



(12) **DEMANDE DE BREVET CANADIEN
CANADIAN PATENT APPLICATION**

(13) **A1**

(22) Date de dépôt/Filing Date: 2014/07/16

(41) Mise à la disp. pub./Open to Public Insp.: 2015/01/29

(62) Demande originale/Original Application: 3 048 715

(30) Priorité/Priority: 2013/07/22 (US61/958,235)

(51) Cl.Int./Int.Cl. *C10G 2/00* (2006.01)

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(54) Titre : PROCÉDE ET SYSTÈME DE CATALYSEUR POUR LA PRODUCTION DE GAZ DE SYNTHÈSE DE HAUTE QUALITÉ À PARTIR D'HYDROCARBURES LÉGERS ET DE DIOXYDE DE CARBONE

(54) Title: PROCESS AND CATALYST SYSTEM FOR THE PRODUCTION OF HIGH QUALITY SYNGAS FROM LIGHT HYDROCARBONS AND CARBON DIOXIDE

(57) **Abrégé/Abstract:**

The present invention describes a process and catalysts for the conversion of a light hydrocarbon and carbon dioxide input stream into high quality syngas with the subsequent conversion of the syngas into fuels or chemicals. In one aspect, the present invention provides an efficient, solid solution catalyst for the production of a carbon containing gas from carbon dioxide and light hydrocarbons. The catalyst comprises a single transition metal, and the transition metal is nickel.

ABSTRACT

The present invention describes a process and catalysts for the conversion of a light hydrocarbon and carbon dioxide input stream into high quality syngas with the subsequent conversion of the syngas into fuels or chemicals. In one aspect, the present invention provides an efficient, solid solution catalyst for the production of a carbon containing gas from carbon dioxide and light hydrocarbons. The catalyst comprises a single transition metal, and the transition metal is nickel.

PROCESS AND CATALYST SYSTEM FOR THE PRODUCTION OF HIGH QUALITY SYNGAS FROM LIGHT HYDROCARBONS AND CARBON DIOXIDE

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FIELD OF THE INVENTION

The present invention describes a process and catalysts for the conversion of light hydrocarbons and carbon dioxide input streams into high quality syngas that is used to produce fuels (e.g. diesel fuel) and chemicals.

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BACKGROUND OF THE INVENTION

The efficient conversion of light hydrocarbon gases, such as natural gas, and carbon dioxide into high quality syngas has several commercial and financial advantages:

A) Some natural gas or light hydrocarbon resources can't be economically recovered since the local infrastructure is not adequate to economically transport this gas to commercial customers. These resources are typically referred to as "stranded resources".

B) Natural gas resources can contain 2-50% (or higher) carbon dioxide which needs to be removed at the extraction site before commercial use.

C) Natural gas resources contain varying amounts of C₂-C₆ hydrocarbons which needs to be removed at the extraction site or from the natural gas pipelines before commercial use of the natural gas.

D) Many other processes (e.g. power plants, cement plants, ethanol production, petroleum refining, chemical plants, etc.) produce carbon dioxide which is usually discharged into the atmosphere. Since carbon dioxide has been identified as a significant greenhouse gas, these carbon dioxide emissions need to be reduced from these processes. Although, this carbon dioxide can be used to enhance oil and gas recovery from wells in limited cases, the majority of this captured carbon dioxide will be emitted into the atmosphere. Since carbon dioxide is a carbon containing gas, the preferred method is to efficiently capture

the carbon dioxide and convert it to fuels (e.g. diesel fuel) and chemicals.

The conversion of light hydrocarbon gases into more valuable chemical products typically involves syngas generation. Syngas generation involves converting natural gas, which is mostly methane, to syngas, which is primarily a mixture of carbon monoxide and hydrogen. Syngas may be used as a feedstock for producing a wide range of chemical products, including liquid fuels, alcohols, acetic acid, dimethyl ether and many other chemical products. However, this syngas needs to be directly produced and converted at the resource site to fuels and/or chemical products since it is not practical to transport the syngas to distant refineries and chemical processing plants.

There are a few possible approaches to converting remote natural gas assets into syngas. Several catalysts are commercially available to convert natural gas into syngas. The syngas produced has a H_2/CO ratio that varies from 3.0-4.5/1.0. However, the H_2/CO ratio needs to be in the proper stoichiometric range of 1.5-2.5/1.0 for the production of fuels and chemicals. Unless otherwise stated, syngas ratios (and percentage compositions) as described herein are in terms of molar ratios (and molar percentages).

Since the syngas generation is a potentially costly step, it is important to produce syngas with the desired H_2/CO ratio for the subsequent production of the desired products. Therefore, several alternative processes for syngas generation have been developed.

One alternative process for syngas generation involves the catalytic or thermal reforming reaction between carbon dioxide and methane (typically referred to as dry reforming). An attractive feature of this method is that carbon dioxide is converted into syngas; however, this method has problems with rapid carbon deposition. The carbon deposition or coke forming reaction is a separate reaction from the one that generates the syngas and occurs subsequent to the syngas formation reaction. However, the reaction of methane in dry reforming is slow enough that long residence times are required for high conversion rates and these long residence times lead to coke formation. The ratio of hydrogen to carbon monoxide, which is formed from this process, is typically

approximately 1.0.

A second alternative process for synthesis gas generation involves partial oxidation of methane using oxygen, where the oxygen can be either air, enriched air, or oxygen with a purity in excess of 90%, preferably in excess of 99%. The ratio of hydrogen to carbon monoxide, which is formed from this process, is typically approximately 2.0. However, in commercial practice, some amount of steam is typically added to a partial oxidation reformer in order to control carbon formation and the addition of steam tends to increase the H_2/CO ratio above 2.0. Likewise it is common to add relatively small amounts of CO_2 to the feed gas mixture in an attempt to adjust the ratio closer to 2.0.

A third approach is to produce syngas with a H_2/CO ratio between 0.5 and 1 using a mixture of LPG and CO_2 (Calcor process). See, *Hydrocarbon Processing*, Vol. 64, May 1985, pp. 106-107 and "A new process to make Oxo-feed," *Hydrocarbon Processing*, Vol. 66, July 1987, pg. 52. However, many natural gas resource sites, in particular the stranded natural gas sites, do not have the infrastructure available to separate LPG and CO_2 from the natural gas.

Many processes and catalyst formulations have been reported in the literature for the reforming of light hydrocarbon gases or carbon dioxide. In the first step in the process, the production of syngas traditional catalysts do not meet the following criteria:

- 1) exhibits high thermal stability up to 1,100 °C; 2) does not produce elemental carbon (coking); 3) has good resistance to contaminants that may be present in captured CO_2 and natural gas streams; 4) can be reduced *in-situ* in the catalytic reactor; 5) exhibits good physical hardness and will not physically degrade over time; 6) will efficiently co-convert CH_4 and CO_2 , with and without the presence of water.

It is possible to produce syngas with a H_2/CO ratio that is above the ratio ideally desired for the process in which the syngas is to be used, and then to remove excess hydrogen to adjust the ratio to the desired value. However, the H_2 removal process employs expensive H_2 separation systems that tend to foul and decline in performance with use.

Some natural gas extraction plants produce LPG as well as the natural gas. The export of LPG from such a facility or from the parent natural gas field is often difficult and expensive. The LPG must be compressed or liquefied, and the shipment requires the use of special transportation vessels. Furthermore, the market for mixtures of propane and butane is limited and of reduced value. Thus, the LPG must be separated into individual propane and butane of sufficient purity to meet commercial specifications. This complicated and expensive operation often results in high costs, which limits the value of the LPG at the production site.

The conversion of natural gas to liquid fuels further involves the production of some quantities of greenhouse gas emissions, such as CO₂, which is environmentally undesirable.

Following the production of the synthesis gas, many processes and catalysts have been proposed for the production of transportation fuels and chemicals. However, the traditional process for production of fuels and chemicals from syngas involves the production first of a paraffinic wax product that is then refined into fuels and/or chemicals. The refining step is capital intensive and complex to operate, therefore requiring large plant sizes to justify this refining system.

