HYBRID ADSORPTIVE MEMBRANE REACTOR

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ABSTRACT

A hybrid adsorbent-membrane reactor in which the chemical reaction, membrane separation, and product adsorption are coupled. Also disclosed are a dual-reactor apparatus and a process using the reactor or the apparatus.

40 Claims, 56 Drawing Sheets
\[ T(0) = 275, P_Or(\text{atm}) = 7.8027, P_Om(\text{atm}) = 1, \text{ST sec} = 10, S_R = 0.25, x_e = 0.93637 \]
FIG. 3

T(C) = 275, P0(atm) = 7.8027, P0m(atm) = 1, ST soc = 10, SR = 0.25, xe = 0.93637

Unconverted CO in catalytic membrane reactor

Unconverted CO in plug flow reactor

Dimensionless length

Uncertened CO

Uncertened CO
FIG. 10

CO conversion in catalytic membrane reactor.

CO conversion in Plug flow reactor.

\[ T(C) = 275, P_0(l atm) = 7.8027, P_0m(l atm) = 1, ST \text{ sec} = 10, SR = 0.25, e = 0.93637 \]
FIG. 13

CO PPM in membrane along the Membrane Side

CO Weight Ratio

Dimensionless length

10^3
10^2
10^1
10^0

0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
FIG. 15

Unconverted CO in catalytic membrane reactor

Unconverted CO in plug flow reactor

Dimensionless length
FIG. 17

CO PPM in membrane along the Membrane Side

Uncovred CO

Dimensionless length

1

0.9

0.8

0.7

0.6

0.5

0.4

0.3

0.2

0.1
FIG. 18

$T(C) = 275, P_r(\text{atm}) = 7.8027, P_0(\text{atm}) = 1, S_T \text{ sec} = 10, S_R = 0.25, e = 0.93637$

- CO conversion in catalytic membrane reactor
- CO conversion in plug flow reactor

CO Conversion

Dimensionless length

Conversion

1 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1

1 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1
Unconverted CO in catalytic membrane reactor

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Unconverted CO in plug flow reactor

$T(C) = 275, P_0 = 6.8027, P_0 m(atm) = 1, ST \ sec = 10, SR = 0.25 x e = 0.93637$
FIG. 24

Hydrogen Recovery Percent

Hydrogen Recovery

Dimensionless length

100 90 80 70 60 50 40 30 20 10 0

0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
FIG. 29

CO PPM in membrane along the Membrane Side

Dimensionless length

$10^3$ $10^2$ $10^1$ $10^0$

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9

Ppm CO
Hydrogen Production via Steam Reforming with Membrane- and Adsorption-Enhanced Reactor at Low Temperature (350 to 400°C)

Figure 30
Figure 31

Figure 32a
Permeance vs. Temperature
Membrane ID: CMS - 136099

- <diamond> Hydrogen
- <square> Helium
- <triangle> Nitrogen

Permeance [m³/m²·bar·h]
Temperature [°C]

Figure 32b
FIG. 35
FIG. 37

Dimensionless Time

0.07 0.06 0.05 0.04 0.03 0.02 0.01 0.0

CO₂ Mol Fraction

HAMR - W/n=50
AR - W/n=50
HAMR - W/n=100
AR - W/n=100
HAMR - W/n=200
AR - W/n=200
HAMR - W/n=300
AR - W/n=300
FIG. 44

Dimensionless Time vs. Recovery for Various HAMR Conditions:
- HAMR - 0.33xΩ
- HAMR - 0.5xΩ
- HAMR - Ω
- HAMR - 2xΩ
FIG. 50

intercept = \ln(k_0) = 25.90
slope = -E = -114218.6
r^2 = 0.9866029922
FIG. 55

% Conversion

CH₄
Figure 56a Prior Art

**Base Case**: Conventional WGS and HT Adsorber

![Diagram of Base Case](image)

Figure 56b

**Case II**: Adsorption Enhanced WGS Reactor

![Diagram of Case II](image)
Figure 57a

Case II: Adsorption Enhanced WGS Membrane Reactor

Figure 57b

Case IIa: WGS Membrane Reactor with Intersstage CO₂ Adsorber
HYBRID ADSORPTIVE MEMBRANE REACTOR

RELATED APPLICATION

This application claims priority to U.S. Provisional Application Ser. No. 60/653,035, filed Feb. 14, 2005, the content of which is incorporated herein by reference in its entirety.

FUNDING

This invention was made with support in part by grants from the United States National Aeronautics and Space Administration (NASA) and Department of Energy (DOE) under cooperative agreement No. DE-FC26-00NT40922. Therefore, the U.S. government has certain rights.

FIELD OF THE INVENTION

The present invention relates generally to chemical reactors. More specifically, the invention relates to a hybrid adsorbent-membrane reactor (HAMR) and uses thereof.

BACKGROUND OF THE INVENTION

As a result of stricter environmental regulations worldwide, hydrogen is progressively becoming a very important clean energy source for both mobile and stationary applications. For hydrogen to replace fossil fuels as the fuel of choice for mobile applications, it requires the creation of a production and delivery infrastructure equivalent to those that currently exist for fossil fuels. As an alternative and an interim step toward the new hydrogen economy, various groups are currently investigating hydrocarbon steam reforming for onboard generation of hydrogen for use in fuel cell-powered vehicles, or for on-site production, in place of compressed or liquid hydrogen gas storage for stationary power generation and delivery infrastructure equivalent to those that currently exist for mobile applications. However, for mobile applications, it requires the creation of a production and delivery infrastructure equivalent to those that currently exist for fossil fuels.

MRs show substantial promise in this area and, typically, utilize nanoporous inorganic or metallic Pd or Pd alloy membranes (Sanchez and Tsotsis (2002) Catalytic Membranes and Membrane Reactors, Wiley-VCH, Weinheim, Germany). The latter are better suited for pure hydrogen production. However, metallic membranes are very expensive and become brittle during reactor operation (Nam et al. (2000) Korean J. Chem. Eng. 17:288) or deactivate in the presence of sulfur or coke. Nanoporous membranes are better suited for the steam reforming environment. They are difficult to manufacture, however, without cracks and pinholes and, as a result, often have inferior product yield. In addition, the hydrogen product in the permeate side contains substantial amounts of other byproducts, particularly CO₂, and may require further treatment for use in fuel cell-powered vehicles.

Adsortive reactors also show good potential (Xiu et al. (2004) Chem. Eng. Res. Des. 82:192). However, metallic membranes are very expensive and become brittle during reactor operation (Nam et al. (2000) Korean J. Chem. Eng. 17:288) or deactivate in the presence of sulfur or coke. Nanoporous membranes are better suited for the steam reforming environment. They are difficult to manufacture, however, without cracks and pinholes and, as a result, often have inferior product yield. In addition, the hydrogen product in the permeate side contains substantial amounts of other byproducts, particularly CO₂, and may require further treatment for use in fuel cell-powered vehicles.

Conventional steam reforming, particularly for methane (CH₄), has been studied extensively and practiced routinely in the industry using a packed bed catalytic reactor (PBR). A high reaction temperature is required (i.e., >800°C for CH₄) to deliver a sufficient reaction rate and to overcome the equilibrium conversion limitations. This introduces an unfavorable environment for the exothermic water-gas-shift (WGS) reaction step. As a result, significant CO is present in the final product, which requires further conversion to H₂ in a separate...
two-stage WGS reactor and additional post-treatment reactors (such as a partial oxidizer and a methanizer) to reduce the CO levels to meet the proton exchange membrane (PEM) feedstock specifications. This multiple-step reforming process adds significant process complexity, and is undesirable, particularly for small-scale distributed-type applications. MR technology (Sanchez-Marcano and Tsotsis (2002) Catalytic Membranes and Membrane Reactors, Wiley VCH), primarily Pd membrane-based, has been proposed to streamline the reforming process by, for instance, integrating the reforming and WGS reaction in a single step or via the use of a one-step WGS. However, this Pd membrane-based MR suffers the following disadvantages: potential coking on the Pd surface as a result of H\textsubscript{2} removal even at the lowest operating temperature, e.g., >450° C.; and only incremental, not dramatic increases in overall conversion resulting from bulk H\textsubscript{2} removal. Theoretically, a nearly 100% conversion can be achieved by completely removing the H\textsubscript{2} from the reactor side; however, the partial pressure of H\textsubscript{2} available for permeation is too low for this to be realized in practice. In the case of natural gas (NG), the reforming reaction is typically modeled as reforming of methane (by far its major component), which consists of the following two reactions: 

\begin{align*}
\text{CH}_4 + H_2O & \rightleftharpoons \text{CO} + 3H_2; \text{AH} = +206.2 \text{ kJ/mol} \\ 
\text{CO} + H_2O & \rightleftharpoons \text{CO}_2 + H_2; \text{AH} = -41.2 \text{ kJ/mol}
\end{align*}

Reaction (1') is endothermic and equilibrium limited, and is, therefore, practiced at higher temperatures (>800° C.). Unfortunately, the WGS reaction (2') is exothermic and is highly unfavorable at higher temperatures. This then necessitates the need for utilizing a separate reactor system for carrying out the WGS step at lower temperatures. The WGS reactor system is typically a dual-reactor system consisting of a high temperature reactor operating at [400–450° C.], followed by a low temperature reactor, which operates at <250–300° C. This, then, adds significant process complexity to the fuel processing section. Nevertheless, even with the separate WGS reactor being present, the product contains ~0.5–1% CO, substantially higher than what is permissible, for example, for PEM fuels cells. To make the use of such fuel cells possible (CO at the tens of ppm level is detrimental to performance) for power generation and mobile applications, an additional processing step for CO removal, typically a partial oxidation step (POX), is required, which further adds to the processing complexity and costs.

**SUMMARY OF THE INVENTION**

The invention is based upon the unexpected discovery that a novel hybrid adsorbent-membrane reactor requires less hostile operating conditions and provides enhanced product yield and purity.

Accordingly, in one aspect, the invention features a reactor comprising a chamber, an inlet for introducing one or more reactants into the chamber, a catalyst disposed in the chamber for facilitating a WGS reaction of the reactants to produce at least one desired product and at least one by-product, a membrane disposed in the chamber for selectively permitting the desired product and the by-product to pass through the membrane, an adsorbent disposed in the chamber for adsorbing the by-product, and an outlet for allowing the desired product to exit the chamber.

In another aspect, the invention features a reactor comprising a chamber, an inlet for introducing one or more reactants into the chamber, a catalyst disposed in the chamber for facilitating a steam reforming reaction of the reactants to produce at least one desired product and at least one by-product, a non-metallic membrane disposed in the chamber for selectively permitting the desired product and the by-product to pass through the membrane, an adsorbent disposed in the chamber for adsorbing the by-product, and an outlet for allowing the desired product to exit the chamber.

The invention further provides a reactor comprising a chamber, an inlet for introducing one or more reactants into the chamber, a catalyst disposed in the chamber for facilitating a steam reforming reaction of the reactants to produce at least one desired product and at least one by-product, a membrane disposed in the chamber for selectively permitting the desired product and the by-product to pass through the membrane, a hydrotalcite (HT) adsorbent disposed in the chamber for adsorbing the by-product, and an outlet for allowing the desired product to exit the chamber.

