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- (71) Applicant (for all designated States except US): EDEN INNOVATIONS LTD. [IE/IE]; 85 Merrion Square, Dublin 2 (IE).
- (72) Inventors; and
- (75) Inventors/Applicants (for US only): ZU, Zhonghua, John [AU/AU]; 8 Serie Street, Middle Park, Brisbane 4072 QLD (AU). CHEN, Jiuling [CH/AU]; 1/39 Grosvenor Road, Indooroopilly, Brisbane, QLD 4068 (AU). LU, Gaoqing, Max [AU/AU]; 38 Debussy Place, Mt Ommaney, Brisbane, QLD 4072 (AU). SOLOMON, Gregory [AU/AU]; 7 Torrens Street, Cottesloe, Western Australia, 6011 (AU).
- (74) Agent: F B RICE & CO; Patent and Trademark Attorneys, Level 23, 200 Queen St, Melbourne, VIC 3000 (AU).
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(54) Title: METHOD AND SYSTEM FOR PRODUCING A HYDROGEN ENRICHED FUEL USING MICROWAVE ASSISTED METHANE DECOMPOSITION ON CATALYST

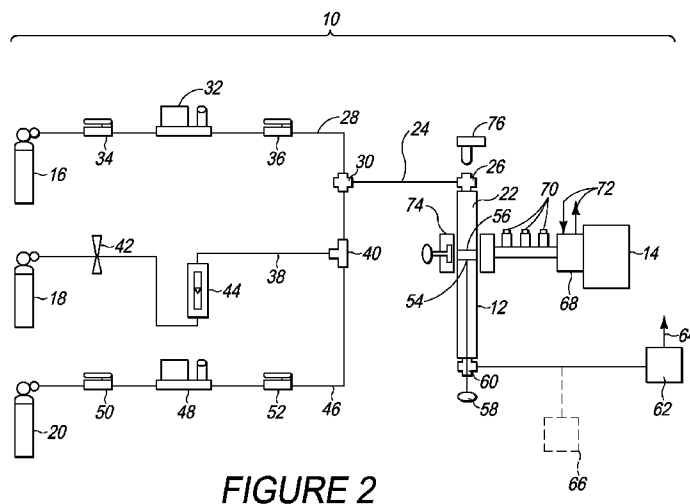


FIGURE 2

(57) Abstract: A method for producing a hydrogen enriched fuel includes the steps of providing a flow of methane gas, and providing a catalyst (56). The method also includes the steps of heating the catalyst (56) instead of the reactor walls and the methane gas using microwave irradiation at a selected microwave power, directing the flow of methane gas over the catalyst (56), and controlling the microwave power to produce a product gas having a selected composition. A system (10) for producing a hydrogen enriched fuel includes a methane gas source (16), a reactor (12) containing a catalyst (56), and a microwave power source (14) configured to heat the catalyst (56).

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METHOD AND SYSTEM FOR PRODUCING A HYDROGEN ENRICHED FUEL USING MICROWAVE ASSISTED METHANE DECOMPOSITION ON CATALYST

Field of the Invention

[0001] This invention relates generally to the production of hydrogen fuels, and particularly to a method and a system for producing a hydrogen enriched fuel suitable for use as an alternative fuel.

Background of the Invention

[0002] Gaseous alternative fuels, such as hydrogen and natural gas, are valued for their clean burning characteristics in motor vehicle engines. Various processes have been developed for producing hydrogen. These processes include electrolysis, exotic water splitting, and separation from industrial waste streams.

[0003] Hydrogen can also be produced by reforming natural gas. Typically, a multi-step process is used to convert a hydrocarbon fuel, such as methane, propane or natural gas, into a high purity hydrogen gas stream. The steps of the process typically include (1) synthesis gas generation, (2) water-gas shift reaction, and (3) gas purification (e.g., CO and CO₂ removal). The hydrogen gas stream can then be used for a variety of purposes including mixture with other gases to produce an alternative fuel.

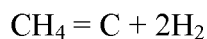
[0004] For example, a particularly clean burning gaseous alternative fuel known as HYTHANE comprises a mixture of hydrogen and natural gas. The prefix "Hy" in HYTHANE is taken from hydrogen. The suffix "thane" in HYTHANE is taken from methane, which is the primary constituent of natural gas. HYTHANE is a registered trademark of Brehon Energy PLC. HYTHANE typically contains about 5% to 7% hydrogen by energy, which corresponds to 15% to 20% hydrogen by volume.

[0005] For producing hydrogen, one type of reformer called a "steam reformer" uses a hydrocarbon fuel and steam (H₂O). In the steam reformer, the hydrocarbon fuel is reacted in a heated reaction tube containing steam (H₂O) and one or more catalysts. In general, the production of a high purity hydrogen gas by reforming requires high temperatures (800-900 °C). Steam reforming also produces

impurities, particularly CO and CO₂, which if not removed, are ultimately released to the atmosphere.