Accordingly, there is a need for a process for producing a syngas with a pre-selected H₂/CO ratio that can be varied according to the process in which the syngas is to be employed and that avoids H₂ separation and coking in the syngas formation step. There is also a need for a process that minimizes or eliminates production of LPG from a processing facility, such as, for example, a hydrocarbon synthesis facility. Furthermore, there is a need to reduce the greenhouse emissions from a processing facility, such as, for example, an on-site fuel production plant. In addition, the need to directly produce a usable diesel fuel without having to refine a hydrocarbon wax is required to justify lower plant capital and operating costs.

BRIEF DESCRIPTION OF THE FIGURES

FIG. 1 shows a graph related to the ability of a catalyst to dry reform mixtures of CO_2 and CH_4 .

FIG. 2 shows a graph related to the performance of a catalyst with a CO_2/CH_4 (1.1/1.0) feed.

FIG. 3 shows a graph related to a dry reforming test run at an intermediate ratio of CO_2/CH_4 (1.5/1.0).

FIG. 4 shows a graph related to a catalyst that was found to be stable with lower water content in the feed (at $< 2.0/1.0 \text{ H}_2\text{O}/\text{CH}_4$) as demonstrated in a test with $\text{CO}_2/\text{CH}_4/\text{H}_2\text{O}$ (0.6/1.0/1.4) at 900°C .

FIG. 5 shows a graph related to a catalyst tested at 900°C and $10,400 \text{ hr}^{-1}$ ($7,800 \text{ cc/g-hr}$) at 850°C using a gas composition of $\text{CO}_2/\text{CH}_4/\text{H}_2\text{O}$ (0.4/1.0/0.93).

FIG. 6 shows a graph related to a catalyst that was stable when operating with a gas composition of $\text{CO}_2/\text{CH}_4/\text{H}_2\text{O}$ (0.6/1.0/1.4) from 800°C - 900°C .

FIG. 7 shows a graph related to a catalyst tested with a gas composition of $\text{CO}_2/\text{CH}_4/\text{H}_2\text{O}$ (0.6/1.0/1.4) at 800°C .

FIG. 8 shows a graph related to a tri-reforming test conducted at CH_4 (1.0)/ CO_2 (1.0)/ H_2O (1.0)/ O_2 (0.1) at 900°C at $13,333 \text{ hr}^{-1}$ ($10,000 \text{ cc/g-hr}$).

FIG. 9 shows a graph related to testing conducted at a feed gas composition CH_4 (1.0)/ CO_2 (1.0)/ H_2O (1.0)/ O_2 (0.05) at 900°C and $16,000 \text{ hr}^{-1}$ ($12,000 \text{ cc/g-hr}$).

FIG. 10 shows a graph related to a test conducted with a feed gas composition of CH_4 (1.0)/ CO_2 (1.0)/ H_2O (1.0)/ O_2 (0.2) at 900°C and $17,333 \text{ hr}^{-1}$ ($13,000 \text{ cc/g-hr}$).

FIG. 11 shows a graph related to a tri-reforming test.

FIG. 12 shows a graph related to a test where the CO_2 ratio was increased to 0.6, the steam ratio was increased to 1.7, and O_2 increased to 0.2. Gas hourly space velocity was $18,666 \text{ hr}^{-1}$ ($14,000 \text{ cc/g hr}$).

FIG. 13 shows a graph related to a test where the carbon dioxide ratio was increased to 0.8, the steam to methane ratio was varied between 1.7 and 1.35, while keeping O_2 at 0.1 ($\text{GHSV} = 16,333 \text{ hr}^{-1}$ or $12,250 \text{ cc/g hr}$).

FIG. 14 shows a graph related to a test where the carbon dioxide ratio was increased to 0.8, the steam to methane ratio was varied between 1.7 and 1.35, while keeping O₂ at 0.1 (GHSV = 18,000 hr⁻¹ or 13,500 cc/g hr).

SUMMARY OF THE INVENTION

The present invention relates to a process whereby a mixture of light hydrocarbons and carbon dioxide is catalytically converted into a high-quality syngas which can then be used to produce diesel fuel grade liquid hydrocarbon and/or other valuable higher hydrocarbon streams, whereby the carbon dioxide stream is generated by separation from a flue gas stream or by other means or exists as part of the natural gas stream. The light hydrocarbons and carbon dioxide are supplied to a first reactor that utilizes a first catalyst whereby the light hydrocarbons and carbon dioxide are converted into high quality syngas. The syngas output of the first reactor is connected as an input to a second reactor that utilizes a second catalyst to form a diesel fuel grade liquid hydrocarbon and other hydrocarbon byproducts.

The first catalyst used in the process is a high-performance solid solution Ni-based catalyst that is highly versatile, and which efficiently produces high-quality syngas under dry reforming (CH₄ and CO₂), combination dry/steam reforming (CH₄, CO₂ & H₂O), or tri-reforming (CH₄, CO₂, H₂O & O₂) conditions. The robust, solid solution Ni-based catalysts have high thermal stability up to 1,100 °C, do not form carbon (coking), and have good resistance to contaminants that may be present in captured CO₂ streams, natural gas, biogas or other gas feedstock sources.

The first catalyst is also capable of reforming complex and higher molecular weight hydrocarbons without coking or other deactivation that occurs on traditional steam methane reforming (SMR) and other reforming catalyst systems. This catalyst exhibits high activity at low Ni concentrations (5-20 wt. %), compared to other catalysts that require at least 30 wt. % Ni. Furthermore, the use of expensive precious metals to enhance catalyst performance is not necessary. High conversion efficiencies of light hydrocarbons in the feed stream of 90-100% are achieved when the catalyst is operated

under the recommended space velocities and temperature conditions outlined in this invention.

The second catalyst contains from about 2 to about 50 parts-by-weight cobalt and from about 0.1 to about 20 parts-by-weight of at least one metal selected from a group consisting of cerium, ruthenium, lanthanum, platinum, or rhenium per 100 parts-by-weight of a support selected from a group consisting of silica, alumina, and combinations thereof.

The carbon dioxide supplied as an input to the process is either contained within the natural gas stream or is obtained by separating the carbon dioxide from a flue gas stream exiting the first reactor, whereby an alkylamine is used to remove the carbon dioxide from the flue gas stream. Alkylamines used in the process include monoethanolamine, diethanolamine, methyldiethanolamine, diisopropylamine, aminoethoxyethanol, or combinations thereof.

DETAILED DESCRIPTION OF THE INVENTION

The present invention describes a process and catalysts for the conversion of a light hydrocarbon and carbon dioxide input stream into a diesel fuel grade liquid hydrocarbon usable as a compression ignition fuel which may contain a majority of C8-C24 paraffins.

The invention utilizes a first reactor system whereby light hydrocarbons which may include but are not limited to natural gas, naphtha, natural gas liquids, bio-gas containing methane, or other similar gases are blended with carbon dioxide and optionally steam, oxygen, or oxygen containing gases such as air.

The first reactor system utilizes a first catalyst that is a robust, Ni based solid-solution catalyst that reforms the feed gases into a carbon containing output gas.

In comparison to other catalysts developed for this application, this first solid-solution catalyst utilizes only one transition metal, Ni, whereas all other reforming catalysts employ two or more transition metals. See, USP 6,423,665, USP 7,432,222, WO 2000/016899, and US Pat. Pub. No. 0314993. Several other prior art formulations

require the use of expensive precious metals (e.g. Pt, Pd, Rh, Ru and Ir). See, USP 6,409,940 and USP 5,431,855.

Other formulations require that the active catalyst material needs to be coated on catalyst substrates (e.g. Al_2O_3). Moreover, this is the only solid-state catalyst formulation
5 that is versatile and is able to produce high-quality carbon containing product gas under dry reforming (CH_4 and CO_2), combination dry/steam reforming (CH_4 , CO_2 & H_2O), or tri-reforming (CH_4 , CO_2 , H_2O & O_2) conditions.