The invention also provides a reactor comprising a chamber, an inlet for introducing one or more reactants into the chamber, a catalyst disposed in the chamber for facilitating a steam reforming reaction of the reactants to produce at least one desired product and at least one by-product, a membrane disposed in the chamber for selectively permitting the desired product and the by-product to pass through the membrane, an adsorbent disposed in the chamber for adsorbing the by-product, and an outlet for allowing the desired product to exit the chamber. The invention also provides a reactor comprising a chamber, an inlet for introducing one or more reactants into the chamber, a catalyst disposed in the chamber for facilitating a steam reforming reaction of the reactants to produce at least one desired product and at least one by-product, a membrane disposed in the chamber for selectively permitting the desired product and the by-product to pass through the membrane, an adsorbent disposed in the chamber for adsorbing the by-product, and an outlet for allowing the desired product to exit the chamber.

Moreover, the invention provides a reactor comprising a chamber, an inlet for introducing one or more reactants into the chamber, a catalyst disposed in the chamber for facilitating a reaction of the reactants to produce at least one desired product and at least one by-product, a membrane disposed in the chamber for selectively permitting the desired product and the by-product to pass through the membrane, a hydrotalcite adsorbent disposed in the chamber for adsorbing the by-product, and an outlet for allowing the desired product to exit the chamber.

Also within the scope of the invention is a process comprising introducing one or more reactants into a reactor of the invention, contacting the catalyst with the reactants to facilitate a reaction of the reactants to produce at least one desired product and at least one by-product, selectively passing the desired product and the by-product through the membrane, adsorbing the by-product with the adsorbent, and withdrawing the desired product from the reactor.

In some embodiments, the invention provides an apparatus comprising at least two reactors of the invention. In particular, the invention features an apparatus comprising at least two reactors, each reactor including a chamber, an inlet for introducing one or more reactants into the chamber, a catalyst disposed in the chamber for facilitating a steam
reforming reaction of the reactants to produce at least one desired product and at least one by-product, a membrane disposed in the chamber for selectively permitting the desired product and the by-product to pass through the membrane, an adsorbent disposed in the chamber for adsorbing the by-product, and an outlet for allowing the desired product to exit the chamber.

Accordingly, the invention provides a process comprising introducing one or more reactants into each reactor of an apparatus of the invention, contacting the catalyst with the reactants to facilitate a reaction of the reactants to produce at least one desired product and at least one by-product in the reactor, selectively passing the desired product and the by-product through the membrane in the reactor, adsorbing the by-product with the adsorbent in the reactor, and withdrawing the desired product and the by-product from the reactor, wherein the reactors of the apparatus are offset in point of time such that, at all times, the desired product is being withdrawn from at least one of the reactors.

In a reactor of the invention, the reaction may be a WGS or steam reforming reaction, the membrane may be a CMS or silicon carbide membrane, and the adsorbent may be a hydrotalcite. A process of the invention may be carried out at 275-700°C.

The above-mentioned and other features of this invention and the manner of obtaining and using them will become more apparent, and will be best understood, by reference to the following description, taken in conjunction with the accompanying drawings. These drawings depict only typical embodiments of the invention and do not therefore limit its scope.

**BRIEF DESCRIPTION OF THE FIGURES**

**FIG. 1** is a schematic diagram of an HAMR. **FIG. 2** shows CO conversion vs. reactor length for HAMR vs. packed bed reactors. T=275° C., P,p=7.8027 atm, P,m=1 atm, Space Time (ST)=10 sec, Sweep Ratio (SR)=0.25, Equilibrium Conversion (Xe)=0.93637. **FIG. 3** shows unconverted CO vs. reactor length for HAMR vs. packed bed reactors. (Conditions same as in **FIG. 2**).

FIG. 4 shows hydrogen recovery (%) in HAMR. (Conditions same as in **FIG. 2**).

FIG. 5 shows permeate CO concentration (in ppm) in HAMR. (Conditions same as in **FIG. 2**).

FIG. 6 shows CO conversion vs. reactor length for HAMR vs. packed bed reactors. T=275° C., P,p=7.8027 atm, P,m=1 atm, ST=10 sec, SR=0.25, Xe=0.93637, H2 permeance=5x 10^-6 mole/(cm²·sec·atm), H2/CO=100, CO2/CO=1.

FIG. 7 shows unconverted CO vs. reactor length for HAMR vs. packed bed reactors. (Conditions same as in **FIG. 6**).

FIG. 8 shows hydrogen recovery (%) in HAMR. (Conditions same as in **FIG. 6**).

FIG. 9 shows permeate CO concentration (in ppm) in HAMR. (Conditions same as in **FIG. 6**).

FIG. 10 shows CO conversion vs. reactor length for HAMR vs. packed bed reactors. T=275° C., P,p=7.8027 atm, P,m=1 atm, ST=10 sec, SR=0.25, Xe=0.93637, H2 permeance=10x 10^-6 mole/(cm²·sec·atm), H2/CO=100, CO2/CO=1.

FIG. 11 shows unconverted CO vs. reactor length for HAMR vs. packed bed reactors. (Conditions same as in **FIG. 10**).

FIG. 12 shows hydrogen recovery (%) in HAMR. (Conditions same as in **FIG. 10**).

FIG. 13 shows permeate CO concentration (in ppm) in HAMR. (Conditions same as in **FIG. 10**).

FIG. 14 shows CO conversion vs. reactor length for HAMR vs. packed bed reactors. T=275°C, P,p=7.8027 atm, P,m=1 atm, ST=10 sec, SR=0.25, Xe=0.93637, H2 permeance=5x 10^-6 mole/(cm²·sec·atm), H2/CO=100, CO2/CO=10.

FIG. 15 shows unconverted CO vs. reactor length for HAMR vs. packed bed reactors. (Conditions same as in **FIG. 14**).

FIG. 16 shows hydrogen recovery (%) in HAMR. (Conditions same as in **FIG. 14**).

FIG. 17 shows permeate CO concentration (in ppm) in HAMR. (Conditions same as in **FIG. 14**).

FIG. 18 shows CO conversion vs. reactor length for HAMR vs. packed bed reactors. T=275°C, P,p=7.8027 atm, P,m=1 atm, ST=10 sec, SR=0.25, Xe=0.93637, H2 permeance=5x 10^-6 mole/(cm²·sec·atm), H2/CO=100, CO2/CO=10.

FIG. 19 shows unconverted CO vs. reactor length for HAMR vs. packed bed reactors. (Conditions same as in **FIG. 18**).

FIG. 20 shows hydrogen recovery (%) in HAMR. (Conditions same as in **FIG. 18**).

FIG. 21 shows permeate CO concentration (in ppm) in HAMR. (Conditions same as in **FIG. 18**).

FIG. 22 shows CO conversion vs. reactor length for HAMR vs. packed bed reactors. T=275°C, P,p=7.8027 atm, P,m=1 atm, ST=10 sec, SR=0.25, Xe=0.93637, H2 permeance=5x 10^-6 mole/(cm²·sec·atm), H2/CO=100, CO2/CO=100.

FIG. 23 shows unconverted CO vs. reactor length for HAMR vs. packed bed reactors. (Conditions same as in **FIG. 22**).

FIG. 24 shows hydrogen recovery (%) in HAMR. (Conditions same as in **FIG. 22**).

FIG. 25 shows permeate CO concentration (in ppm) in HAMR. (Conditions same as in **FIG. 22**).

FIG. 26 shows CO conversion vs. reactor length for HAMR vs. packed bed reactors. T=275°C, P,p=7.8027 atm, P,m=1 atm, ST=10 sec, SR=0.25, Xe=0.93637, H2 permeance=5x 10^-6 mole/(cm²·sec·atm), H2/CO=100, CO2/CO=100.

FIG. 27 shows unconverted CO vs. reactor length for HAMR vs. packed bed reactors. (Conditions same as in **FIG. 26**).

FIG. 28 shows hydrogen recovery (%) in HAMR. (Conditions same as in **FIG. 26**).

FIG. 29 shows permeate CO concentration (in ppm) in HAMR. (Conditions same as in **FIG. 26**).

FIG. 30 is a schematic diagram showing hydrogen production via steam reforming with membrane- and adsorption-enhanced reactor at low temperature (350-400°C).

**FIG. 31** shows a Media and Process Technology, Inc. (M&P) CMS membrane.

**FIG. 32a** shows temperature dependence of the permeance and selectivity of an M&P CMS membrane (targeting 50 to 250° C. applications).

**FIG. 32b** shows temperature dependence of the permeance of an M&P CMS membrane.

**FIG. 33** shows hydrothermal stability of a CMS membrane at 30 to 50 psig steam and 220° C.

**FIG. 34** shows resistance to poisoning of CMS membranes.

**FIG. 35** shows a schematic diagram of a HAMR system.

**FIG. 36** shows H2 yield for HAMR and AR systems for different W/CH4,o.

**FIG. 37** shows CO2 concentration (wet basis) profiles at the reactor outlet for AR and HAMR systems at different W/CH4,o.
The components of a reactor include: (a) a chamber, (b) an inlet for introducing one or more reactants into the chamber, (c) a catalyst disposed in the chamber for facilitating a reaction of the reactants to produce at least one desired product and at least one by-product, (d) a membrane disposed in the chamber for selectively permitting the desired product and the by-product to pass through the membrane, (e) an adsorbent disposed in the chamber for adsorbing the by-product, and (f) an outlet for allowing the desired product to exit the chamber. Conventional membrane reactors are well-known in the art. See, e.g., "Hydrogen Production from Methane Steam Reforming Assisted by Use of Membrane Reactor," Natural Gas Conversion, pp 509-515, Elsevier Science Publishers B. V., Amsterdam (1991). In contrast to the conventional membrane reactors, a reactor of the invention couples the chemical reaction and membrane separation with product adsorption. This reactor can be used for equilibrium- or selectivity-limited reactions such as esterification, WGS, steam reforming, and various dehydrogenation, dehydration, and condensation reactions. The reactants can be either liquids or gases, e.g., steam and methane, natural gas, or naphtha.

For example, the most common industrial process for the production of hydrogen involves steam reforming and WGS reactions. Steam reforming is the reaction between methane or naphtha (e.g., heptane) and steam to produce H\(_2\) (desired product) and CO (by-product). WGS is the reaction between CO and steam to produce H\(_2\) (desired product) and CO\(_2\) (by-product).

Any of the commonly used catalysts can be employed in a reactor of the invention. Examples of catalysts for steam reforming and WGS reactions include nickel-alumina, nickel-magnesium alumina, and the noble metal catalysts. A membrane of the invention preferably has high permeation rates and permselectivities towards reaction products. Examples of membranes for steam reforming and WGS reactions include CMS, silicon carbide, Pd and its alloys, aluminium nitride, and various dense, and other nanoporous membranes. In some embodiments, the product (desired product or by-product) permeance of such a membrane may be in the range of 1.153e-7 to 1.153e-5 mole/(cm\(^2\)·sec·atm), the permselectivity of desired product/reactant may be in the range of 10-200, and the permselectivity of desired product/by-product may be in the range of 10-200.

In some embodiments, the membrane may be attached to a supporting substrate as a top layer. The supporting substrate (e.g., a ceramic support) is mechanically strong, is stable under reaction conditions, and shows high permeation rates such that it does not limit the membrane throughput.

An adsorbent of the invention is used to sorb a by-product either by physical or chemical sorption and release the sorbed by-product under reduced partial pressure of the by-product. The adsorbent should be effectively non-catalytic and otherwise inert as to reactants and products as well as to any purge or pressurizing gases so as to avoid any significant occurrence of side reactions. An exemplary adsorbent for carbon dioxide is a hydrotalcite such as Al\(_2\)Mg\(_{25}\)CO\(_3\)(OH)\(_2\)(CO\(_2\))\(_{0.5}\). Other adsorbents include various activated aluminas and carbons, zeolites, CaO, various commercial dolomites, drierite, and other inorganic desiccant compounds.