[0006] The production of a high purity hydrogen gas by reforming also requires large capital costs for the equipment, and large operating costs, particularly for power. In addition to these shortcomings, it is difficult to manufacture a compact embodiment of a steam reformer. It would be advantageous for a hydrogen production system to have a relatively compact size, such that alternative fuels could be produced at a facility the size of a gas station, rather than at a facility the size of a refinery.

[0007] Another process for producing hydrogen from natural gas involves the thermal decomposition of methane. For example, methane decomposes into hydrogen by the reaction:



For example, the thermal decomposition of natural gas has been used in the "Thermal Black Process" for producing carbon black and hydrogen. Using thermal decomposition, the energy requirements per mole of hydrogen produced (37.8 kJ/mol H₂) is considerably less than the energy requirements of the steam reforming process (63.3 kJ/mol H₂). However, the process still requires high temperatures (e.g., 1400 °C), high equipment costs, and high energy expenditures.

[0008] Recently, thermal decomposition of natural gas has been investigated in combination with various catalysts, which allow the reaction to proceed at lower temperatures. For example, US Patent No. 7,001,586 B2, to Wang et al. discloses a thermal decomposition process in which two catalysts having the formula Ni_xMg_yO and Ni_xMg_yCu_zO, respectively, are used to decompose methane to carbon and hydrogen. The former needs a lower temperature from about 425°C to 625°C, but the lifetime is shorter and the activity is lower. The latter's lifetime is longer and the activity is higher, but the required reaction temperature is much higher, from about 600°C to 775°C. More importantly, however, these processes require high energy expenditures to heat the wall of the reactor, the gas and the catalysts.

[0009] It would be advantageous for a hydrogen production system to be capable of performance at lower temperatures and lower energy expenditures, with a variety of catalysts active for long periods, and with minimal carbon emissions (e.g., CO, CO₂). In addition, it would be advantageous for a hydrogen production system to

have a size and configuration adaptable to the production of alternative fuels containing hydrogen. The present disclosure is directed to a method and a system for producing a hydrogen enriched fuel that overcomes many of the shortcomings of prior art hydrogen production systems.

[0010] The foregoing examples of the related art and limitations related therewith are intended to be illustrative and not exclusive. Other limitations of the related art will become apparent to those of skill in the art upon a reading of the specification and a study of the drawings. Similarly, the following embodiments and aspects thereof are described and illustrated in conjunction with a system and method, which are meant to be exemplary and illustrative, not limiting in scope.

Summary of the Invention

[0011] A method for producing a hydrogen enriched fuel includes the steps of providing a flow of methane gas, providing a catalyst, selectively heating the catalyst instead of the reactor walls and the methane gas using microwave irradiation at a selected microwave power, directing the flow of methane gas over the catalyst, and controlling the microwave power to produce a product gas having a selected composition.

[0012] The method can be performed in a reactor having a reaction chamber with microwave transparent walls. In addition, the catalyst can comprise a metal, such as a Ni-based compound prepared by coprecipitation. On the surface of the catalyst reactions occur in which methane (CH_4) dissociates into hydrogen (H_2) and solid carbon (C) in the form of fibrous carbon. In addition, some of the methane gas fails to react (methane slip) such that the product gas comprises methane and hydrogen. The catalyst is selected and formulated to remain stable under operating conditions (e.g., gas flow rate, microwave power, catalyst amount), such that costs are minimized. In addition, the catalyst maintains active characteristics through many hours of reactions.

[0013] The flow of methane gas and the microwave power can be controlled such that the composition of the product gas approximates the chemical composition of HYTHANE. For example, the product gas can comprise from about 20% to 30% hydrogen by volume, and from about 70% to 80% methane by volume. Advantageously, the product gas contains almost no carbon impurities (e.g., CO,

CO₂), as carbon is converted to solid fibrous carbon which drops out of the product gas as a useful by-product. In addition, the product gas contains only negligible amounts of higher order hydrocarbons (e.g., C₂H₄, C₂H₂, C₃H₆, C₃H₈, C₃H₄).

[0014] A system for producing a hydrogen enriched fuel includes a methane gas source configured to provide a methane gas flow. The system also includes a reactor having a reaction chamber in flow communication with the methane gas source configured to contain a catalyst, and to circulate the methane gas in contact with the catalyst. The system also includes a microwave power source configured to heat the catalyst in the reaction chamber to form a product gas having a selected volumetric percentage of hydrogen and methane.

[0015] In an alternate embodiment of the method, the product gas is further processed to recover hydrogen in substantially pure form. To recover substantially pure hydrogen, the product gas can be flowed under a vacuum through a Pd/Ag membrane coated on a porous metal or ceramic plate.

Brief Description of the Drawings

[0016] Exemplary embodiments are illustrated in the referenced figures of the drawings. It is intended that the embodiments and the figures disclosed herein are to be considered illustrative rather than limiting.

[0017] Figure 1 is a flow diagram illustrating steps in a method for producing a hydrogen enriched fuel;

[0018] Figure 2 is a schematic drawing of a system for producing a hydrogen enriched fuel;

[0019] Figure 3 are overlaid graphs illustrating CH₄ conversion, H₂ content, and carbon formation versus reaction time for Example 1 using a Ni₅₄Cu₂₇Al catalyst; and

[0020] Figure 4 are overlaid graphs illustrating CH₄ conversion, H₂ content, and carbon formation versus reaction time for Example 2 using a Ni₈₁Al catalyst.