The carbon containing product gas is then fed into a second reactor system that utilizes a second catalyst that contains from about 2 to about 50 parts-by-weight cobalt
10 and from about 0.1 to about 20 parts-by-weight of at least one metal selected from a group consisting of cerium, ruthenium, lanthanum, platinum, or rhenium per 100 parts-by-weight of a support selected from a group consisting of silica, alumina, and combinations thereof.

The integrated process above requires a carbon dioxide input. In one
15 embodiment, the carbon dioxide is supplied from the separation of the carbon dioxide in the flue gas stream exiting the first reactor, and the separation is done using an alkylamine.

Alkylamines used in the process can include monoethanolamine, diethanolamine, methyldiethanolamine, diisopropylamine, aminoethoxyethanol, or combinations thereof. In
20 another embodiment, the carbon dioxide is already contained in the natural gas feedstock.

In another embodiment, the carbon dioxide exists as part of the natural gas or natural gas liquids stream.

The manufacturing process for the first catalyst is important as well in that it produces a catalyst that forms a unique solid solution phase, bi-metallic crystalline phase
25 that leads to no segregation of the metal phases. This unique chemical structure leads to enhanced resistance to coking, when compared to conventional metal supported reforming catalysts. This also leads to enhanced resistance to syngas poisons such as sulfur and ammonia. In addition, this catalyst has enhanced catalytic activity at lower surface area compared to monometallic segregated catalyst phase for example Ni on

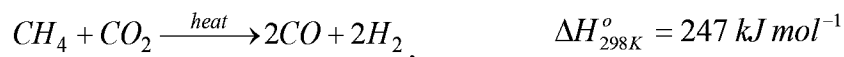
alumina. This catalyst requires no alkali promotion needed to curb the carbon deposition typically seen with feed gases as described herein. The catalyst is operable in a variety of dry, steam, combined dry/steam and tri-reforming feeds. Mixes of higher hydrocarbon feedstocks are also achievable with this catalyst.

The first catalyst manufacturing may involve some or all of the following steps that will achieve a commercial solid solution catalyst: A) mixing of Ni₂O powders at the 5-15 wt. % level with one or more alkali metal oxides (e.g. MgO, CaO); B) fusing of these oxide mixtures at temperatures in the range of 900-1,100 °C for 4-12 hours; C) calcining the catalyst the first time; D) grinding of the fused mixtures to produce the proper catalyst size, typically in the 500-3,000 um range; E) calcining the catalyst the second time.

EXAMPLES

A variety of tests were conducted on the first catalyst including dry reforming (CO₂ and CH₄), combination dry/steam reforming (CO₂, CH₄ & H₂O), and tri-reforming (CO₂, CH₄, H₂O & O₂). CH₄ and CO₂ conversions averaged up to 95-100% at the optimum temperatures and gas space velocities. No formation of carbon deposits (coking) on the catalyst was observed in any of these tests. The following sections provide examples that support the superior performance of these catalysts over currently available technologies.

Dry Reforming - In Dry (or CO₂) Reforming, methane and carbon dioxide are reacted and produce a syngas with low H₂/CO ratio of 0.7-1.0:

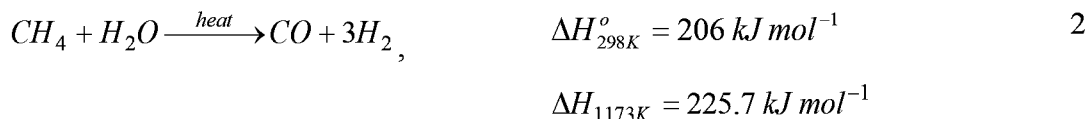


$$\Delta H_{1173K} = 258.5 \text{ kJ mol}^{-1}$$

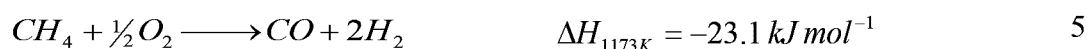
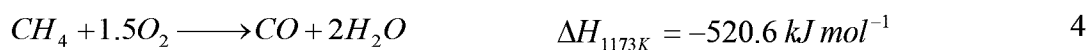
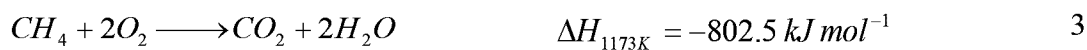
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Steam Reforming - Steam Methane Reforming (SMR) is an endothermic process where methane is reacted with steam at high temperatures to produce a syngas with a

high H₂/CO ratio:



Partial Oxidation - Reactions for the exothermic oxidation of methane are shown below:



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Water-Gas-Shift Equilibrium - The Water-Gas Shift (WGS) equilibrium reaction, equation 6, also occurs during reforming and will adjust the final syngas product ratio depending on how the equilibrium is influenced. If, for instance, dry reforming is conducted in an excess of CO₂, then the reverse WGS will be favored which will increase the CO content and produce water. Likewise, excess steam in the SMR reaction will tend to drive the forward water gas shift resulting in higher H₂ and some CO₂ products.

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Reactions for Coke Formation and Destruction - The desired reforming reactions above are often accompanied by side or intermediate reactions that involve elemental carbon (or coke). The equations below show some of the ways that carbon can be formed and reformed from the reactants and products. One possible pathway to the desired products of CO and H₂ is methane decomposition on the catalyst (Eq. 7) and or carbon monoxide disproportionation (Eq. 8) followed by carbon reforming (Eq. 9-11). However, it is the buildup of elemental carbon in reactors that is one of the main factors of catalyst lifetime and much research is focused on limiting its formation. Catalysts were analyzed for carbon formation during test runs.

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As discussed above, this catalyst performed well under mixed reforming conditions and was selected based on several reasons. First, the catalyst shows high thermal stability and negligible carbon formation under a variety of target reforming conditions including dry reforming, which is typically a challenge for other reforming catalysts. Another benefit of the catalyst is that the base material has high thermal stability and shock resistance, both of which are important for commercial plants. Also, the catalyst provides acceptable commercial costs as well as good conversion efficiencies and stability over time. In addition, another benefit is that this catalyst performs well in the reformation of the small percentage of higher hydrocarbons that are in the feed stream from both natural gas and other feed streams. Experimental results on the catalyst for tri-reforming, dry-reforming, and combination reforming are summarized below.

Example #1 - In this example, the ability of the catalyst to dry reform mixtures of CO₂ and CH₄ are described. Dry reforming tests were initiated at 1.75/1.0 CO₂/CH₄ and 900°C (Run A). The results are shown in **FIG. 1**. The ratio of CO₂/CH₄ changed slightly as the space velocity was altered due to insufficient calibration of the flow meters. This problem was discovered during data analysis and was corrected in later runs. At 900°C, full methane conversion was achieved, and the sample operated without loss of activity or pressure increase. At 650°C, the methane conversion was low. The catalyst achieved 95% methane conversion at 800°C and demonstrated stable performance without pressure increase.

In the next set of tests, the performance of the catalyst under more challenging

conditions was examined (see **FIG. 2**). The performance of the catalyst with a CO₂/CH₄ (1.1/1.0) feed was carried out. At 900°C, the complete conversion of methane and carbon dioxide was observed over the first several hours, and complete conversion continued overnight at 800°C for 18 hours. There was no loss in performance at the higher
5 temperatures, although the pressure drop through the reactor increased from 2 psi to about 4 psi overnight.

The catalyst was tested at 650°C the following day, but immediate loss in performance and reactor blockage quickly ensued. Analysis of the sample, as discussed in the following section, confirmed that the catalyst coked (produced carbon that plugged
10 the reactor). This is typical for reforming catalysts at lower temperatures under dry reforming conditions and the catalyst performed well, without carbon deposition, at CO₂/CH₄ ratios greater than 1.5/1.0 and temperatures greater than 800° C.