In some embodiments, the catalyst is disposed in the feed side of the membrane, while the adsorbent is disposed in the permeate side of the membrane. The feed side of the membrane is where the reactants are fed and the permeate side of the membrane is the other side. In this case, a membrane highly selective for the product is preferred. For example, the permselectivity of product/reactant may be larger than 50.

In other embodiments, a mixture of the adsorbent and the catalyst is disposed in the feed side of the membrane.

In still other embodiments, while a mixture of the adsorbent and the catalyst is disposed in the feed side of the mem-
bran, an additional amount of the adsorbent is disposed in the permeate side of the membrane.

In yet other embodiments, the adsorbent is disposed in a separate compartment away from the catalyst and the membrane. See, for example, Case IIA in Example I below.

In some embodiments, the catalyst and adsorbent are preferably in granular form or pelletized so that they can be readily mixed and not tend to stratify during the operation. Such granules can be suspended in a porous matrix or in a free form. Other methods of securing the catalyst and adsorbent in fixed beds can be employed, provided they do not impede access of the reactants and products to the surfaces of these materials.

A process of the invention generally includes the steps of (a) introducing one or more reactants into a reactor of the invention, (b) contacting the catalyst with the reactants to facilitate a reaction of the reactants to produce at least one desired product and at least one by-product, (c) selectively passing the desired product and the by-product through the membrane, (d) adsorbing the by-product with the adsorbent, and (e) withdrawing the desired product from the reactor.

Preferably, a process of the invention is carried out at 75-750°C, e.g., 75-95, 110-175, 150-200, 200-300, 250-325, 350-500, 500-650, or 650-750°C. In some embodiments, the pressure of the reactants is in the range of 0-2,500 psig, e.g., 0-20, 20-100, 100-250, 250-500, 500-1,000, or 1,000-2,500 psig upon entering into the reactor.

The preferred molar ratio of reactants upon entering into a reactor may vary according to the type of the reaction. For example, for a steam-methane reforming reaction, the molar ratio of H₂O:CH₄ upon entering into a reactor is preferably in the range of 2-5. For a steam-naphtha (heptane) reforming reaction, the molar ratio of H₂O:CH₃C₆H₁₄ upon entering into a reactor is preferably in the range of 7-14. For a WGS reaction, the molar ratio of H₂O:CO upon entering into a reactor is preferably in the range of 1-4.

In some embodiments, an apparatus of the invention contains at least two reactors of the invention. In operation of such an apparatus, each reactor is used as described above, and the reactors are offset in point of time such that, at all times, a desired product is being withdrawn from at least one of the reactors.

As used herein, a range of X-Y includes X, Y, and any number between X and Y.

The following examples are intended to illustrate, but not to limit, the scope of the invention. While such examples are typical of those that might be used, other procedures known to those skilled in the art may alternatively be utilized. Indeed, those of ordinary skill in the art can readily envision and produce further embodiments, based on the teachings herein, without undue experimentation.

Example 1

CO₂ Selective Ceramic Membrane for Water-Gas-Shift Reaction with Concomitant Recovery of CO₂

Two process schemes were investigated for the use of hydrotalcites as CO₂ adsorbents to enhance WGS reaction: Case I (FIG. 56a) involved the adsorption-enhanced WGS packed bed reactor (AR) and Case II (FIG. 57a) involved the adsorption-enhanced WGS membrane reactor (HAMR). They are presented here along with Base Case (FIG. 56a) (WGS Packed Bed Reactor in conjunction with CO₂ removal via pressure swing adsorption (PSA)). Both cases were to improve the WGS reactor efficiency via the concomitant removal of CO₂ for sequestration. The AR system has been discussed in the literature (see, e.g., Waldron et al. (2001) AIChE J. 47:1477 and Hufon et al. (1999) AIChE J. 45:248).

The HAMR system included a packed bed catalytic membrane reactor (hydrogen selective) coupling the WGS reaction (in a porous hydrogen selective membrane) with CO₂ removal with an adsorbent in the permeate side. The reactor characteristics were investigated for a range of permeance and selectivity relevant to the aforementioned application. The HAMR system showed enhanced CO conversion, hydrogen yield, and product purity, and provided good promise for reducing the hostile operating conditions of conventional WGS reactors, and for meeting the CO₂ sequestration objective.

In Base Case, the hydrotalcite adsorber was used as a 2nd stage separator for the removal of CO₂ for sequestration. As a conventional adsorber, it did not involve in the WGS reaction. Case I involved the use of the hydrotalcite adsorber mixed with the WGS catalyst in a packed bed; thus, the reaction product CO₂ could be removed in situ to enhance the WGS reaction. Since the adsorbent was used in the process, multiple beds with switching bed operation were usually required to reach a steady state production of hydrogen. Case II integrated a hydrogen and CO₂ selective membrane (used as a WGS membrane reactor) which was packed with hydrotalcite for CO₂ removal in the permeate side. Thus, both reaction products, i.e., hydrogen and CO₂, could be removed via the membrane. In addition to the removal of CO₂, the hydrotalcite adsorption in the permeate side could enhance the CO₂ permeance in order to produce a high purity hydrogen product stream efficiently. Again, the use of adsorbent mandated switching bed type operation as in Case I. Case IIA (FIG. 57b) was also proposed as a modifier of Case II. Instead of using a hybrid single stage reactor, Case IIA employed an interstage hydrotalcite adsorber as a separator. Although the process scheme required an additional stage, the adsorber could be operated independent of the WGS reactor.

The carbon molecular hydrogen selective membrane (available from M&P) demonstrated its efficacy for this purpose. Such membrane can be tailored with a high hydrogen selectivity (i.e., K(H₂/CO₂)=10) or a balanced selectivity with K(H₂/CO₂)=10. For Case II, a compromised membrane is recommended, while for Case IIA, a highly hydrogen selective membrane is preferred. Other alternative membranes can be considered here. For instance, a CO₂ selective hydrotalcite membrane has the advantage of high selectivity of the dense membrane made with non-metallic materials. Hydrotalcite, a well-known CO₂ affinity adsorbent, was used in the simulation as an example.

The simulation of both Case I and II for comparison with Base Case would offer the preferred performance of the hydrotalcite adsorbent and its operating condition for each case. Further, its operating economic analysis would define the performance requirement of the hydrotalcite adsorbent.

A HAMR system involving a hybrid-type packed bed catalytic membrane reactor coupling the WGS reaction through a porous carbon membrane with a CO₂ adsorption system was investigated. This HAMR system showed behavior more advantageous than either the membrane or the conventional reactors in terms of the attained yields and selectivities. In addition, the HAMR system allowed potentially for significantly greater process flexibility than either the membrane or the adsorptive reactor system. The membrane, for example, could be used to separate the catalyst from the adsorbent phases, thus allowing for in situ continuous regeneration of the adsorbent. This would offer a significant advantage over the adsorptive reactors which are, by definition, discontinu-
uous systems and require the presence of multiple beds (one being in operation while the other being regenerated) to simulate continuous operation. The HAMR system showed, furthermore, significant potential advantages with respect to the conventional MR system. Beyond the improved yields and selectivities, the HAMR system had the potential for producing a fuel cell grade hydrogen product without CO2, which is of significance for the hydrogen production from coal gasification.

Theory
A mathematical model for Case II, i.e., HAMR system, is presented and analyzed, for a range of temperature and pressure conditions without any intention to be bound by such theory. The behavior of the HAMR system is compared with Base Case, i.e., conventional packed bed reactor. The feed into the WGS HAMR reactor is the exit stream from a conventional steam reformer.

Kinetics for WGS Reaction
For the WGS reaction, a catalytic reaction rate first proposed by Ovesen et al. (1996) J. Catal. 158:170 is utilized as follows:

\[ CO + H_2O = CO_2 + H_2 \quad (1) \]

\[ r = \frac{\alpha_o}{\alpha_o + \alpha_i} \frac{1}{\alpha_i} n_{CO} n_{H_2O} \quad (2) \]

\[ \beta = \frac{1}{\alpha_o} \frac{n_{CO}}{n_{CO} + n_{H_2O}} \quad (3) \]

\[ \phi = \phi_o \quad (4) \]

The Mathematical Model of the HAMR System
A schematic of the HAMR system is shown in Fig. 1. In this figure, the catalyst is packed in the interior of the membrane (signified by the superscript F, for feed side), while the adsorbent is packed in the exterior membrane volume (signified by the superscript P, for permeate side). There are, of course, a number of other potential reactor configurations. For example, the adsorbent and catalyst can be loaded together in the internal membrane space, while the adsorbent may also be loaded in the external membrane space. Or the catalyst and adsorbent may only be loaded in the internal membrane space. To simplify matters, in the development of the model, it is assumed that external mass transfer resistances are negligible for the transport through the membrane, as well as for the reaction steps, and that internal diffusion limitations for the catalyst, and internal or external transport limitations for the adsorbent are accounted for by overall rate coefficients. Also, plug-flow conditions are assumed to prevail for both the interior and exterior membrane volumes, as well as ideal gas law conditions. The HAMR system is assumed, furthermore, to operate under quasi-steady conditions with reaction/transport processes in the catalyst and transport properties through the membrane relaxing much faster than the slow changes in the adsorbent state due to saturation.

It is assumed further that the reactor utilizes a porous, inactive CMS membrane, and that transport through the membrane is Fickian. Here, mass transfer through the porous membrane is described through the following equation:

\[ F_j = \frac{U_j n_j + P_j ^F}{R_j} \quad (5) \]

where \( F_j \) is the molar flux (mol/m²-s), \( P_j ^F \) partial pressure of component j on the membrane feed-side (bar), \( U_j \) the membrane permeance for component j (mol/m²-bar-s). To simplify calculations in this preliminary "proof of concept" phase, it is assumed that \( U_j \) depends only on the membrane properties, like the thickness and the pore characteristics of the membrane layer. For CMS membranes, \( U_j \), in addition, depends both on the upstream and downstream pressures. For the reactor calculations here, however, it is taken to be pressure-independent.

The mass balance on the feed side of the reactor packed with WGS catalyst and, potentially, with an adsorbent is described by the following equation for CO, H2, H2O, and an inert species (potentially used as a sweep gas or a blanketing agent—for the WGS reaction, a practical sweep gas would be either steam or hydrogen, however):

\[ \frac{dn_j}{dt} = -\alpha_o U_j (P_j^F - P_j^P) + \left(1 - e^F\right) \phi_j \frac{R_j}{R_F} U_j \quad (6) \]

where \( n_j \) is the molar flow rate for species j (mol/s), \( V \) the feed-side reactor volume variable (m³), \( \alpha_o \) the membrane area per feed side reactor volume (m²/m³), \( e^F \) the feed side bed porosity, \( \beta \) the fraction of the solid volume occupied by catalysts (\( \beta = 1 \), when no adsorbent is present—then, Eqn. 5 is also valid for \( CO \)), \( p_\alpha \) the catalyst density (Kg/m³), and \( R_j \) the reaction rate expression, which is either described by Eqn. 1 above (mol/Kg/s), or is equal to zero if j is an inert species.

