be 1 micron or less and may operate in tandem with another or more filters so one is filtering while the other is cleaned. The final filter may have a dead area before it to let the carbon settle. An electrostatic precipitator separator may optionally be included.

[0048] Once the carbon is removed, the hydrocarbon stream (which may primarily be comprised of methane) and hydrogen gas may go to either a pressure swing absorption system or to a membrane separation system that separates the hydrogen and hydrocarbon gases. It may be that the membrane separation system provides hydrogen of up to or close to 99.99% pure hydrogen with all other gases being recycled back. Because gas separation systems tend to have difficulty with high temperatures, also provided may be a cooling phase before separation and a heating stage for the recycled hydrocarbon gases before returning to the feed gases for the reactor. Pipes may be used for heating and cooling or to use the incoming gas to heat the outgoing gas to the reactor. Any leftover heat may be used to heat original gas feed.

[0049] FIG. 5 illustrates another example embodiment of a system for producing graphene and hydrogen, comprising a hydrocarbon feed 402 (as described above) which may optionally combine with a recycle stream to create feed 401 which may enter a fluid bed reactor 400 containing metal catalyst through which the feed 402 may pass to produce a mixture of graphene, hydrocarbon, hydrogen and other by products (stream 404). The reactor may, alternatively or in combination with catalyst fluid, include catalyst deposited on reactor walls, and/or may have catalyst in aerosol form mixed with the feed upon entry into the reactor 400. The stream 404 may then enter a pre-heater 406 which may be heated by any of the means discussed above, and may optionally include sonic elements to facilitate the passage of produced solids therethrough. The pre-heated stream 408 produced by the pre-heater 406 may then enter a further heater 410 which may include sonic elements (not shown) to facilitate the passage of produced solids therethrough, as previously mentioned. Any of the vessels described herein that may benefit from the inclusion of sonic elements (i.e., for creating vibration of the vessel) therein to facilitate passage of solids (e.g., graphene/graphite) therethrough may include such sonic elements. The heater 410 may

optionally be a reactor, e.g., as described in FIG. 6, which produces a first hydrogen stream 412 and a first hydrogen, hydrocarbon and graphene output stream 414. The stream 414 may be passed to a solids separator 416 (which may be any vessel suitable to separate graphene/solid carbon from hydrocarbons and residual hydrogen) which may in turn produce solids 420 for storage in solids storage unit 418. The separator 416 may also produce a hydrogen and hydrocarbon stream 422 that may then enter a hydrocarbon/hydrogen separation unit 424 (which may be, e.g., a PSA unit), producing a purified hydrogen stream 426 that may be combined with the first hydrogen stream 412 and combined to create purified hydrogen stream for storage at hydrogen storage vessel 430. The separator may also produce a hydrocarbon recycle stream that may be passed through a compressor 407 to create a compressed hydrocarbon recycle stream 409 to be combined with the feed 402 to create the feed 401. As mentioned, the hydrogen stream 412 is optional and may be used alone or in combination with a reactor type vessel (e.g., as described with respect to FIG. 6) in addition to or in combination with the reactor vessel 400.

[0050] FIG. 6 illustrates a reactor which may be used as the heater 410 discussed above, or may be suitably implemented in the other processes described herein and variations above that would be apparent to those skilled in the art. The reactor 500 may receive a hydrocarbon feed 502 comprising primarily methane and which may also comprise other light hydrocarbon gases such as ethane and propane and optionally other suitable additives that may facilitate graphene formation as discussed further above. The reactor may comprise a selective permeation reactor core 504 having metal, preferably ferrous catalytic packing 506 (e.g., the catalysts discussed above). The core 504 may be permeable to hydrogen gas which may exit the core 504 into a space 514 and/or directly from the reactor. The reactor may be heated by induction coils 512 as shown in FIG. 6 and/or using other suitable means. Product stream 510 comprising hydrocarbons, residual hydrogen and graphene may exit from the core 504 and be sent for further processing (e.g., utilizing the processes/vessels described herein).

[0051] FIG. 7 is a more detailed version of a process similar to that illustrated in FIG. 3, including the same reference characters for similar elements, and additional details concerning process conditions (e.g., temperature, pressure and flow rate ratio of stream 122).

[0052] FIG. 8 illustrates an example embodiment of a reactor vessel 600 in which a hydrocarbon feed (e.g., feed 102) may be converted into graphene, hydrogen and residual hydrocarbons. Vessel 600 may contain iron wool or another form of metal matrix to facilitate conversion of hydrocarbons to graphene. The vessel 602 is a drawing of the vessel 600, but

showing how the gas feed may enter the side of the reactor, and the top of the reactor may open to change the catalyst matrix and/or packing as needed.

[0053] FIG. 9 illustrates another example embodiment of a reactor vessel 604 for catalytic pyrolysis of hydrocarbons into hydrogen and graphene wherein the catalyst may be introduced into the top of the reactor to be deposited on the reactor walls. As shown, the feed may (e.g., feed 102) may enter the top of the vessel 604.