Finally, a dry reforming test was run (Test C) at an intermediate ratio of CO₂/CH₄ (1.5/1.0) as shown in **FIG. 3**. At 900°C, the catalyst was stable for 2 days of operation
15 before the run was terminated to analyze the catalyst for carbon. The pressure didn't increase during the test, and the activity did not change.

Dry reforming, under all of the conditions described above, produces a syngas with a H₂/CO < 1.0 that is not entirely suitable for subsequent conversion to diesel fuel. However, if a source of external renewable hydrogen was available or if hydrogen
20 already exists in the flue gas stream from a stationary emissions source (for example in IGCC power plants), then dry reforming is an attractive option for use in this catalytic system which provides high CO₂ conversion efficiencies and a methane to carbon dioxide input ratio that provides very attractive commercial economics (since the feed gas can contain up to ~70% CO₂).

Example #2 - The ability of the catalyst to carry out a combination of dry and
25 steam reforming of CO₂, CH₄ & H₂O is summarized in this example. Combination dry reforming/steam methane reforming tests includes CO₂, CH₄ and H₂O reactants in various molar ratios. In addition to the dry reforming reactions, Steam Methane Reforming (SMR) also occurs and is an endothermic process where methane reacts with steam at

high temperatures to produce syngas.

By combining dry and steam reforming, a syngas with an ideal H_2/CO can be produced. Mixed steam and dry methane reforming tests were conducted to demonstrate activity and determine product composition with methane, CO_2 , and steam in the feed. In the first test, the reforming mixture was run with the following gas composition: $CO_2/CH_4/H_2O$ (0.9/1.0/2.2) at $900^\circ C$.

The catalyst was found to be stable with lower water content in the feed (at $< 2.0/1.0 H_2O/CH_4$) as demonstrated in a test with $CO_2/CH_4/H_2O$ (0.6/1.0/1.4) at $900^\circ C$ (Test D). Stable catalyst performance was achieved as shown in **FIG. 4**.

In the next set of test conditions using a gas composition of $CO_2/CH_4/H_2O$ (0.4/1.0/0.93), the catalyst was tested at $900^\circ C$ and $10,400 \text{ hr}^{-1}$ ($7,800 \text{ cc/g-hr}$) at $850^\circ C$ (see **Fig. 5**).

As shown in **Fig. 6** (test F), the catalyst was stable when operating with a gas composition of $CO_2/CH_4/H_2O$ (0.6/1.0/1.4) from 800 - $900^\circ C$.

Additional testing was carried out with the same gas composition of $CO_2/CH_4/H_2O$ (0.6/1.0/1.4) at $800^\circ C$ (see **Fig. 7**, Test G). Post-testing Temperature Programmed Oxidation (TPO) and optical analysis did not show any signs of carbon deposition.

In conclusion, it was found that a combination of steam methane and dry reforming (including the reactants CO_2 , CH_4 , and H_2O) produce a syngas with a H_2/CO ratio of 1.8-2.0 that is ideal for subsequent liquid fuel production. Typically a H_2O/CO_2 ratio of 2.0-1.0 would be targeted in order to produce syngas in this ratio.

Example #3 - The capability of the catalyst to tri-reform CO_2 , CH_4 , H_2O & O_2 is presented in this example. Tri-reforming is typically defined as a combination of endothermic CO_2 (or Dry) reforming (Eq. 3) and steam reforming (Eq. 4) with exothermic oxidation of methane (Equations 5, 6, 7 described above).

Tri-reforming utilizes a single catalyst and the reactions outlined above occur in a single catalytic reactor system. This combination of reactions produces syngas with a H_2/CO ratio in the proper range for subsequent diesel fuel production. Note again that

oxygen is not required for achieving the appropriate syngas ratio and for stable operation of the catalyst, however since oxygen is available at in some flue gas applications and operation with some oxygen in the feed stream can allow for the flue gas to be used directly without separation.

5 When tri-reforming is used, oxygen levels should be kept under 6% of the total feed gas. Higher oxygen levels start to negatively affect CO₂ conversion. This fact has been recognized by several groups and this is one of the reasons that under auto-thermal reforming (ATR), CO₂ conversion is poor even at elevated temperatures.

10 In the first test, reforming was conducted at CH₄ (1.0)/CO₂ (1.0)/H₂O (1.0)/O₂ (0.1) at 900°C at 13,333 hr⁻¹ (10,000 cc/g-hr) and the data for tri-reforming test H is shown in **Fig. 8**.

Fig. 9 shows the results for Test I at a feed gas composition CH₄ (1.0)/CO₂ (1.0)/H₂O (1.0)/O₂ (0.05) at 900°C and 16,000 hr⁻¹ (12,000 cc/g-hr).

15 **Fig. 10** shows results (test J) for a feed gas composition of CH₄ (1.0)/CO₂ (1.0)/H₂O (1.0)/O₂ (0.2) at 900°C and 17,333 hr⁻¹ (13,000 cc/g-hr) (Oxygen levels were 200% of Tri-reforming Test H).

 In the next test (E), the CO₂ ratio was increased to 0.6, the steam ratio was increased to 1.7, and O₂ increased to 0.2. Gas hourly space velocity was 18,666 hr⁻¹ (14,000 cc/g hr) as shown in **Fig. 12** (Test L).

20 Under the final two conditions, the carbon dioxide ratio was increased to 0.8, the steam to methane ratio was varied between 1.7 and 1.35, while keeping O₂ at 0.1. The results of these tests are shown in **Fig. 13** (GHSV = 16,333 hr⁻¹ or 12,250 cc/g hr) and **Fig. 14** (GHSV = 18,000 hr⁻¹ or 13,500 cc/g hr). Both tests were stable during the 20 hours of testing at 900°C for each condition. Decreasing the steam in the feed improves
25 carbon dioxide conversion. Overall, the catalyst was very stable for all of the tri-reforming conditions examined. No carbon formation or deactivation of the catalyst was observed.

 In conclusion, tri- reforming was found to provide high gas hourly space velocities (GHSV), stable catalyst performance, and the proper H₂/CO ratio (~2.0) for

subsequent conversion to diesel fuel or chemicals.

CLAIMS

1. A process for converting carbon dioxide into diesel fuel grade liquid hydrocarbons, wherein the process comprises:
 - a) using an alkylamine to remove carbon dioxide from a gas;
 - b) introducing the carbon dioxide into a first reactor system, wherein the first reactor system comprises a first catalyst, and wherein the first catalyst comprises a single transition metal with a grain size of 500-3,000 μm , and wherein the single transition metal is present in the catalyst at a concentration ranging from 5 percent to 20 weight percent, to provide syngas;
 - c) feeding the syngas into a second reactor system, wherein the second reactor comprises a second catalyst thereby producing the diesel fuel grade liquid hydrocarbon.
2. The process of claim 1, wherein the alkylamine comprises one or more of: include monoethanolamine, diethanolamine, methyldiethanolamine, diisopropylamine, aminoethoxyethanol and combinations thereof.
3. The process according to any one of claims 1-2, wherein the gas is flue gas steam.
4. The process according to any one of claims 1-3, wherein the process comprises separating of a product stream from the second catalyst into diesel fuels comprising C8 - C24 hydrocarbons, reformulated gasoline blendstocks comprising C4-C8 hydrocarbons and oxygenated hydrocarbons and light gas streams comprising C1 – C4 hydrocarbons and oxygenated hydrocarbons.
5. The process of claim 4, further comprising introducing the product stream from the second reactor system into a single vessel and condensing the product stream below about 80 °F into two liquid fractions in the single vessel, wherein the top fraction contains the diesel fuel and the bottom fraction comprises water.