For CO2, when adsorbent is present, the following equation applies:

\[ \frac{dn_{CO_2}}{dt} = -\alpha_o U_j (P_{CO_2} - P_{CO_2}^P) + \left(1 - e^F\right) \phi_j \frac{R_{CO_2}}{R_F} U_j \frac{G_{CO_2}}{1 - \beta} \quad (7) \]

where \( p_{CO_2} \) is the adsorbent density (Kg/m³), and \( G_{CO_2} \) is the rate of CO2 adsorption (mol/Kg/s). One finds a number of approaches in the literature for describing \( G_{CO_2} \). Ideally, both external and internal mass transport as well as finite rates of adsorption would be explicitly accounted for. Traditionally, in the modeling of adsorptive reactors, simpler models have been utilized, instead (Ding and Alpay (2000) Chem. Eng. Sci. 55:3929 and Ding and Alpay (2000) Chem. Eng. Sci. 55:346). Two such models have received the most attention. They are: (i) the model based on the assumption of instantaneous local adsorption equilibrium (ILE) between the gas and the adsorbent phases (Ding and Alpay (2000) Chem. Eng. Sci. 55:3929, Ding and Alpay (2000) Chem. Eng. Sci. 55:346), and Park and Tsotsis (2004) System. Chem. Eng. Proc. 43:1171), and the linear driving force models (LDF), according to which (Karger and Ruthven (1992) Diffusion in zeolites and other microporous solids, New York, Wiley), \( G_{CO_2} \) is described by the following expression:

\[ G_{CO_2} = k_0 (C_{eq} - C_j) \quad (8) \]

where \( C_{eq} \) is the adsorption equilibrium CO2 concentration on the adsorbent (mol/Kg), \( C_j \) is the existing adsorbed CO2 concentration (mol/Kg), and \( k_0 \) (s⁻¹) is a parameter which "lumps" together the effects of external and intraparticle mass transport and the sorption processes, and which, as a result, is often a strong function of temperature and pressure (Ding and Alpay (2000) Chem. Eng. Sci. 55:3929 and Ding and Alpay (2000) Chem. Eng. Sci. 55:346)—although, typically, in modeling, is taken as temperature/pressure-independent. For
calculating $C_{eq}$ for CO$_2$ adsorption on a potassium-promoted hydrotalcite (LDH), it has been shown (Ding and Alpay 2000 Chem. Eng. Sci. 55:3929 and Ding and Alpay (2000) Chem. Eng. Sci. 55:346) that this adsorbent follows a Langmuir adsorption isotherm both under dry and wet conditions, described by the following equation:

$$C_{eq} = \frac{m_{CO_2} \cdot b_{CO_2} \cdot P_{CO_2}}{1 + b_{CO_2} \cdot P_{CO_2}}$$  \hspace{1cm} (8)

where $m_{CO_2}$ (mol/Kg) is the total adsorbent capacity, and $b_{CO_2}$ (bar$^{-1}$) the adsorption equilibrium constant described in the van’t Hoff equation:

$$b_{CO_2} = b_{CO_2}(T_o) \exp\left(\frac{-A_{Ha}}{RT_o}\right)$$  \hspace{1cm} (9)


Eqns. 5 and 6 are complemented by the initial conditions:

$$V=0; \quad n_j(0) = n_j^0$$
$$P(P_0) = P_0$$

where $F_{op}$ is the volumetric flow rate at the inlet of the reactor feed-side (m$^3$/s), $x_j$, the inlet mole fraction for species $j$, and $P_0$ the inlet total pressure on the feed-side (bar).

Pressure drop in a packed bed can be calculated using the Ergun equation:

$$\frac{dP}{dV} = 10 \times 10^{-7} \frac{f^p(G_p^2)^{1.5}}{d_P \mu_F \rho_F}$$  \hspace{1cm} (11a)

where $f^p$ is the pressure drop in feed side (bar), $\mu_F$ the viscosity in feed side (poise), $d_P$ the particle diameter in feed side (cm), $G_p$ the superficial mass velocity in feed side (gr/(cm$^2$•sec)), $Z$ the reactor length (cm), and $\rho_F$ the fluid density in feed side (gr/cm$^3$).

By dividing both sides of the Ergun equation by the cross-sectional area ($A^f$) of the reactor feed side, the pressure drop per unit volume of the reactor can be expressed as:

$$\frac{dP}{dV} = 10 \times 10^{-7} \frac{f^p(G_p^2)^{1.5}}{A^f d_P \mu_F \rho_F}$$  \hspace{1cm} (12a)

at $V = 0, \quad f^p = F_0^p$

For the permeate side, the equation for CO, H$_2$, H$_2$O, and the inert (if utilized) is as follows:

$$\frac{dn_j^p}{dV} = a_n U_j (P_j^p - P_j^p)$$  \hspace{1cm} (13)

For CO$_2$ on the permeate side, when adsorbent is present, the equation is:

$$\frac{dn_{CO_2}^p}{dV} = a_n U_{CO_2} (P_{CO_2}^p - P_{CO_2}^p)$$  \hspace{1cm} (14)

where $\epsilon^p$ is the permeate side bed porosity (when $\epsilon^p$=1 no adsorbent is present and 14 reduces to Eqn. 13) and $y$ the ratio of the cross-sectional area on the permeate side to cross-sectional area on the feed side.

The reactor conversion (based on CO, typically the limiting reagent) is defined by the following equation:

$$X_{CO} = \frac{n_{CO,ex}^p + n_{CO,ex}^p}{n_{CO,po}}$$  \hspace{1cm} (17)

where $n_{CO,ex}^p$ and $n_{CO,ex}^p$ are the CO molar flow rates at the exit of the reactor feed and permeate-sides correspondingly (mol/s). The product hydrogen yield is defined by the following equation:

$$Y_{H_2} = \frac{n_{H_2,ex}^p + n_{H_2,ex}^p}{n_{CO}}$$  \hspace{1cm} (18)

where $n_{H_2,ex}^p$ and $n_{H_2,ex}^p$ are the hydrogen molar flow rates at the exit of the reactor feed and permeate-sides correspondingly (mol/s). In the HAMR simulations, the hydrogen recovery ratio is also calculated. The hydrogen recovery ratio is defined as the fraction of product hydrogen that is recovered in the membrane permeate side and the amount of CO impurity (in ppm) that the permeate hydrogen stream contains.
The exit from the steam reformer was assumed to be at equi-
librium and was used intact (without any water make-up) as
the feed to the WGS reactors. The conditions in the WGS
reactors were as follows:
\[ T = 275^\circ \text{C}. \]
\[ P = 100 \text{ psig}. \]
The membrane was hydrogen selective and the ideal separa-
tion factors (ratios of individual permeances) were assumed
as follows:
\[ \frac{(H_2/CO)}{(H_2/CO)} = \frac{(H_2/H_2O)}{(H_2/CH_4)} = 100:1 \]
The effect of permeance was first investigated. FIGS. 2-5
are for the case where the hydrogen permeance was equal to
1x10^{-6} mole/(cm^2·sec·atm). For FIGS. 6-9, the hydrogen
permeance was taken equal to 5x10^{-6} mole/(cm^2·sec·atm).
FIGS. 10-13 are for a hydrogen permeance of 10x10^{-6} mole/
(cm^2·sec·atm).

It is obvious from FIGS. 2-13 that the HAMR system
clearly outperformed the conventional WGS reactor. The
membrane permeance had a very significant effect on reactor
performance. Very desirable hydrogen recoveries and CO
contaminant levels were attained for the higher permeances.
In terms of the overall performance, the above results point
out that there is an optimal value of permeance that provides
a good performance in terms of yield and hydrogen recovery
without unduly impacting the CO contaminant levels in the
hydrogen product. It should be noted that the above values of
permeances and separation factors were attained with CMS
membranes available from M&P.

It should be noted that the CO contaminant levels in the
hydrogen product can be further reduced by improving the
membrane CO separation characteristics. FIGS. 14-17 are
from a simulation run with a hydrogen membrane permeance
of 5x10^{-6} mole/(cm^2·sec·atm) and the following separation
characteristics:
\[ \frac{(H_2/CO)}{(H_2/CO)} = \frac{(H_2/H_2O)}{(H_2/CH_4)} = 100:1 \]
\[ (H_2/CO) = 10^{-6} \text{ mole/(cm}^2\text{·sec·atm}) \]
For the next set of runs, the effect of the membrane’s
separation characteristics were investigated. The other condi-
tions remained the same and the permeance was taken equal
to 5x10^{-6} mole/(cm^2·sec·atm). For FIGS. 18-21, the
membrane was assumed to exhibit the following separation
factors:
\[ \frac{(H_2/CO)}{(H_2/CO)} = \frac{(H_2/H_2O)}{(H_2/CH_4)} = 100:1 \]
\[ (H_2/CO) = 10^{-5} \text{ mole/(cm}^2\text{·sec·atm}) \]
For FIGS. 22-25, the membrane was assumed to exhibit the
following separation factors:
\[ \frac{(H_2/CO)}{(H_2/CO)} = \frac{(H_2/H_2O)}{(H_2/CH_4)} = 100:1 \]
\[ (H_2/CO) = 10^{-5} \text{ mole/(cm}^2\text{·sec·atm}) \]
From FIGS. 26-29, the membrane was assumed to exhibit the
following separation factors:
\[ \frac{(H_2/CO)}{(H_2/CO)} = \frac{(H_2/H_2O)}{(H_2/CH_4)} = 100:1 \]
\[ (H_2/CO) = 10^{-5} \text{ mole/(cm}^2\text{·sec·atm}) \]

From FIGS. 18-29, it is noted that the separation character-
istics had a significant effect on reactor performance. As the
CO₂/H₂ permeance ratio decreased, hydrogen yield, recovery,
and purity all improved.

The HAMR combines the reaction and membrane separa-
tion steps with adsorption on the membrane permeate sides
using the hydrotalcite material. This HAMR system is of
potential interest to pure hydrogen production for hydrogen
production from coal gasification off-gas. The reactor per-
formance was investigated for a range of membrane character-
istics and compared with the behavior of the traditional
packed bed reactor. The HAMR outperformed the conven-
tional reactor system. It showed enhanced CO conversion,
hydrogen yield, and product purity, and provided good prom-
ise for meeting the product purity requirements for PEM
operation.

Example II

A High Efficiency, Low Temperature Reformer for
Hydrogen Production

Description of the Technology

The technology involves the use of a high-efficiency, low-
temperature reactor for steam reforming. With this reactor
system, H₂ production can be operated at 350 to 400° C., as
opposed to >800° C. The essence of the process is the employ-
ment of a unique membrane- and adsorption-enhanced reformer, which can preferentially allow H₂ permeation and
CO₂ adsorption simultaneously, the two ultimate reaction
products from steam reforming. Thus, the reformer can pro-
duce a H₂ product continuously until the adsorbent is satu-
rated for regeneration via PSA. This unique reactor configu-
ration can be viewed as a simplified MR under PSA operation,
suitable for a scaled-down version of the steam reforming
process. MR technology and sorption-enhanced PSA pro-
posed in the literature allow only one of the reaction products,
such as H₂ or CO₂, to be removed; the reaction rate enhance-
ment that results is not sufficient, however, to achieve signifi-
cant reforming at such low temperatures.

The membrane utilized is a CMS nanoporous membrane
originally developed by USC and currently offered commer-
cially by M&P for lab and field-testing. Its unique H₂ perm-
selectivity at the proposed temperature is ideal for this appli-
cation. (As noted above, Pd membranes are also known for
their unique H₂ permeaselectivity; however, several barriers
related to material stability remain to be overcome. Moreover,
their viable operating temperature range is incompatible with
the proposed temperature range for reactor operation). The
adsorbent selected is a hydrotalcite-based adsorbent, which
has been intensively studied (Yang et al. (2002) Chem. Eng.
43:4559); its CO₂ affinity at this operating condition has also
been well-documented in the literature (see Yang et al. (2002)
Chem. Eng. Sci. 57:2945 for additional references). A math-
ematical model has been developed and a numerical simu-
lation has been performed to support the technical feasibility of
the process. FIG. 30 shows a schematic of the process
together with the results of process design calculations using
this model. Combining the adsorbent with the reforming cata-
lyst in a packed bed MR utilizing the CMS membranes results
in hydrocarbon conversion four times higher than the ther-
modynamic equilibrium conversion level; thus, efficient
reforming can be accomplished at this low temperature range.
The reformed product is low in CO (e.g., <10 ppm), and is,
therefore, ready as a feedstock for fuel cell applications. The
product, if desired, can be further enriched by processing it in
a down-stream H₂ separator (see process scheme in FIG. 30).