Detailed Description of the Preferred Embodiments

[0021] The following definitions are used in the present disclosure. HYTHANE means a hydrogen enriched alternative fuel comprised of hydrogen and methane and impurities included in hydrogen and natural gas.

[0022] Methane slip means unreacted methane which passes through a system without reacting.

[0023] Microwave irradiation means electromagnetic irradiation in the range of 0.3 to 300 GHz.

Method

[0024] Referring to Figure 1, steps in a method for producing a hydrogen enriched fuel are illustrated. The first step comprises "providing a flow of methane gas at a selected flow rate". By way of example, the methane gas can be in the form of pure methane gas. Alternately, the methane gas can be in the form of natural gas obtained from a "fossil fuel" deposit. Natural gas is typically about 90+% methane, along with small amounts of ethane, propane, higher hydrocarbons, and "inerts" like carbon dioxide or nitrogen. In addition, the methane gas can be supplied from a tank (or a pipeline) at a selected temperature and pressure. Preferably, the methane gas is provided at about room temperature (20 to 25 °C), and at about atmospheric pressure (1 atmosphere). Further, the methane gas can be provided at the selected flow rate. In the examples to follow, the selected flow rate of the methane gas is about 120 ml/minute (STP).

[0025] As also shown in Figure 1, the method includes the step of "providing a catalyst". Preferably, the catalyst is provided in the form of particles having a diameter of from 74 μm to 140 μm . In addition, the catalyst is preferably contained on a holder, which allows the methane gas to flow freely along the surfaces of the catalyst particles. In addition, catalysts in the form of metal oxides can be pre-treated using H_2 to reduce the metal oxide to a metal.

[0026] A preferred metal for the catalyst comprises Ni, or an alloy containing Ni. For example, the metal can comprise NiAl, or Ni doped with Cu, Pd, Fe, Co, or an oxide such as MgO, ZnO, Mo_2O_3 or SiO_2 . Specific catalysts include Ni81Al, Ni93Al, Ni77Cu16Al, Ni54Cu27Al and Ni83Mg6Al. In addition, nickel based catalyst precursors can be prepared by coprecipitation from a mixed aqueous solution of nitrates with sodium carbonate.

[0027] The following Table I provides information on catalyst preparation of nickel-based precursors for the above catalysts. These catalysts were prepared by coprecipitation from a mixed aqueous solution of nitrates with sodium carbonate.

Table 1-Catalyst Preparation**Catalyst Composition**

1	Ni81Al	81 wt.%NiO-19 wt.%Al ₂ O ₃
2	Ni93Al	93 wt. %NiO-7 wt.%Al ₂ O ₃
3	Ni77Cu16Al	77 wt.%NiO-16wt.%CuO-7 wt.%Al ₂ O ₃
4	Ni54Cu27Al	54 wt.%NiO-27 wt.%CuO-9 wt.%Al ₂ O ₃
5	Ni83Mg6Al	83 wt.%NiO-6 Wt.%MgO-11 wt.%Al ₂ O ₃

[0028] However, rather than Ni or an alloy thereof, the catalyst can comprise another metal, such as a metal selected from group VIII of the periodic table including Fe, Co, Ru, Pd and Pt. In any case the catalyst is selected and formulated to remain stable under reaction conditions for long periods of time. In the examples to follow there was no indication that the catalyst was going to be deactivated, even after over 16 hours of reaction time.

[0029] As also shown in Figure 1, the method includes the step of "heating the catalyst using microwave irradiation at a selected microwave power". This step can be performed using a conventional microwave generator and microwave circulator configured to irradiate the catalyst with microwave irradiation. In general, the catalyst will absorb microwave energy through relaxation mechanisms (e.g., dipolar, ion jump, ohmic losses), which selectively heat the metal catalyst instead of the reactor wall and the methane gas, thus significantly saving the energy consumption of the catalyst/microwave heating process.

[0030] Heating the catalyst by microwave irradiation provides the following advantages:

- a.) volumetric heating, fast,
- b.) selectively heating the catalyst instead of the reactor wall and the methane gas, high efficiency,
- c.) low temperature gradient,
- d.) hot spot to prevent serial reaction of product,

e.) may also influence catalytic reaction by changing the electronic properties of the catalyst in the microwave electromagnetic field.

[0031] In the examples to follow, the microwave generator was operated at a power of about 250 watts, and the catalyst was heated to a temperature of from about 600 to 700 °C. However, it is to be understood that the method can be practiced at a microwave power that is selected to achieve a desired product gas composition. For example, a representative range for the microwave power can be from 150 watts to 300 watts. Also in the examples to follow, the microwave generator was operated at a frequency of 2.45 GHz. For performing microwave irradiation, the reactor and the holder for the catalyst must be made of a microwave transparent material able to withstand high temperatures. One suitable material for the reactor and the holder comprises quartz.