6. The process according to claim 4 or 5, in which a condenser is operated at selected temperatures to increase or reduce the proportion of reformulated gasoline blendstocks comprising C4-C8 hydrocarbons and oxygenated hydrocarbons.
7. The process according to any one of claims 4-6, in which the light hydrocarbon gases comprising C1 – C4 hydrocarbons and oxygenated hydrocarbons, unreacted carbon monoxide and hydrogen gases are recycled back to the first catalyst for the production of additional hydrocarbon products.
8. The process according to any one of claims 4-7 in which the light gas stream comprising C1 – C4 hydrocarbons and oxygenated hydrocarbons are recycled back to the first catalyst for the production of additional syngas.
9. The process according to any one of claims 4-8 in which the produced reformulated gasoline blendstocks comprising C4-C8 hydrocarbons and oxygenated hydrocarbons are recycled back to the first catalyst for the production of additional syngas.
10. The process according to any one of claims 1-9, wherein the single transition metal is nickel.
11. The process according to any one of claims 1-10, wherein the process comprises introducing one or more light hydrocarbons into the first reactor system.
12. The process according to any one of claims 1-11, wherein the second catalyst contains from about 2 to about 50 parts-by-weight cobalt and from about 0.1 to about 20 parts-by-weight of at least one metal selected from a group consisting of cerium, ruthenium, lanthanum, platinum, or rhenium per 100 parts-by-weight of a support selected from a group consisting of silica, alumina, and combinations thereof.