The Advantages

Existing processes for hydrogen production are (i)
extrremely energy-intensive due to the requirement of steam
(as a reactant) supply at this high temperature, and the need
for providing the energy for the endothermic reforming reac-

In comparison with the conventional reforming process, the proposed process is ultra-compact, offering the following advantages:

1. No WGS reactor is required.
2. No post-treatment for CO clean-up is necessary. The CO level is expected to meet the specifications with the low temperature reformer and the in situ removal of H₂ and CO₂.
3. All heating and cooling requirements involve the temperature range of up to 400° C. vs. >800° C. of existing reforming.
4. The process is ultra-compact, offering two simplified MR for PSA operation, one heat exchanger, and one steam generator/boiler. Further down-stream H₂ enrichment, if desired, can be achieved by a simplified treatment-train comprising one membrane separator and one compressor.

HAMR is also fuel-flexible. Using the mathematical model, its application to the case of liquid hydrocarbon fuels such as naphtha has been simulated. According to Darwish et al. (2004) Fuel 83:409), naphtha can be represented as C₇H₁₆, where m = 7.3 and n = 15.5. In the simulations presented here, naphtha is represented as a heptane molecule; other authors in their reactor simulations of naphtha reforming (Chen et al. (2003) AIChE J. 49:1250, Chen et al. (2003) Ind. Eng. Chem. Res. 42:6549, and Chen et al. (2004) Ind. Eng. Chem. Res. 43:1323) have also used heptane as a model compound to represent naphtha. For such a fuel, in addition to reactions (1') and (2') above, the following reaction also takes place:

\[
C_7H_{16} + 7H_2O \leftrightarrow 7CO + 15H_2; \Delta H = 1108 \text{ kJ/mol}
\]

(3)

The reforming temperature for liquid hydrocarbons is lower, i.e., ~600° C, and no thermodynamic equilibrium conversion limitation exists in this temperature range according to the literature (Darwish et al. (2004) Fuel 83:409). Unfortunately, the methanation reaction (the reverse of the reforming reaction (1')) above) becomes significant and results in the formation of CH₄ in addition to significant unconverted CO. In the proposed dual-enhanced process, the removal of H₂ as a product in conjunction with the adsorption of CO₂ in situ can aggressively promote the conversion of the CO to H₂ via the WGS reaction (2') above; thus, the methanation reaction is kept at a minimum, while the CO contaminant in the final product is extremely low. The simulations (see Table 1' with HAMR using M&P CMS membranes at temperatures from 300-400° C. indicate that the heptane steam reforming benefits significantly from being carried out in such a reactor. As noted in Table 1', the H₂ yield in the proposed reactor system (defined as the mol of H₂ produced per mol of heptane fed) is many times higher than the corresponding yield of a PBR containing the same amount of catalyst and operating with the same feed as the HAMR system. For a range of operating conditions, the H₂ product contains only a minor amount of CH₄ (~3%) and very little CO (<10 ppm), which makes it usable in a fuel cell without further treatment. More importantly, the CO₂ is concentrated in the reject stream and is, therefore, ready for sequestration.

In the simulations, the naphtha reforming reaction was taken to be irreversible. This is the assumption also made in prior studies (Chen et al. (2003) AIChE J. 49:1250, Chen et al. (2003) Ind. Eng. Chem. Res. 42:6549, and Chen et al. (2004) Ind. Eng. Chem. Res. 43:1323) under similar pressure and temperature conditions. The primary effect of H₂ removal through the CMS membrane is through its influence on the reaction rate. The reaction rate for heptane reforming has a non-monotonic dependence on H₂ partial pressure (Tottrup (1982) Appl. Catal. 4:377), i.e.; there is a certain value of H₂ partial pressure that maximizes the rate. Removing H₂ from the reactor through the membranes has the effect in that it maintains the H₂ pressure everywhere in the reactor at or near this optimum level, thus favorably impacting the rate of H₂ production. In fact, the thermodynamic simulations indicate that equilibrium limitations arise for temperatures less than 400° C. (although in the reactor simulations, this has not been taken into consideration, since the published rate data do not account for such effects). Under such conditions, additional beneficial effects from the HAMR system are expected, since removing the H₂ tends to shift the reaction equilibrium towards the product side. It is the synergy between adsorbent and membrane that makes it possible to attain CO levels in the H₂ product <10 ppm. The ability to attain very high H₂ yields at low temperatures (<400° C) vs. the significantly higher temperatures normally practiced in conventional reformers has two additional advantages. One such advantage involves lowering the rate of coke production, and, the potential for catalyst deactivation. The other relates to energy savings (since the feed mixture needs to be heated to a lower temperature), and potentially to the ability to utilize waste heat that may be available in the flue-gas/exhaust of the power producing devices (fuel cells, internal combustion engines, turbines, etc.).

### Novel CMS Membranes

CMS membranes represent a “next generation” membrane material, because they vastly improve on the limits of the selectivity vs. permeability relationship set by the polymeric membranes for gas separations. However, in the past, these membranes have been limited purely to an academic novelty.

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**Table 1'**

<table>
<thead>
<tr>
<th>Reactor Type</th>
<th>Reactor Pressure (atm)</th>
<th>Yield (mol of Hz produced per mole heptane feed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Packed CO</td>
<td>0.30</td>
<td>0.29</td>
</tr>
<tr>
<td>Bed CO₂</td>
<td>22.23</td>
<td>21.61</td>
</tr>
<tr>
<td>Re却or H₂</td>
<td>35.11</td>
<td>19.31</td>
</tr>
<tr>
<td>N₂</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>CH₄</td>
<td>42.37</td>
<td>58.79</td>
</tr>
<tr>
<td>C₂H₁₀</td>
<td>0.00</td>
<td>1.73E-45</td>
</tr>
<tr>
<td>C₂H₁₆</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Proposed CO</td>
<td>2.91E-04</td>
<td>6.91E-04</td>
</tr>
<tr>
<td>Re却or CO₂</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>H₂</td>
<td>98.18</td>
<td>96.07</td>
</tr>
<tr>
<td>N₂</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>CH₄</td>
<td>2.81</td>
<td>3.93</td>
</tr>
<tr>
<td>C₂H₁₀</td>
<td>3.65E-04</td>
<td>3.96E-04</td>
</tr>
<tr>
<td>C₂H₁₆</td>
<td>0.39</td>
<td>0.79</td>
</tr>
</tbody>
</table>

**Table 2**

<table>
<thead>
<tr>
<th>Reactor</th>
<th>Composition (%)</th>
<th>Type</th>
<th>Reactor Pressure (atm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Packed H₂</td>
<td>3.79</td>
<td>2</td>
<td>3.17</td>
</tr>
<tr>
<td>Bed CH₄</td>
<td>4.57</td>
<td>3</td>
<td>4.73</td>
</tr>
<tr>
<td>Proposed H₂</td>
<td>20.55</td>
<td>4</td>
<td>18.94</td>
</tr>
<tr>
<td>Re却or CH₄</td>
<td>0.39</td>
<td>5</td>
<td>0.79</td>
</tr>
</tbody>
</table>

Theoretical max. for H₂ yield is 22, i.e., 22 mol H₂ produced per mole heptane fed.

Theoretical max. for CH₄ yield is 7, i.e., 7 mol CH₄ produced per mole heptane fed.
for three primary reasons, specifically: (i) they suffer several process-related problems including membrane performance deterioration due to temporary and/or permanent poisoning by organics and other impurities, (ii) they are very fragile, when unsupported (as hollow fiber/tubular products), and (iii) they can be very costly given the high performance polymers generally required as precursors. M&P recently developed a commercially viable CMS membrane based upon the R&D work by USC. To do so required innovative solutions to the above application-related barriers. To overcome the fragility and cost problems, the M&P CMS membrane consists of an ultrathin (0.5 to 3 µm thick) CMS layer supported on M&P high performance, high-strength hollow-fiber ceramic membranes (see FIG. 31). In the design, the tube spacing can be arbitrarily selected to maintain the flexibility of the reactor design, if the catalyst is packed in the shell side. For applications >300°C in the presence of steam, graphite seals with ceramic-glass potting ends are utilized. Membrane H₂ permeances ranging from 0.8 to >5 m³/m²/hr/bar (27 to 168 scfh/ft²) have been demonstrated. Selectivities for H₂ to N₂ are 25 to >100 even at temperatures up to 400°C. Nitrogen is used here to represent gas components rejected by this CMS membrane, including CO₂ and CO and light hydrocarbons. Water, as H₂O, is permeable through the membrane. A typical permeance vs. temperature for H₂ and N₂ is presented in FIGS. 32a and 32b as well as Table 2. The H₂ permeance increase is consistent with activated diffusion via molecular sieving. The maximum in selectivity is due to the N₂ permeance, which at low temperatures displays Knudsen type diffusivity (i.e., decreases with temperature) but at higher temperatures becomes activated as molecular sieving begins to dominate (about 150-400°C for this membrane). As is well-known, carbon, particularly microporous carbon, reacts with steam at sufficiently high temperatures. Although 180 to 400°C is generally considered low for carbon steam gasification, long-term thermal and hydrothermal stability testing has been conducted to demonstrate the CMS/C membrane suitability for the proposed reaction environment. FIG. 33 shows the H₂ permeance and H₂/N₂ selectivity of one of the membranes in a hydrothermal stability test conducted at 220°C in a 25-day test run (other tests indicate similar hydrothermal stability at 350°C). The test result demonstrates the hydrothermal stability of the CMS membrane. In addition, although porous carbon poisoning by organic vapors is well-known, it can be prevented by operation at high temperatures, e.g., >200°C, as shown in FIG. 34. Thus far, no other membrane has offered a similar functional performance in this intermediate temperature range (180-400°C). This temperature range is too high for even the most advanced polymer-based membranes. As for inorganic membranes (e.g., silica, zeolite, and others), operating temperatures >>300°C are required to achieve appreciable (economic) permeances. The cost of the CMS membranes is $800/m² (≤$80/ft²), which is significantly lower than the cost of competing (e.g., Pd) membranes.

### Table 2 - continued

<table>
<thead>
<tr>
<th>Part ID</th>
<th>Temperature [°C]</th>
<th>H₂ Permeances [m³/m²/hr/bar]</th>
<th>α-H₂/N₂</th>
<th>α-H₂/CO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>DZ-143856</td>
<td>170</td>
<td>2.41</td>
<td>94</td>
<td>14</td>
</tr>
<tr>
<td>DZ-148020</td>
<td>220</td>
<td>1.1</td>
<td>85</td>
<td></td>
</tr>
<tr>
<td>DZ-148834</td>
<td>220</td>
<td>1.1</td>
<td>85</td>
<td></td>
</tr>
<tr>
<td>DZ-193454</td>
<td>35</td>
<td>19.2</td>
<td>1.2</td>
<td>0.75</td>
</tr>
<tr>
<td>Other Membranes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Adsorbent

In some embodiments, the HAMR system utilizes LDH adsorbents, which have emerged as standard CO₂ adsorbents for high temperature applications, i.e., up to ~400°C. Although many different compositions of LDH can be formulated, one example is Al₉₀Mg₀₂(OH)₂(OH)₁₅. According to the literature and prior studies (Yang et al. (2002) Chem. Eng. Sci. 57:2945 and Kim et al. (2004) Ind. Eng. Chem. Res. 43:4559), about 1.5 to 2.0 wt% CO₂ can be adsorbed with this type of adsorbent at the proposed temperature. Preliminary simulations indicate that this existing hydroxide adsorbent is adequate for application in the HAMR system.