[0032] As also shown in Figure 1, the method includes the step of "directing the flow of methane gas over the catalyst". This step can be performed by placing the catalyst in a microwave transparent reactor having a reaction chamber configured to contain the catalyst, and to direct the flow of methane gas over the catalyst.

[0033] As also shown in Figure 1, the method includes the step of "controlling the microwave power at the selected flow rate to produce a product gas having a selected composition". This step can be performed using a microwave generator having variable power controls.

System

[0034] Referring to Figure 2, a system 10 for producing a hydrogen enriched fuel, in accordance with the previously described method, is illustrated. The system 10 includes a reactor 12, and a microwave generator 14. The system also includes a methane supply 16, a hydrogen supply 18, and an inert gas supply 20 in flow communication with the reactor 12.

[0035] The reactor 12 (Figure 2) can comprise a conventional tube reactor made of a microwave transparent material, such as quartz. In addition, the reactor 12 includes a sealed process chamber 22 having an inlet 26 in flow communication with a supply conduit 24.

[0036] The supply conduit 24 (Figure 2) is in flow communication with a methane conduit 28 via a union 30, which is in flow communication with the methane

supply 16. In addition, the methane conduit 28 includes a methane mass flow controller 32 configured to remotely control the flow of methane gas into the reaction chamber 22, and shut off valves 34, 36 on either side of the methane mass flow controller 32. In the illustrative embodiment, the methane supply 16 is configured to provide pure methane. However, it is to be understood that the system 10 can include, and the method can be practiced, using another methane source, such as natural gas.

[0037] The supply conduit 24 (Figure 2) is also in flow communication with a hydrogen conduit 38 via a union 40, which is in flow communication with the hydrogen gas supply 18. The hydrogen conduit 38 includes a needle valve 42 configured to manually regulate the flow of hydrogen gas into the reaction chamber 22, and a rotameter 44 configured to measure the hydrogen flow.

[0038] The supply conduit 24 (Figure 2) is also in flow communication with an inert gas conduit 46, which is in flow communication with the inert gas supply 20. The inert gas can comprise Ar or another inert gas, such as He or Ne. The inert gas conduit 46 also includes an inert gas mass flow controller 48 configured to remotely control the flow of inert gas into the reaction chamber 22, and shut off valves 50, 52 on either side of the inert gas mass flow controller 48. The inert gas conduit 46 can be used to purge the reaction chamber 22.

[0039] In addition to the reaction chamber 22 (Figure 2), the reactor 12 includes a holder 54 configured to hold a catalyst 56 in the reaction chamber 22. As with the reactor 12 and the walls of the reaction chamber 22, the holder 54 is made of a microwave transparent material. In addition, the holder 54 has a cup like configuration with openings that permit gas flow through the holder 54 and around the catalyst 56. The holder 54 also includes a handle 58 configured to permit removal of the holder 54 and the catalyst 56 from the reaction chamber 22.

[0040] The reactor 12 (Figure 2) also includes an outlet 60 in flow communication with the reaction chamber 22. The outlet 60 of the reactor 12 is configured to exhaust the product gas formed in the reaction chamber 22. The outlet 60 is in flow communication with a gas chromatograph 62 configured to analyze the chemical composition of the product gas exiting the reaction chamber 22. In addition, the gas chromatograph 62 is in flow communication with a vent 64 configured to vent product gases, which have been analyzed to the atmosphere. The outlet 60 of the

reactor 12 can also be in flow communication with a product gas storage vessel 66 configured to store the product gas for future use.

[0041] The microwave generator 14 (Figure 2) of the system 10 is configured to direct microwave radiation through a microwave circulator 68, and through a three stub tuner 70, to the catalyst 56 held on the holder 54 in the reaction chamber 22. The microwave circulator 68 also includes a cooling system 72. In addition, a microwave adjust plug 74 is configured to remotely adjust the reflected power of the microwave generator 14.

[0042] The system 10 (Figure 2) also includes an infrared temperature sensor 76 configured to measure the temperature of the catalyst 56.

Example 1

[0043] Using the previously described method (Figure 1), and the previously described system 10 (Figure 2), a hydrogen enriched fuel comprising CH_4 and H_2 was produced under the following conditions.

A. Pure methane gas (99.7% purity) was supplied through the methane supply conduit 28 to the reactor 12 (Figure 12).

B. Methane flow rate (i.e., selected flow rate in Figure 1): 120 ml/minute.

C. Catalyst 56 (Figure 2): Ni₅₄Cu₂₇Al.

D. The catalyst 56 (Figure 2) was initially reduced for a period of several minutes in H_2 plasma at a microwave power of 160 W. For reducing the catalyst 56 (Figure 2), a flow of H_2 gas was supplied through the hydrogen supply conduit 38 (Figure 2) to the reaction chamber 22 (Figure 2), and irradiated with microwave energy from the microwave generator 14 (Figure 2) to form a plasma.

E. Reaction pressure: atmospheric pressure (1 atm).

F. Products (hydrogen enriched fuel): H_2 , solid carbon C and unreacted CH_4 , by the reaction $\text{CH}_4 = \text{C} + 2\text{H}_2$. SEM (scanning electron microscopy) pictures of the solid carbon demonstrate that the carbon is in the form of fibrous carbon rather than carbon black. In addition, the fibrous carbon is a useful by-product that can be used for other applications.