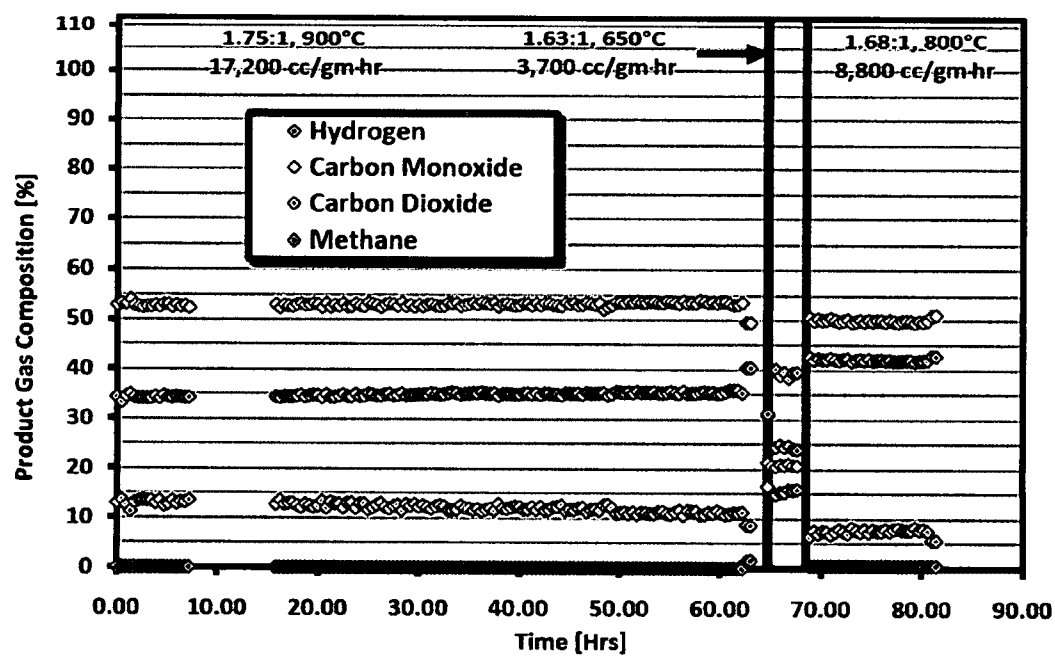


FIG. 1

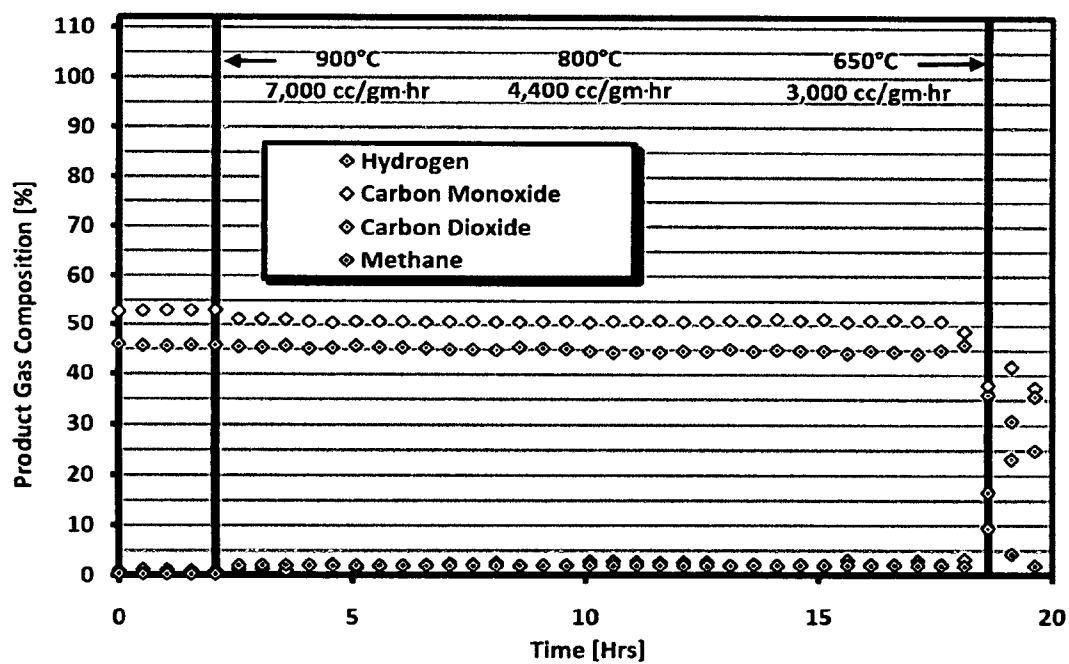


FIG. 2

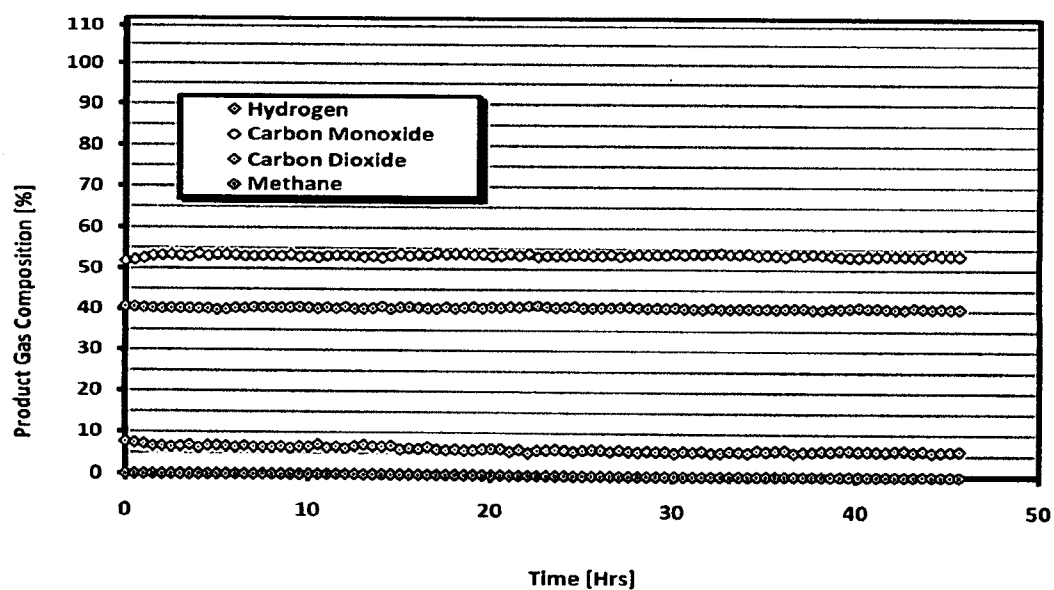


FIG. 3

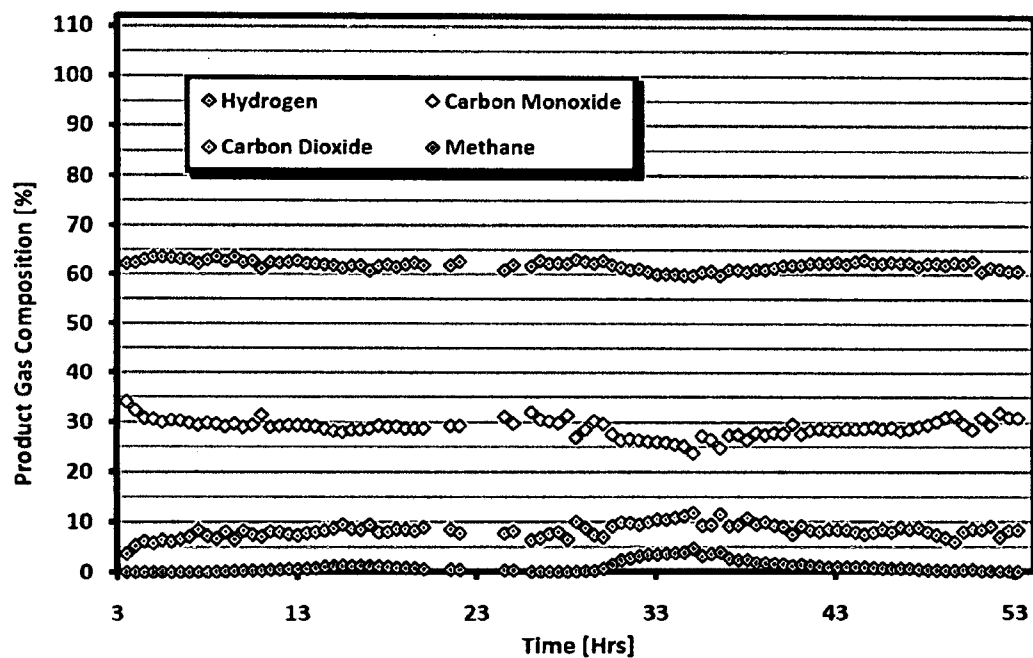


FIG. 4

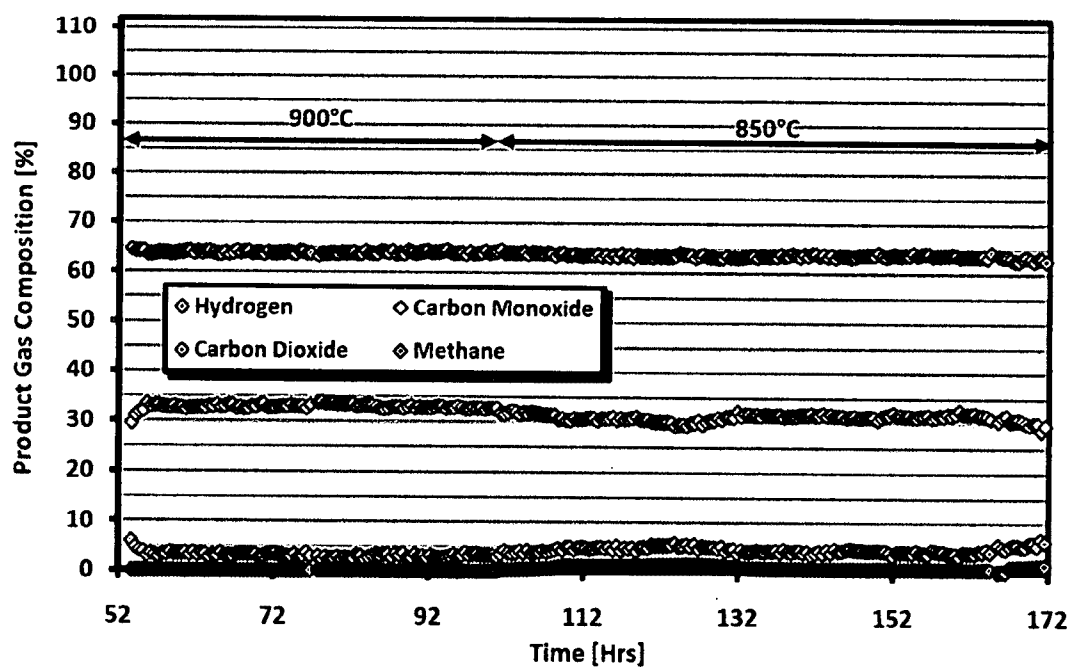