### Design Simulations

The performance of the HAMR system depends upon many system/intrinsic and operating parameters. Key system/intrinsic parameters include catalyst reaction rate, H₂ permeation rate, adsorption capacity vs. pressure, catalyst and adsorbent volumes, and their relative ratio. The operating variables include temperature and pressure of the reactor, contact time, and membrane (steam) purge rate. The mathematical model based upon the existing system and intrinsic parameters has produced outstanding reforming performance. This design tool allows defining of a suitable range of the operating variables for a given application and generation of performance vs. time information for determining when the adsorbent requires pressure swing desorption for regeneration. Further, mathematical simulations can be performed to incorporate both adsorption and desorption steps to determine the net H₂ yield and purity for the proposed application and for process optimization and economic analysis.

### Example III

**A High Efficiency, Low Temperature Reformer for Hydrogen Production**

Introduction


The HAMR configuration can be potentially used with equilibrium- or selectivity-limited reactions in which one of the products can be adsorbed while another (or the same) product can be simultaneously removed via a membrane. What limits the application of the concept is the availability of efficient adsorbents that are also stable at reaction conditions. Esterification reactions (like the ethanol reaction with acetic acid to produce ethyl acetate previously studied (Park (2001) Models and Experiments with Pervaporation Membrane Reactors Integrated with a Water Removal Adsorbent System, Ph.D. Thesis, University of Southern California, Los Angeles, Calif, and Park and Tsotsis (2004) System. Chem. Eng. Proc. 43:1171)), the methane steam reforming reaction or the WGS reactions are two key potential applications. Here, a HAMR system involving a hybrid packed bed catalytic MR, coupling the methane steam reforming reaction through a porous ceramic membrane with a CO₂ adsorption system was investigated. This HAMR system exhibited behavior that is more advantageous than either the MRs or ARs, in terms of the attained yields and selectivities. Theory

A mathematical model for the HAMR system is presented and analyzed for a range of temperature and pressure conditions without any intention to be bound by such theory. The behavior of the HAMR system is compared with the conventional packed bed reactor, as well as an MR and an AR system. Kinetics for Methane Steam Reforming

For the methane steam reaction, a catalytic reaction scheme first proposed by Xu and Froment ((1989) AIChE J. 35:88) is utilized. This scheme has found widespread application. According to Xu and Froment (see also Elnashaie et al. (1990) Chem. Eng. Sci. 45:491 and Nam et al. (2000) Korean J. Chem. Eng. 17:288), the methane steam reforming reaction consists of two major endothermic reforming reaction steps, together with the exothermic WGS reaction (see Table 1), with the overall reaction being highly endothermic. The rate expressions, heats of reaction, and thermodynamic constants for the three reaction steps are shown in Table 1. The kinetic parameters, as reported by Xu and Froment, are shown in Table 2.

### TABLE 1

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Rate Expression</th>
<th>Heat of Reaction at 298 K, ( \Delta H^0 ) (kJ/mol)</th>
<th>Equilibrium Constant, ( K_{eq} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( CH_4 + H_2O \rightarrow CO + 3H_2 )</td>
<td>( r_1 = k_1P_{CH_4}^{1+1/2}P_{H_2O}^{-3/2}(P_{CO}P_{H_2})^{3/2}(P_{CO}P_{H_2}/K_{eq})^{1/2} )</td>
<td>( 206.1 )</td>
<td>( K_{eq} = \exp[-30.114 - 26830/T] )</td>
</tr>
<tr>
<td>( 2CO + H_2O \rightarrow CO_2 + H_2 )</td>
<td>( r_2 = k_2P_{CH_4}^{3/2}P_{H_2O}^{3/2}(P_{CO}P_{H_2})^{1/2}(P_{CO_2}P_{H_2}/K_{eq})^{1/2} )</td>
<td>( -41.15 )</td>
<td>( K_{eq} = \exp[-4.036 + 4400/T] )</td>
</tr>
<tr>
<td>( 3CH_4 + 2H_2O \rightarrow CO + 4H_2 )</td>
<td>( r_3 = k_3P_{CH_4}^{5/4}(P_{CO}P_{H_2})^{1/4}(P_{CO_2}P_{H_2}/K_{eq})^{1/4} )</td>
<td>164.9</td>
<td>( K_{eq} = K_{eq} )</td>
</tr>
</tbody>
</table>

\( DEN = 1 + K_{CO}P_{CO} + K_{H_2}P_{H_2} + K_{CH_4}P_{CH_4} + K_{H_2O}P_{H_2O}/P_{H_2} \)

### TABLE 2

<table>
<thead>
<tr>
<th>Kinetic Parameter</th>
<th>Preexponential Terms, ( k_0 )</th>
<th>Activation Energies or Heats of Adsorption, ( E_a, \Delta H^0 ) (kJ/mol)</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>( k_1 )</td>
<td>( 4.225 \times 10^{15} )</td>
<td>240.1</td>
<td>( \text{kmol} \cdot \text{bar}^{0.5/3} )</td>
</tr>
<tr>
<td>( k_2 )</td>
<td>( 1.955 \times 10^{5} )</td>
<td>67.13</td>
<td>( \text{kmol/} \text{kg of catalyst/h} )</td>
</tr>
<tr>
<td>( k_3 )</td>
<td>( 1.020 \times 10^{15} )</td>
<td>243.9</td>
<td>( \text{kmol} \cdot \text{bar}^{-1/2} )</td>
</tr>
<tr>
<td>( K_{CO} )</td>
<td>( 8.23 \times 10^{-9} )</td>
<td>-70.65</td>
<td>( \text{kg of catalyst/h} )</td>
</tr>
<tr>
<td>( K_{H_2} )</td>
<td>( 6.12 \times 10^{-9} )</td>
<td>-82.90</td>
<td>( \text{bar}^{-1} )</td>
</tr>
<tr>
<td>( K_{CH_4} )</td>
<td>( 6.65 \times 10^{-4} )</td>
<td>-38.28</td>
<td>( \text{bar}^{-1} )</td>
</tr>
<tr>
<td>( K_{H_2O} )</td>
<td>( 1.77 \times 10^{3} )</td>
<td>88.68</td>
<td></td>
</tr>
</tbody>
</table>

Formation rates for the \( H_2, CO, \) and \( CO_2 \) products and the disappearance rates for \( CH_4 \) and \( H_2O \) are given by the following equations:

\( R_{H_2} = r_1 + r_2 + 4r_3 \)  
\( R_{CO} = r_1 - r_2 \)  
\( R_{CO_2} = r_1 + 3r_2 + r_3 \)  
\( R_{H_2O} = r_1 + r_2 + 3r_3 \)  
\( R_{CO_2} = r_2 + r_3 - 2r_3 \)

Mathematical Model of the HAMR System

A schematic of the HAMR system is shown in FIG. 35. In this figure, the catalyst and adsorbent are packed in the exterior of the membrane (signified by the superscript P, or the feed side), with additional adsorbent also packed in the interior of the membrane volume (signified by the superscript I, or the permeate side). There are, of course, a number of other potential reactor configurations, as previously noted. For example, the catalyst may be loaded in the feed side, while the adsorbent may also be loaded in the permeate side, or the catalyst and adsorbent may only be loaded in the feed side, with no adsorbent or catalyst being present in the permeate side, which is the configuration that is analyzed here. To simplify matters, in the development of the model, it is assumed that the reactor operates isothermally, that external mass transfer resistances are negligible for the transport through the membrane as well as for the catalysts, and that internal diffusion limitations for the catalyst, and internal or external transport limitations for the adsorbent, are accounted for by the overall rate coefficients. Moreover, plug-flow conditions are assumed to prevail for both the interior and exterior membrane volumes as well as ideal gas law conditions.
In the simulations, the experimentally measured transport characteristics of a microporous SiC membrane (Ciora et al. (2004) Chem. Eng. Sci. 59:4957) is utilized. These membranes have been shown previously to be thermally and hydrothermally stable under conditions akin to the steam reforming reaction conditions (Ciora et al. (2004) Chem. Eng. Sci. 59:4957). Further details about their preparation and characterization can be found in the original publication. The SiC membranes are highly permeable toward hydrogen, with gases having larger kinetic diameters permeating only by Knudsen diffusion through membrane pinholes and cracks (Ciora et al. (2004) Chem. Eng. Sci. 59:4957). Mass transfer through the porous membrane is described by the following empirical equation:

\[ F_j = \frac{P_j - P_m}{\alpha_j} \]  

(6)

where \(F_j\) is the molar flux (mol/m²·s), \(P_j\) the partial pressure of component \(j\) on the membrane feed side (bar), \(P_m\) the partial pressure of component \(j\) on the membrane permeate side (bar), and \(\alpha_j\) the membrane permeance for component \(j\) (mol/m²·bar·s). Equation 6 is, of course, a simplified empirical expression for describing flux through a nanoporous membrane for which the size of the pores approaches that of the diffusing molecules.

The mass balance on the feed side of the reactor packed with methane steam reforming catalyst and, potentially, an adsorbent is described by the following equations for CO₂, CO, H₂, H₂O, CH₄, and an inert species (potentially used as a sweep gas and adsorbing agent, for catalytic steam reforming, a practical sweep gas would be either steam or hydrogen, however):

\[
\begin{align*}
\frac{dQ}{dt} + \frac{\partial Q}{\partial V} &= \alpha_{\text{as}} U_j (P_j - P_m) + (1 - \epsilon) \frac{\partial}{\partial V} \left( \rho_j \frac{\partial C_j}{\partial V} - \frac{\partial}{\partial V} \left( \frac{D_j \epsilon}{\rho_j} \frac{\partial C_j}{\partial V} \right) \right) \\
&= (1 - \epsilon) \frac{\partial}{\partial V} \left( \rho_j \frac{\partial C_j}{\partial V} - \frac{\partial}{\partial V} \left( \frac{D_j \epsilon}{\rho_j} \frac{\partial C_j}{\partial V} \right) \right) \\
&= (1 - \epsilon) \frac{\partial}{\partial V} \left( \rho_j \frac{\partial C_j}{\partial V} - \frac{\partial}{\partial V} \left( \frac{D_j \epsilon}{\rho_j} \frac{\partial C_j}{\partial V} \right) \right)
\end{align*}
\]

(7)

where \(Q\) is the molar flow rate (mol/s) for species \(j\) and \(C_j\) is the gas-phase concentration (kmol/m³) equal to \(\frac{n_j}{V}\), where \(V\) is the volumetric flow rate (m³/s). \(V\) is the feed side reactor volume variable (m³), \(\alpha_{\text{as}}\) is the membrane area per feed side reactor volume (m²/m³), \(\epsilon\) is the bed porosity on the feed side, \(\rho_j\) is the total feed side bed porosity (it includes the bed porosity and catalyst porosity), \(\beta_j\) is the fraction of the solid volume occupied by catalysts (\(\beta_j = 1\) when no adsorbent is present), \(\rho_a\) the catalyst density (kg/m³), \(\rho_a\) the adsorbent density (kg/m³), and \(R_j\) is the reaction rate expression, which is either described by Eqs. 1-5 (mol/kg·s) or is equal to zero if \(j\) is an inert reactor volume variable (m²/s).