[0054] FIG. 10 is a more detailed version of a process similar to that illustrated in FIG. 4, including the same reference characters for similar elements, and additional details concerning process conditions (e.g., temperature, pressure and flow rate ratio of stream 122).

[0055] FIG. 11 illustrates another example embodiment of a process for the catalytic conversion of a hydrocarbon feed 702, which may primarily consist of methane, into hydrogen and graphene. As illustrates, the feed 702 may be heated and may have catalyst introduced therein, after which it may enter a reaction vessel 700. The heated feed combined with the catalyst may enter a matrix of tubes 708 wherein the hydrocarbon may be heated by the surrounding space 710, similar to a shell and tube heat exchanger arrangement. A heated fluid may be circulated through the space 710 after being heated by, e.g., heater 706. The heated fluid may be, for example, molten salts. Hydrogen and graphene may collect in a tank 712, and the hydrogen may be removed therefrom to hydrogen storage.

[0056] For simplicity and clarity of illustration, where considered appropriate, reference numerals may be repeated among the figures to indicate corresponding or analogous elements. In addition, numerous specific details are set forth in order to provide a thorough understanding of the examples described herein. However, it will be understood by those of ordinary skill in the art that the examples described herein may be practiced without these specific details. In other instances, well-known methods, procedures and components have not been described in detail so as not to obscure the examples described herein. Also, the description is not to be considered as limiting the scope of the examples described herein.

[0057] The examples and corresponding diagrams used herein are for illustrative purposes only. Different configurations and terminology can be used without departing from the principles expressed herein. For instance, components and modules can be added, deleted, modified, or arranged with differing connections without departing from these principles.

[0058] The steps or operations in the flow charts and diagrams described herein are just for example. There may be many variations to these steps or operations without departing

from the principles discussed above. For instance, the steps may be performed in a differing order, or steps may be added, deleted, or modified.

[0059] Although the above principles have been described with reference to certain specific examples, various modifications thereof will be apparent to those skilled in the art as outlined in the appended claims.

Claims:

1. An apparatus for graphene and hydrogen production, the apparatus comprising:
an elongate reactor having:
a first end and a second end, the first end being configured to receive a hydrocarbon feedstock;
a channel defined therein for conveying a fluid between the first and second ends, wherein the fluid is a reaction mixture comprising the hydrocarbon feedstock;
a terminal section attached to the second end, the terminal section being selectively permeable to hydrogen gas and impermeable to other components of the reaction mixture; and
a hydrogen collection section attached to the second end to receive hydrogen gas from the terminal section, the hydrogen collection section being impermeable to hydrogen gas.
2. The apparatus of claim 1, wherein the reactor further comprises an inlet intermediate the first and second ends, the inlet being for addition of catalytic metal particles to the reaction mixture.
3. The apparatus of claim 1 or 2, wherein the reactor is made from iron.
4. The apparatus of any one of claims 1 to 3, wherein the terminal section is made from stainless steel.
5. The apparatus of any one of claims 1 to 4, wherein the reactor further comprises at least one heating element for heating the reaction mixture in the channel.
6. The apparatus of claim 5, further comprising a sleeve provided around the reactor near the at least one heating element, the sleeve being made from a hydrogen impermeable material and defining a sealed space between the sleeve and the reactor.
7. The apparatus of claim 6, wherein the hydrogen impermeable material is a ceramic material.
8. The apparatus of any one of claims 1 to 7, wherein the channel comprises catalytic packing in the form of metal beads.

9. The apparatus of claim 8, wherein the metal beads are ferrous compounds.
10. A method for producing graphene and hydrogen, the method comprising:
 - introducing a hydrocarbon feed into a first region of a reactor;
 - heating the first region to about 300°C or higher to decompose hydrocarbons therein to create a reaction mixture comprising nascent carbon;
 - introducing the reaction mixture to a second region of the reactor;
 - heating the second region to about 1000°C or higher and reacting the nascent carbon with catalytic metal particles to generate graphene fibers; and
 - extracting hydrogen gas from the reaction mixture as the mixture exits the second region and contacts a terminal end of the reactor that is covered with a material permeable only to hydrogen gas.
11. The method of claim 8, wherein the reaction mixture comprises entrained catalytic metal particles.
12. The method of claim 8, wherein an inner surface of the second region is nucleated with metal particles before the hydrocarbon feed is introduced into the reactor.
13. A method for producing graphene and hydrogen, the method comprising:
 - introducing a hydrocarbon feed into a first region of a reactor;
 - heating the first region to about 300°C or higher to decompose hydrocarbons therein to create a reaction mixture comprising nascent carbon;
 - introducing the reaction mixture to a second region of the reactor;
 - heating the second region to about 1000°C or higher and reacting the nascent carbon with catalytic metal particles to generate graphene fibers; and
 - extracting hydrogen gas from the reaction mixture as the mixture exits the second region and contacts a terminal end of the reactor that is covered with a material permeable only to hydrogen gas.