FIG. 5

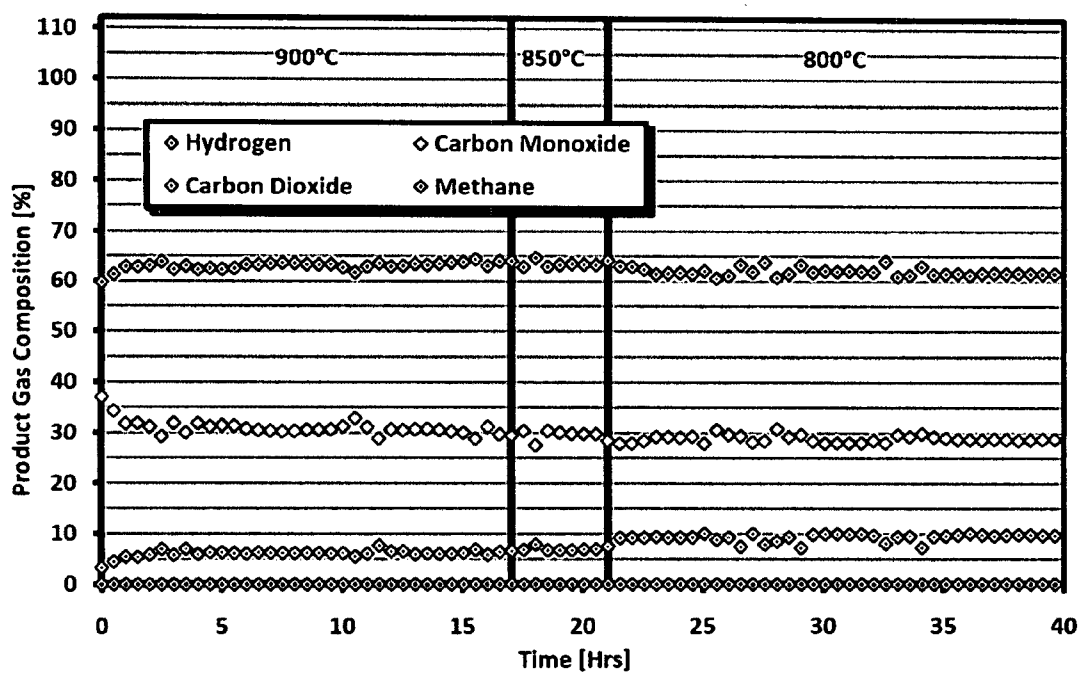


FIG. 6

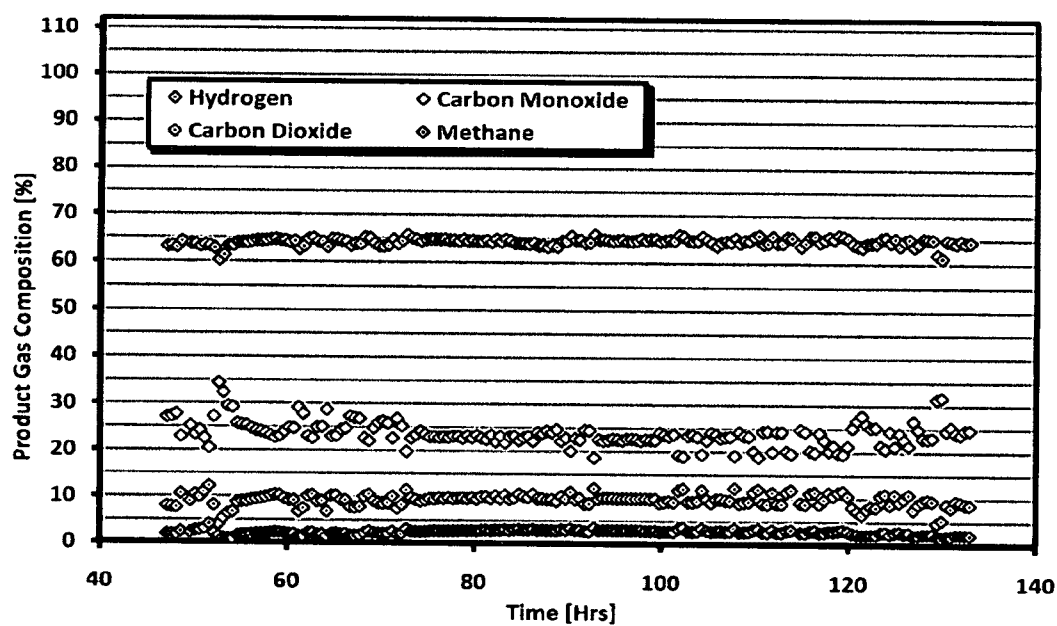


FIG. 7

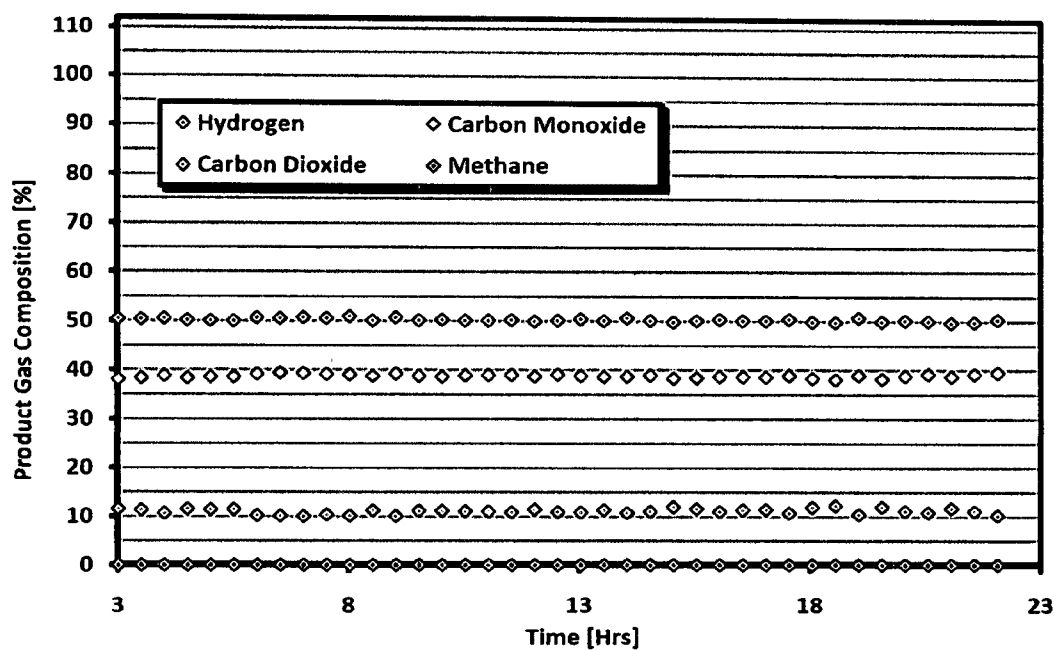


FIG. 8

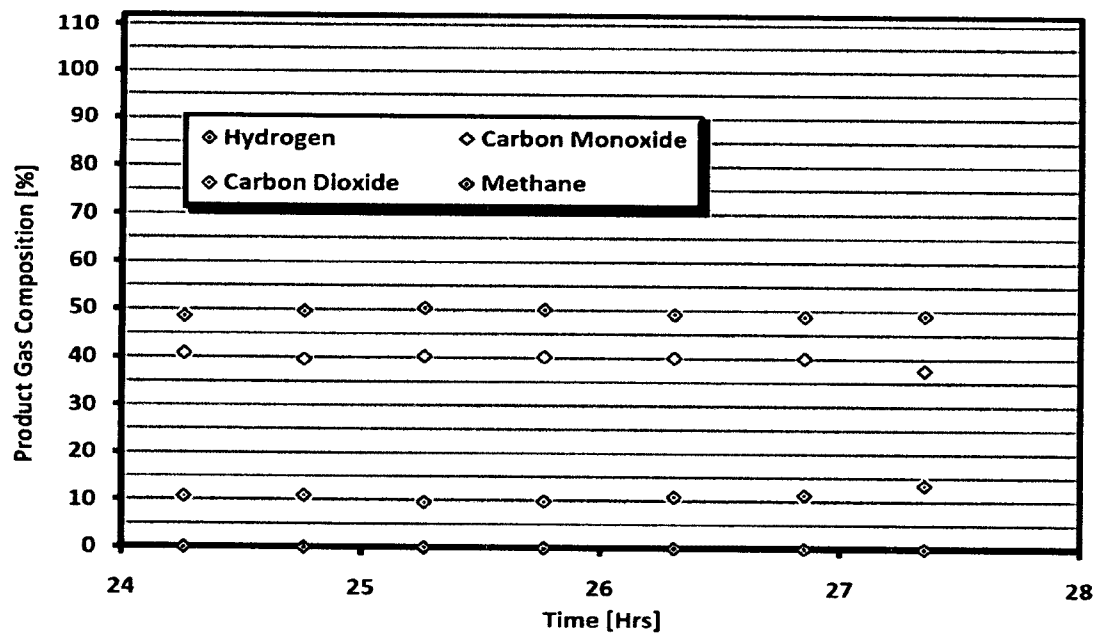


FIG. 9