\[

dC_j \frac{dt}{dt} = G_{\text{CO}_2} = \frac{k_j (C_{\text{eq}} - C_j)}{1 + b_{\text{CO}_2} P_{\text{CO}_2}}
\]

(9)

where \(C_{\text{eq}}\) is the adsorption equilibrium CO₂ concentration on the adsorbent (mol/kg) corresponding to the prevailing gas phase concentration. \(C_j\) is the existing adsorbed CO₂ concentration (mol/kg), and \(k_j\) is a parameter that “lumps” the effects of external and intraparticle mass transport and the sorption processes and that, as a result, is often a strong function of temperature and pressure (Ding and Alpay (2000) Chem. Eng. Sci. 55:3461) although, typically, in modeling, it is taken as temperature/pressure-independent. To calculate \(C_{\text{eq}}\), the data reported by Ding and Alpay (2000) Chem. Eng. Sci. 55:392927 and (2000) Chem. Eng. Sci. 55:3461) for CO₂ adsorption on potassium-promoted LDH are utilized. Their data show that the CO₂ adsorption on this adsorbent follows a Langmuir adsorption isotherm under both dry and wet conditions, described by the following equation:

\[
C_{\text{eq}} = \frac{m_{\text{CO}_2} b_{\text{CO}_2} P_{\text{CO}_2}}{1 + b_{\text{CO}_2} P_{\text{CO}_2}}
\]

(10)

where \(m_{\text{CO}_2}\) (mol/kg) is the total adsorbent capacity and \(b_{\text{CO}_2}\) (bar⁻¹) the adsorption equilibrium constant, which is described by the van’t Hoff equation:

\[
b_{\text{CO}_2} = b_{\text{CO}_2} (T_0) \exp \left( -\frac{\Delta H_{\text{ads}}}{R} \left( \frac{1}{T} - \frac{1}{T_0} \right) \right)
\]

(9)

The heat of adsorption, \(\Delta H_{\text{ads}}\) (kJ/mol), under wet conditions for a region of temperatures from 481 to 753 K is calculated to be -17 kJ/mol, while \(b_{\text{CO}_2}\), at 673 K is equal to 23.6 bar (Ding and Alpay (2000) Chem. Eng. Sci. 55:3461). Eqs. 7 and 9 must be complemented by initial and boundary conditions. For simplicity, it is assumed that the reactor, prior to the initiation of the reaction/adsorption step, has undergone an initialization procedure as described by Ding and Alpay ((2000) Chem. Eng. Sci. 55:3929). One model that involves (i) heating the reactor to the desired temperature under atmospheric pressures by feeding H₂ on the reactor feed side and the chosen sweep gas on the permeate side, (ii) supplying water to the system so that the reactor temperature is increased to the desired temperature, and (iii) pressurizing the feed and permeate sides to the desired pressure conditions, and (iv) switching from H₂ to CH₄ to initiate the reaction/adsorption step. In the simulations, the conditions prevailing at the start of step (iv) are those prevailing at steady state during step (iii).

\[ \frac{\partial C_j}{\partial t} + \frac{u^P_j}{r} \frac{\partial C_j}{\partial r} + k \frac{\partial (C_j D_m^P)}{\partial r} = 0 \quad (14) \]

where \( k = \frac{A^L}{A^T} \), with \( A^T \) being the cross-sectional area on the permeate side (m\(^2\)), and \( D_m^P \) (m\(^2\)/s) is the axial Taylor-Aris dispersion coefficient on the permeate side (Levenspiel 1998 Chemical Reaction Engineering, 3rd ed., Wiley, New York) for empty tubes given as:

\[ D_m^P = \frac{1}{1920^a_u} \left( \frac{\nu^P u_r}{D_m^P} + \frac{\nu^P u_r}{D_m^P} \right) \]

where \( D_m^P \) is the molecular diffusivity (m\(^2\)/s), \( u^P \) is the velocity at the permeate side (m/s), and \( D_m^P \) is the membrane inside diameter (m). In the simulations, the conditions prevailing in the permeate side at the start of step (iv) are those prevailing at steady state during step (iii). In addition, during step (iv) the following conditions prevail in the permeate side:

\[ \frac{\partial x_j^P}{\partial t} + \frac{u_j^P}{r} \frac{\partial x_j^P}{\partial r} = 0 \quad (16a) \]

where \( x_j^P \) is the mole fraction, \( u_j^P \) the inlet mole fraction for species \( j \) on the permeate side, and \( u_j^P \) the superficial flow velocity (m/s) at the inlet. Because no adsorbent or catalyst is present in the permeate side, any potential pressure drops is ignored.

The reactor conversion (based on methane, which is typically the limiting reagent) is defined by the following equation:

\[ y_{CH4} = \frac{n_{CH4,i} - n_{CH4,f}}{n_{CH4,i}} \]

where \( n_{CH4,i} \) is the inlet molar flow rate of CH\(_4\) and \( n_{CH4,f} \) are the methane molar flow rates at the exit of the reactor feed and permeate sides correspondingly (mol/s). The yield of product hydrogen, defined as the fraction of moles of methane fed into the reactor that have reacted to produce hydrogen, is given by the following equation:

\[ Y_H2 = \frac{1}{4} \left( n_{H2,i} - n_{H2,f} \right) \]

where \( n_{H2,i} \) and \( n_{H2,f} \) are the hydrogen molar flow rates at the exit of respectively the reactor feed and permeate sides and \( n_{H2,i} \) and \( n_{H2,f} \) the H\(_2\) molar flow rates potentially present at the inlet of the reactor feed and permeate sides (mol/s). \( Y_{H2} \) when all of the methane has reacted completely to produce CO\(_2\) and H\(_2\), Eqs. 6-18 can be written in dimensionless form by defining the following variables and groups:
where in dimensionless form:

\[ G_{\text{CO}_2} = \theta_{\text{CO}_2} \]

\[ \theta_{\text{eq}} = \frac{\beta_{\text{CO}_2} \theta_{\text{CO}_2} G_{\text{CO}_2}}{1 + \beta_{\text{CO}_2} \theta_{\text{CO}_2} G_{\text{CO}_2}} \]

and \( R'_i \) are dimensionless forms of \( R_i \), which are described by Eqs. 1-5, with the dimensionless forms of the rates \( r'_1 \) to \( r'_3 \) shown in Table 3.

**TABLE 3**

<table>
<thead>
<tr>
<th>i reaction</th>
<th>rate expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 CH\textsubscript{4} + H\textsubscript{2}O → CO + 3H\textsubscript{2}</td>
<td>( r'<em>1 = \frac{1}{[\text{H}</em>{2}\text{O}]^2} )</td>
</tr>
</tbody>
</table>


The system of partial differential equations was converted to a set of ordinary differential equations by discretizing the spatial derivative in the \( \eta \) direction using a five-point-biased upwind finite-difference scheme to approximate the convective term. A fourth-order central-difference scheme has been used to approximate the diffusive term. For finite differences, the reactor volume is divided into \( n \) sections with \( n+1 \) nodes.

The initial value boundary conditions at the start of the adsorption/reaction step are those prevailing during step 3 previously described. In addition, the following boundary conditions also apply:

for \( r > 0 \), at \( \eta = 0 \):

\[ \Psi' = 1, \quad \Psi = 0 \]

\[ \xi' = 1, \quad \xi = 0 \]

The behavior of the HAMR and AR at two temperatures (400 and 480° C.) for which experimental data for the adsorption/reaction rates were previously reported by Ding and Alpay (2000) Chem. Eng. Sci. 55:3929 and (2000) Chem. Eng. Sci. 55:3461) is reported here. The Xu and Froment steam reforming kinetics were used previously at temperatures as low as 450 and 480° C.)

A potential disadvantage of the HAMR system, when compared to the AR system, is that only a fraction of the hydrogen product ended up in the permeate stream, while the rest remained mixed with the unreacted CH4 and the CO and CO2 products in the feed side stream. FIG. 39 shows the hydrogen recovery rate, which is defined as the fraction of the total hydrogen that is produced in the HAMR that ends up in the permeate stream, that is, the hydrogen molar flow in the permeate side divided by the total hydrogen molar flow (feed side plus permeate side). The increase in the hydrogen recovery, shown in FIG. 39, coincided with the CO2 breakthrough, which resulted in a sharp decrease in the molar flow of hydrogen in the feed side (less hydrogen was produced there because the adsorbent no longer removed the CO2 produced). Because the total hydrogen molar flow rate also declined, hydrogen recovery increased and finally leveled off at the corresponding steady state (AR or MR) levels. The hydrogen recovery is, of course, a strong function of the membrane permeance characteristics and the other operating conditions in the reactor, increasing with increasing membrane permeance and feed side pressure. Furthermore, it must be also taken into account, when comparing both reactors, that even for the AR system, the hydrogen must be eventually separated out of the exit stream and that similar hydrogen losses are likely to occur.

FIG. 40 shows the effect of βc (the fraction of reactor volume occupied by catalyst) on the hydrogen yields, while keeping the total volume occupied by the solids and the W/νCH4,0 constant. Decreasing βc, i.e., increasing the fraction of sorbent present, while maintaining W/νCH4,0 constant, had a significant beneficial effect on the hydrogen yield and also on the product purity for both the HAMR and AR systems (see FIG. 41 for the CO content of the hydrogen product).

The effect of using an adsorbent with improved characteristics is shown in FIG. 42. The hydrogen yields for the HAMR and AR systems were compared for three values of A, one corresponding to the adsorbent of Ding and Alpay ((2000) Chem. Eng. Sci. 55:3461) (for the reactor temperature and pressure conditions utilized, this corresponds to A = 2.67) and...
two other cases with corresponding A values 5 and 10 times larger. A more effective adsorbent significantly expanded the “time window” of operation for both the AR and HAMR systems before regeneration must commence. It also significantly increased the hydrogen yields attained.

The effect of membrane transport characteristics is shown in FIG. 43, where the reactor yields corresponding to four different membranes (i.e., four different values of Ω) are shown. For the SiC membrane used in the simulations, Ω=1.54. The other three membranes had Ω values that were 0.333, 0.5, and 2 times the base Ω value (because Ω is inversely proportional to permeance, these Ω values corresponded to permeances that were 3.2, and 0.5 times that of the base case corresponding to Ω=1.54). The HAMR system hydrogen yields did benefit from increased hydrogen permeance, but the effect saturated beyond a certain value. FIG. 44 shows the effect that Ω has on hydrogen recovery. As expected, increasing the hydrogen permeance had a very beneficial effect on hydrogen recovery, with very high hydrogen recoveries (≈87%) attained for 0.333 times the base case Ω. FIG. 45 shows the effect of the sweep ratio on the hydrogen yield of the HAMR system. Increasing the sweep ratio improved the reactor performance; however, the effect saturated quickly, as shown in FIG. 45. FIGS. 46 and 47 show the behavior of the two systems at 400° C. FIG. 46 shows the hydrogen yield, while FIG. 47 presents the time-averaged CO content in the hydrogen product stayed below 50 ppm (140 ppm on a dry basis).