G. Microwave power applied to the catalyst: 250W.

H. Methane conversion: approximately 20%.

I. Unreacted methane: approximately 80%.

J. Production rate: about 48 ml/minute of H₂ at stable conditions.

K. In Example 1 the only energy consumed was in heating the catalyst. Accordingly the process is energy efficient.

[0044] Figure 3 illustrates the results of CH₄ conversion assisted by microwave heating using Ni₅₄Cu₂₇Al as the catalyst 56 (Figure 2). Example 1 was a continuous process. In Figure 3, the reaction time in hours (h) denotes the length of time that the process was performed.

[0045] In Figure 3 there are three separate graphs. The lower graph plots the conversion rate "X %" of the CH₄ on the y-axis (expressed as a volume percentage) versus the reaction time in hours on the x-axis. The middle graph plots the content "C %" of H₂ on the y-axis (expressed as a volume percentage) versus the reaction time in hours on the x-axis. The upper graph plots the amount of solid carbon (Solid C (g)) on the y-axis (expressed in grams) versus the reaction time in hours on the x-axis.

Example 2

[0046] Example 2 was performed using the same conditions as outlined above for Example 1 but with the catalyst comprising Ni₈₁Al rather than Ni₅₄Cu₂₇Al.

[0047] Figure 4 illustrates the results of CH₄ conversion assisted by microwave heating using Ni₈₁Al as the catalyst 56 (Figure 2). Example 2 was a continuous process. In Figure 4, the reaction time in hours (h) denotes the length of time that the process was performed.

[0048] In Figure 4 there are three separate graphs. The lower graph plots the conversion rate "X %" of the CH₄ on the y-axis (expressed as a volume percentage) versus the reaction time in hours on the x-axis. The middle graph plots the content "C %" of H₂ on the y-axis (expressed as a volume percentage) versus the reaction time in hours on the x-axis. The upper graph plots the amount of solid carbon (Solid C (g)) on the y-axis (expressed in grams) versus the reaction time in hours on the x-axis.

[0049] From these two examples it was determined that a product gas containing 30% by volume of H₂ can be produced continuously and stably by microwave heating a Ni₅₄Cu₂₇Al catalyst. A product gas containing 20% by volume of H₂ can be produced continuously and stably by microwave heating a Ni₈₁Al catalyst.

Alternate Embodiment For Producing Pure Hydrogen

[0050] An alternate embodiment of the method includes the additional step of further processing the product gas to recover hydrogen in substantially pure form. One method for recovering pure hydrogen is to flow the product gas under a vacuum through a Pd/Ag membrane coated on a porous metal or ceramic substrate. US Patent No. 6,165,438, to Willms et al., which is incorporated herein by reference, discloses an apparatus and method for the recovery of hydrogen from a gas containing hydrocarbons.

[0051] Thus the disclosure describes an improved method and system for producing a hydrogen enriched fuel. While the description has been with reference to certain preferred embodiments, as will be apparent to those skilled in the art, certain changes and modifications can be made without departing from the scope of the following claims.

WHAT IS CLAIMED IS:

1. A method for producing a hydrogen enriched fuel comprising:
providing a flow of methane gas;
providing a catalyst;
heating the catalyst using microwave irradiation at a selected microwave power;
directing the flow of methane gas over the catalyst; and
controlling the microwave power to produce a product gas having a selected composition.
2. The method of claim 1 wherein the product gas comprises about 20% to 30% hydrogen by volume, and from about 70% to 80% methane by volume.
3. The method of claim 1 wherein the catalyst comprises Ni or a Ni alloy.
4. The method of claim 1 wherein the providing step provides the methane gas at about room temperature and at about 1 atmosphere.
5. The method of claim 1 further comprising pretreating the catalyst with a hydrogen gas prior to the heating step.
6. The method of claim 1 wherein the directing step is performed in a tube reactor made of a microwave transparent material.
7. The method of claim 1 wherein the directing step is performed with the catalyst placed on a microwave transparent holder configured to allow the flow of methane gas to pass through the catalyst.
8. The method of claim 1 further comprising processing the product gas to recover substantially pure hydrogen.
9. A method for producing a hydrogen enriched fuel comprising:

providing a flow of methane gas;
providing a catalyst;
heating the catalyst using microwave irradiation at a selected microwave power;
directing the flow of methane gas over the catalyst to convert at least some of the methane gas to hydrogen; and
selecting the catalyst, controlling the flow of methane gas, and controlling the microwave power to produce a product gas comprising methane and hydrogen in selected volume percentages.

10. The method of claim 9 wherein the controlling step is performed to produce the product gas with about 20% to 30% hydrogen by volume.

11. The method of claim 9 wherein the controlling step is performed to convert approximately 10%-20% of the methane gas to hydrogen.

12. The method of claim 9 wherein the controlling step is performed to produce the product gas with from about 70% to 80% methane by volume.