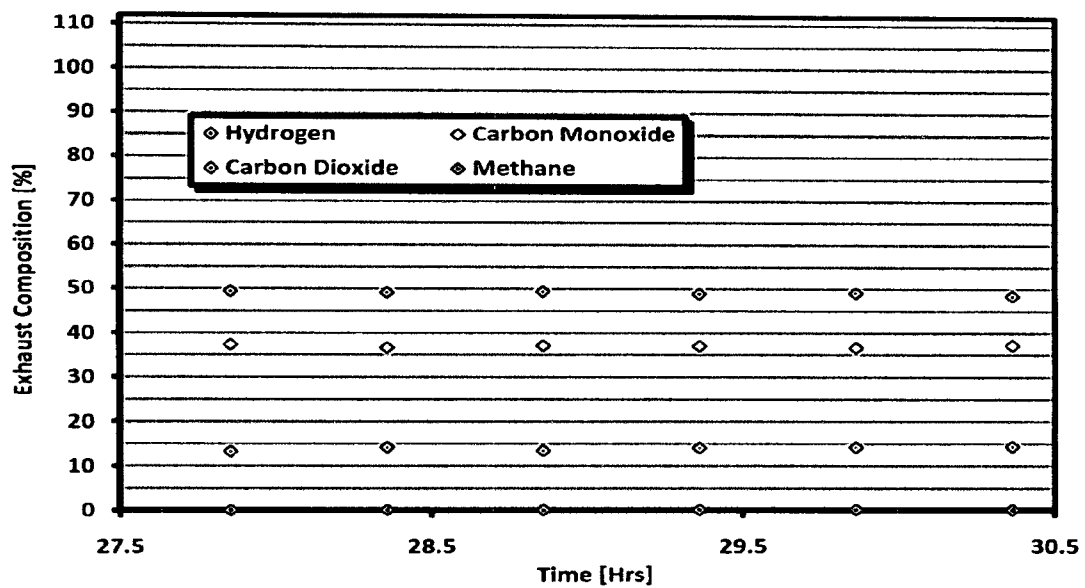


FIG. 10

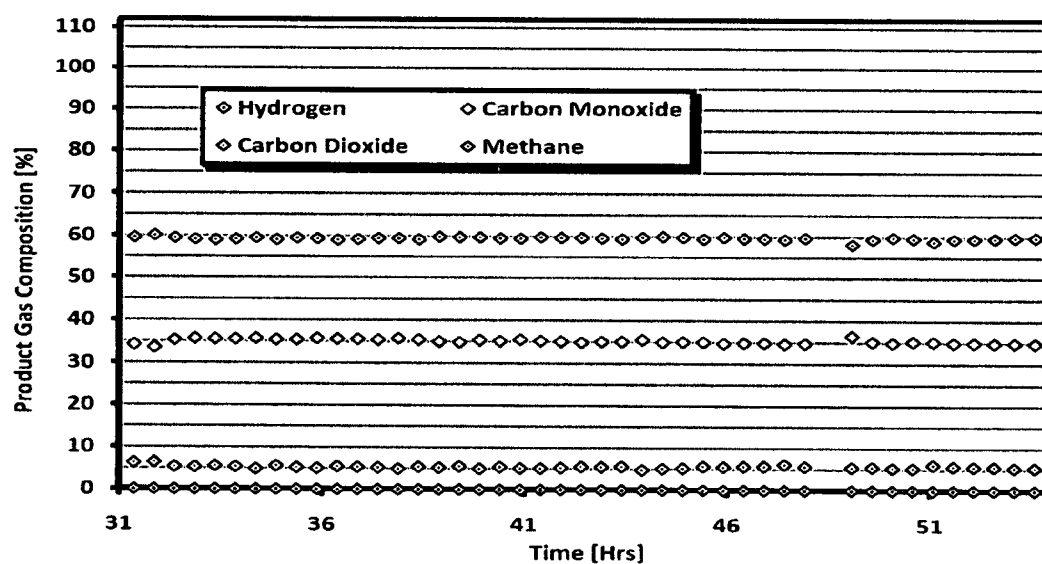


FIG. 11

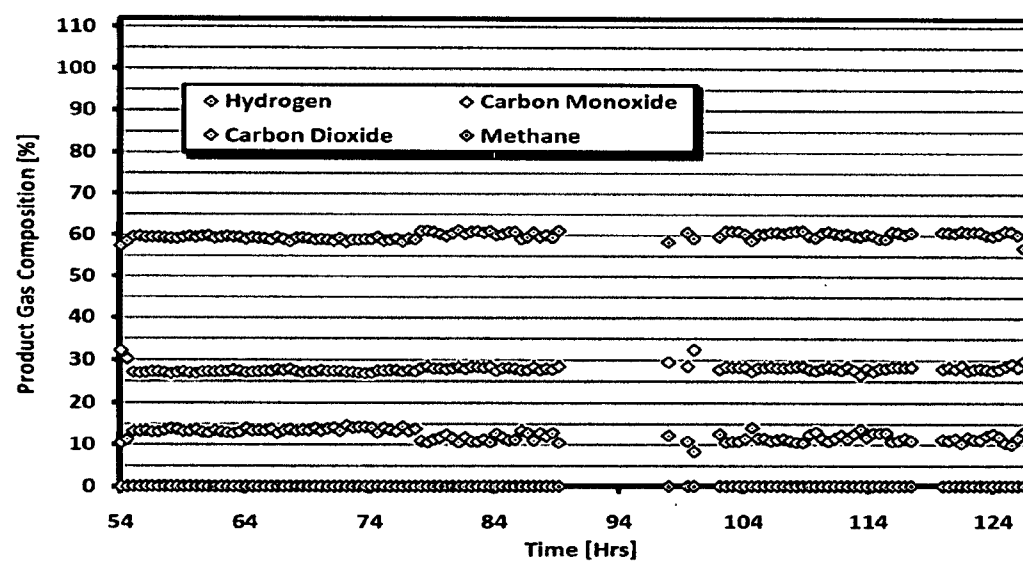


FIG. 12

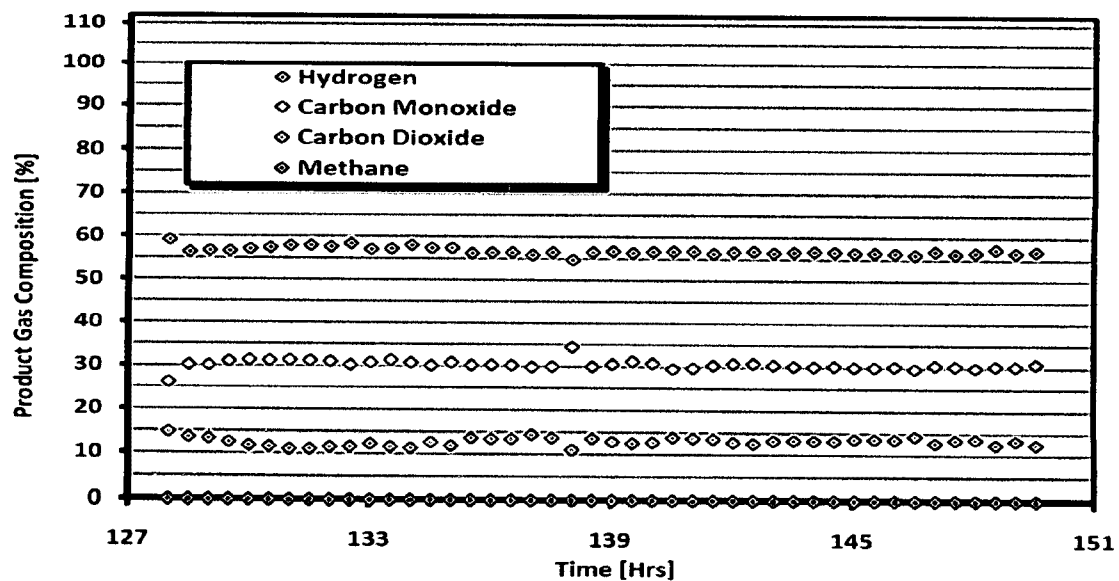


FIG. 13

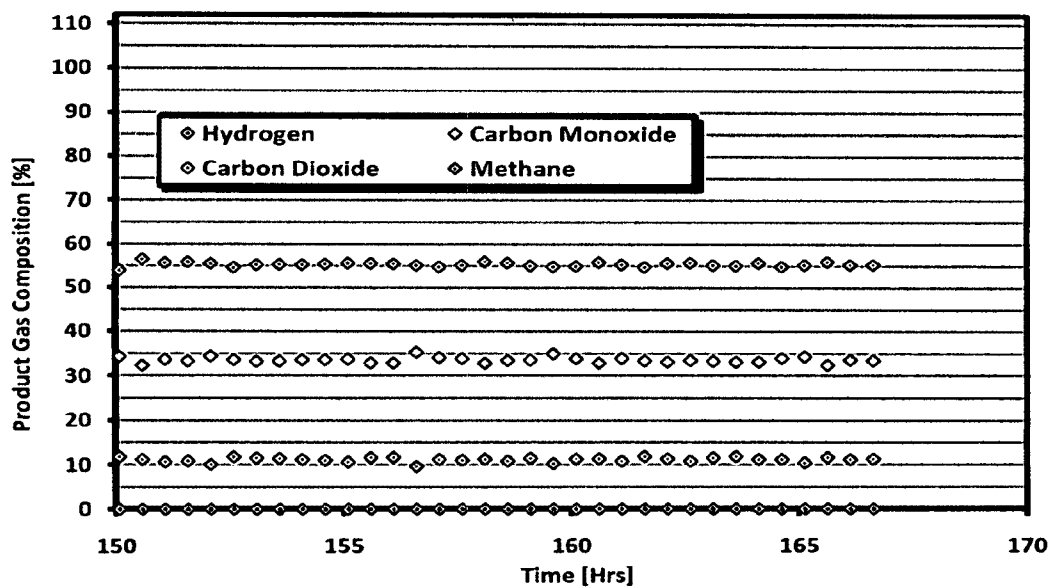


FIG. 14