13. The method of claim 9 wherein the selected microwave power is from about 150 watts to 300 watts.

14. The method of claim 9 further comprising pretreating the catalyst with a hydrogen gas prior to the directing step.

15. The method of claim 9 wherein the directing step is performed in a tube reactor, and the heating step is performed in a microwave transparent holder placed in the tube reactor.

16. The method of claim 9 wherein the catalyst comprises a metal selected from the group consisting of Ni₈₁Al, Ni₉₃Al, Ni₇₇Cu₁₆Al, Ni₅₄Cu₂₇Al and Ni₈₃Mg₆Al.

17. A method for producing a hydrogen enriched fuel comprising:
providing a tube reactor having a reaction chamber with microwave transparent walls in flow communication with a methane source;
placing a catalyst in the reaction chamber;
providing a microwave generator;
irradiating the catalyst using microwave irradiation at a selected microwave power of the microwave generator;
directing a flow of methane gas through the reaction chamber into contact with the catalyst; and
controlling the microwave power to produce a product gas comprising hydrogen and methane in selected volumetric percentages.
18. The method of claim 17 wherein the catalyst is heated to a temperature between about 600 °C to 700 °C.
19. The method of claim 17 wherein the microwave power is about 150-300 W.
20. The method of claim 17 wherein the directing step converts approximately 10% to 20% of CH₄ in the methane gas to H₂.
21. The method of claim 17 wherein the directing step and the controlling step are performed to produce solid carbon in the form of fibrous carbon which drops out of the product gas as a useful by-product.
22. The method of claim 17 further comprising processing the product gas to recover substantially pure hydrogen.
23. The method of claim 22 wherein the processing step comprises flowing the product gas under a vacuum pressure through a Pd/Ag membrane.
24. A system for producing a hydrogen enriched fuel comprising:
a methane gas source configured to provide a methane gas flow;

a reactor having a reaction chamber with microwave transparent walls in flow communication with the methane gas source configured to contain a catalyst and to circulate the methane gas in contact with the catalyst; and

a microwave power source configured to heat the catalyst in the reaction chamber to form a product gas having a selected volumetric percentage of hydrogen and methane.

25. The system of claim 24 wherein the reactor includes a microwave transparent holder configured to hold the catalyst in contact with the methane gas flow.

26. The system of claim 24 wherein the reactor comprises a tube reactor.

27. The system of claim 24 further comprising a hydrogen source in flow communication with the reactor configured to provide a flow of hydrogen gas for pretreating the catalyst.

28. The system of claim 24 further comprising an inert gas source in flow communication with the reactor configured to provide a flow of inert gas for purging the reaction chamber.

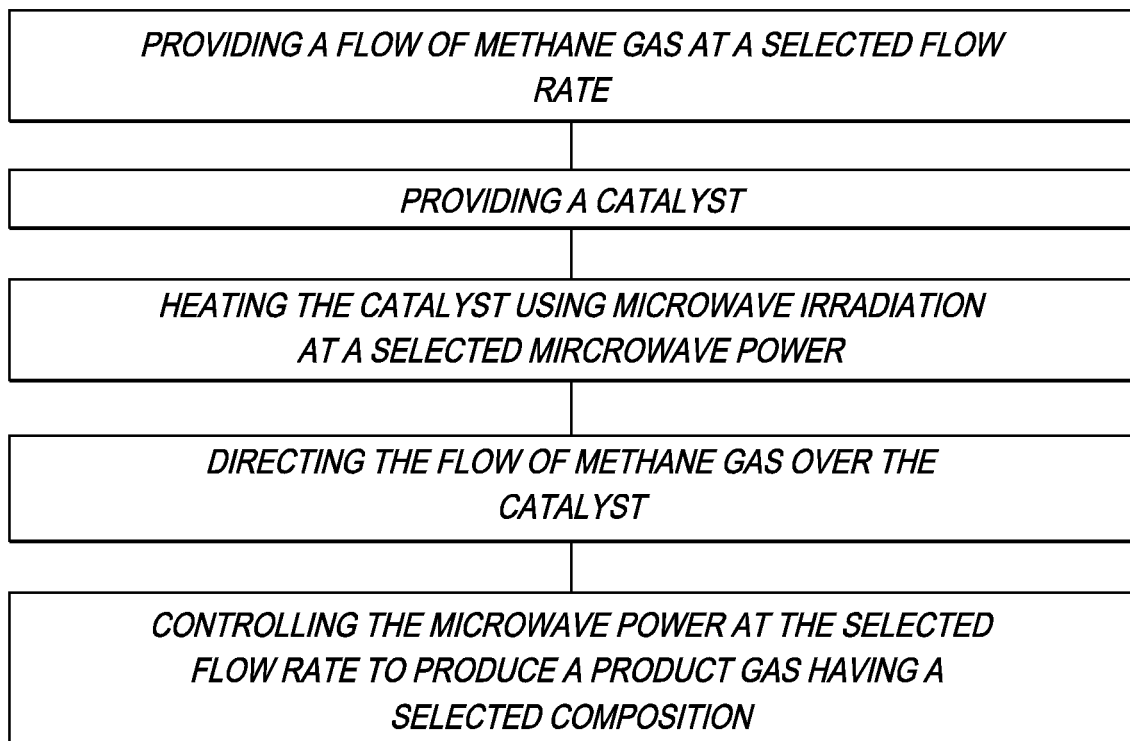
29. The system of claim 24 wherein the catalyst comprises Ni or a Ni alloy.

30. The system of claim 24 wherein the product gas comprises about 20% to 30% hydrogen by volume, and from about 70% to 80% methane by volume.

31. The system of claim 24 further comprising an infrared sensor configured to measure a temperature of the catalyst.

32. The system of claim 24 further comprising a gas chromatograph configured to analyze a chemical composition of the product gas.

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**FIGURE 1**

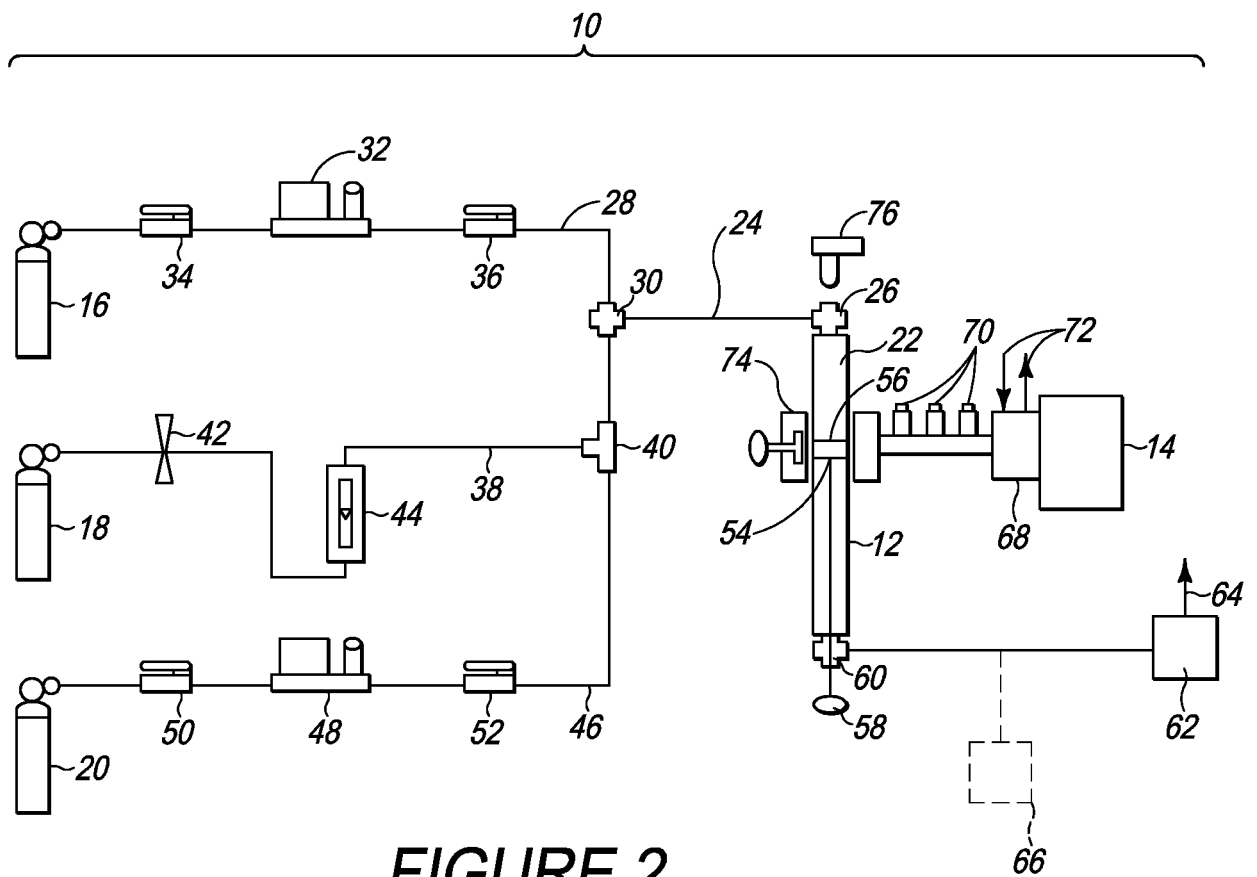


FIGURE 2

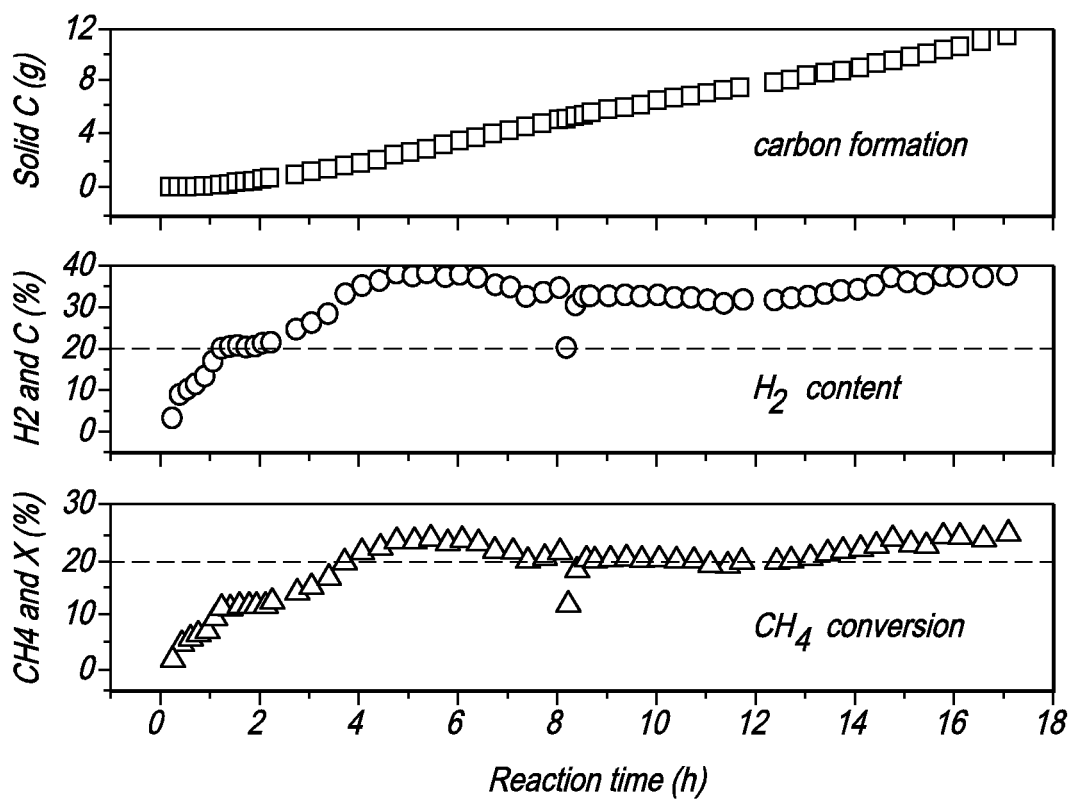


FIGURE 3

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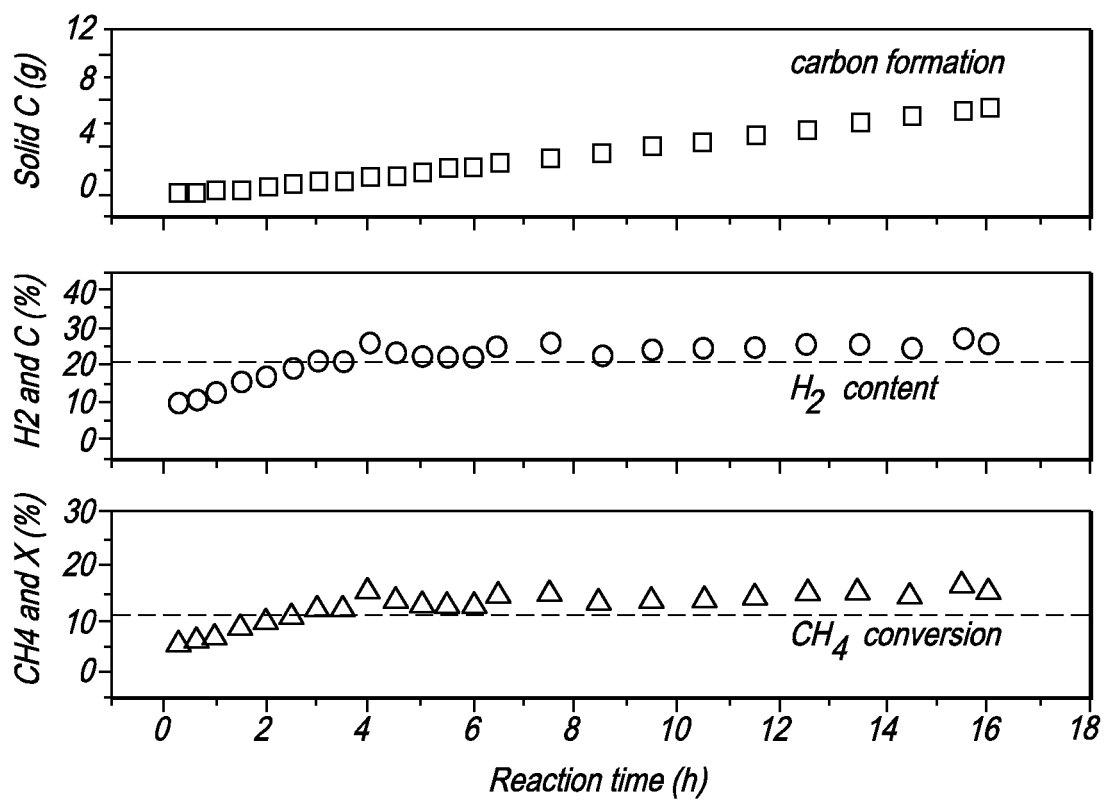


FIGURE 4