Conclusions

A novel reactor system, termed HAMR, for hydrogen production through methane steam reforming was investigated. The HAMR combines the reaction and membrane separation steps with adsorption on the membrane feed or permeate sides. The HAMR system is of potential interest to pure hydrogen production for PEM fuel cells for various mobile and stationary applications. The reactor characteristics have been investigated for a range of temperature, pressure, and other experimental conditions relevant to the aforementioned applications and compared with the behavior of the traditional packed bed reactor, the conventional MR, and an AR. The HAMR outperformed all of the other more conventional reactor systems. It exhibited enhanced methane conversion, hydrogen yield, and product purity and showed good promise for reducing the hostile operating conditions of conventional methane steam reformers and for meeting the product purity requirements for PEM operation. The performance of the HAMR system depended on the various operating parameters, including the reactor space time, the temperature, and the membrane and adsorbent properties. Use of more effective adsorbents, for example, resulted in increased yields and longer operational windows. More highly permeable membranes also increased the reactor yield but, more importantly, also increased the hydrogen recovery ratio. One of the key advantages of the HAMR system over the corresponding AR system (in addition to improvements in yield) is its ability to deliver a product with a significantly lower CO content through the use of membranes, which preferentially allow the permeation of the hydrogen while excluding CO and other reactants and products. This may be the primary reason for adopting such reactors for fuel cell application, where a CO-free product is at a premium.

Example IV

The adsorption equilibrium capacity and rate for the CO₂ affinity adsorbent, hydrotalcite, used in this study were experimentally determined. The lab scale adsorption isotherm study was performed using a gravimetric technique. The adsorption isotherms for CO₂ on hydrotalcite at 250-450° C. were determined by measuring the CO₂ uptake data. The experimental data were then fitted with the Langmuir adsorption isotherm as presented in FIG. 48. Table 5 shows the Langmuir parameters obtained by fitting the adsorption data for various temperatures. The transient CO₂ uptake data were measured at each elevated temperature, and then the diffusion coefficients were estimated by fitting acquired experimental data to the solution of the relevant diffusion equation. Table 6 gives the diffusivity data obtained by fitting the experimental data to the diffusion equation for the temperatures studied.

**TABLE 5**

<table>
<thead>
<tr>
<th>Temperature, °C</th>
<th>m_{CO₂, minol/g sample}</th>
<th>b_{CO₂, kPa⁻¹}</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>0.534</td>
<td>0.05</td>
</tr>
<tr>
<td>350</td>
<td>0.387</td>
<td>0.088</td>
</tr>
<tr>
<td>450</td>
<td>0.337</td>
<td>0.099</td>
</tr>
</tbody>
</table>

**TABLE 6**

<table>
<thead>
<tr>
<th>Temperature, °C</th>
<th>D/k², s⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>9.52 x 10⁻⁴</td>
</tr>
<tr>
<td>350</td>
<td>3.42 x 10⁻⁴</td>
</tr>
<tr>
<td>450</td>
<td>6.00 x 10⁻⁴</td>
</tr>
</tbody>
</table>

Kinetic constants for WGS reaction are critical input parameters for the performance simulation of the HAMR. A laboratory scale reactor system was established as shown in FIG. 49 to study the reaction kinetics, which was then employed for the HAMR study. Synthetic feed was prepared from pure gas cylinders with mass flow controllers. The reactor temperature was kept at the target temperature within a constant temperature box. The effluent from the reactor was analyzed with a mass spectrometer after water dropout via condensation.
Three different temperatures were selected, i.e., 205, 225 and 250° C., which covered the temperature range recommended by the catalyst manufacturer for the low temperature shift catalyst. Pressure of the reactor was kept at ~50 psig. The feed composition selected for this study was CO:H₂: H₂O = 1:0:4:0:1.1. W/Fo selected ranged from ~30 to as high as ~467, which spanned a wide operating condition for obtaining representative kinetic parameters. The reaction rate constants obtained experimentally were then used to determine the pre-exponential factor and the activation energy required. The pre-exponential factor and the activation energy determined based upon the operating condition are listed in Table 7. These kinetic parameters were used in the mathematical simulation.

![Table 7: Reaction Rate and Kinetic Parameters for WGS.](image)

Experimental investigations of HAMR systems using CO₂ hydrotalcite-type adsorbents and a porous H₂ selective membranes (similar to the one shown in Example 1) were also carried out. The behavior of the HAMR and conventional PBR for the WGS reaction for hydrogen production with concomitant CO₂ removal were simulated. The adsorption rates and constants were taken from the adsorption studies. The reaction rate constants and the membrane permeances were experimentally determined, as outlined above. The reactor characteristics have been investigated for a range of temperature and pressure conditions and compared with the predictions of the mathematical model. The reactor temperature utilized was 250° C., and a CO:H₂:H₂O feed ratio of 1:4:1.1 was employed. Steam was used as the sweep gas. FIGS. 51 and 53 show the CO conversion attained by both the PBR and HAMR as a function of time for Wc/F, 300 and 350 (Wc is the total weight of the catalyst). The reactor showed complete conversion, while the adsorbent was still active. After the adsorbent saturated, the conversion settled to the value corresponding to the membrane reactor conditions, which was still significantly higher than the conversion of the PBR system and the corresponding equilibrium.

| Reaction Rate and Kinetic Parameters for WGS. |
|---------------------|---------------------|
| r = k \cdot \exp(-E_o/RT) \cdot \frac{P_{CO}}{P_{CO}^{1/F_o} + \frac{P_{H_2}}{P_{H_2}^{1/F'}} + \frac{P_{CO_2}}{P_{CO_2}^{1/F''}}} |
| k_o = \frac{g - mol}{(g\text{ cat} \times hr \times bar \times 0.4)} |
| E (kJ/mol) = 114.22 |

What is claimed is:

1. A reactor comprising:
   - a chamber;
   - an inlet for introducing one or more reactants into the chamber;
   - a catalyst disposed in the chamber for facilitating a reaction of the reactants to produce at least one desired product and at least one by-product, wherein the reaction is a water-gas-shift (WGS) reaction;
   - a membrane disposed in the chamber for selectively permitting the desired product and the by-product to pass through the membrane;
   - an adsorbent disposed in the chamber for adsorbing the by-product; and
   - an outlet for allowing the desired product to exit the chamber.

2. The reactor of claim 1, wherein the membrane is a carbon molecular sieve (CMS) or silicon carbide membrane.

3. The reactor of claim 1, wherein the adsorbent is a hydrotalcite.

4. An apparatus comprising at least two reactors of claim 1.

5. A reactor comprising:
   - a chamber;
   - an inlet for introducing one or more reactants into the chamber;
   - a catalyst disposed in the chamber for facilitating a reaction of the reactants to produce at least one desired product and at least one by-product, wherein the reaction is a steam reforming reaction;
   - a non-metallic membrane disposed in the chamber for selectively permitting the desired product and the by-product to pass through the membrane;
   - an adsorbent disposed in the chamber for adsorbing the by-product; and
   - an outlet for allowing the desired product to exit the chamber.

6. The reactor of claim 5, wherein the membrane is a CMS or silicon carbide membrane.

7. The reactor of claim 5, wherein the adsorbent is a hydrotalcite.

8. A reactor comprising:
   - a chamber;
   - an inlet for introducing one or more reactants into the chamber;
   - a catalyst disposed in the chamber for facilitating a reaction of the reactants to produce at least one desired product and at least one by-product, wherein the reaction is a steam reforming reaction;
   - a membrane disposed in the chamber for selectively permitting the desired product and the by-product to pass through the membrane;
   - a hydrotalcite adsorbent disposed in the chamber for adsorbing the by-product; and
   - an outlet for allowing the desired product to exit the chamber.

9. The reactor of claim 8, wherein the membrane is a CMS or silicon carbide membrane.

10. A reactor comprising:
   - a chamber;
   - an inlet for introducing one or more reactants into the chamber;
a catalyst disposed in the chamber for facilitating a reaction of the reactants to produce at least one desired product and at least one by-product, wherein the reaction is a steam reforming reaction;
a membrane disposed in the chamber for selectively permitting the desired product and the by-product to pass through the membrane;
an adsorbent disposed in the chamber for adsorbing the by-product; and
an outlet for allowing the desired product to exit the chamber, wherein neither the catalyst nor the adsorbent is disposed in a circulating fluidized bed.

The reactor of claim 10, wherein the membrane is a CMS or silicon carbide membrane.

The reactor of claim 10, wherein the adsorbent is a hydrotalcite.

An apparatus comprising:
at least two reactors, each reactor including:
a chamber;
an inlet for introducing one or more reactants into the chamber;
a catalyst disposed in the chamber for facilitating a reaction of the reactants to produce at least one desired product and at least one by-product, wherein the reaction is a steam reforming reaction;
a membrane disposed in the chamber for selectively permitting the desired product and the by-product to pass through the membrane;
an adsorbent disposed in the chamber for adsorbing the by-product; and
an outlet for allowing the desired product to exit the chamber.

The reactor of claim 13, wherein the membrane is a CMS or silicon carbide membrane.

The reactor of claim 13, wherein the adsorbent is a hydrotalcite.

A reactor comprising:
a chamber;
an inlet for introducing one or more reactants into the chamber;
a catalyst disposed in the chamber for facilitating a reaction of the reactants to produce at least one desired product and at least one by-product;
a CMS or silicon carbide membrane disposed in the chamber for selectively permitting the desired product and the by-product to pass through the membrane;
an adsorbent disposed in the chamber for adsorbing the by-product; and
an outlet for allowing the desired product to exit the chamber.

An apparatus comprising at least two reactors of claim 16.

A process comprising:
introducing one or more reactants into the reactor of claim 1; contacting the catalyst with the reactants to facilitate a reaction of the reactants to produce at least one desired product and at least one by-product; selectively passing the desired product and the by-product through the membrane;
adsorbing the by-product with the adsorbent; and
withdrawing the desired product from the reactor.

The process of claim 21, wherein the process is carried out at 275-700°C.

A process comprising:
introducing one or more reactants into each reactor of the apparatus of claim 14;
contacting the catalyst with the reactants to facilitate a reaction of the reactants to produce at least one desired product and at least one by-product in the reactor;
selectively passing the desired product and the by-product through the membrane in the reactor;
adsorbing the by-product with the adsorbent in the reactor; and
withdrawing the desired product from the reactor,
wherein the reactors of the apparatus are offset in point of time such that, at all times, the desired product is being withdrawn from at least one of the reactors.

The process of claim 23, wherein the process is carried out at 275-700°C.

A process comprising:
introducing one or more reactants into the reactor of claim 15;
contacting the catalyst with the reactants to facilitate a reaction of the reactants to produce at least one desired product and at least one by-product;
selectively passing the desired product and the by-product through the membrane;
adsorbing the by-product with the adsorbent; and
withdrawing the desired product from the reactor.

The process of claim 25, wherein the process is carried out at 275-700°C.

A process comprising:
introducing one or more reactants into the reactor of claim 17;
contacting the catalyst with the reactants to facilitate a reaction of the reactants to produce at least one desired product and at least one by-product;
selectively passing the desired product and the by-product through the membrane;
adsorbing the by-product with the adsorbent; and
withdrawing the desired product from the reactor.

The process of claim 27, wherein the process is carried out at 275-700°C.

A process comprising:
introducing one or more reactants into the reactor of claim 20;
contacting the catalyst with the reactants to facilitate a reaction of the reactants to produce at least one desired product and at least one by-product;
selectively passing the desired product and the by-product through the membrane;
adsorbing the by-product with the adsorbent; and
withdrawing the desired product from the reactor.

The process of claim 29, wherein the process is carried out at 275-700°C.
31. A process comprising:
introducing one or more reactants into each reactor of the apparatus of claim 13;
contacting the catalyst with the reactants to facilitate a reaction of the reactants to produce at least one desired product and at least one by-product in the reactor;
selectively passing the desired product and the by-product through the membrane in the reactor;
adsorbing the by-product with the adsorbent in the reactor;
and withdrawing the desired product from the reactor.
wherein the reactors of the apparatus are offset in point of time such that, at all times, the desired product is being withdrawn from at least one of the reactors.
32. The process of claim 31, wherein the process is carried out at 275-700° C.
33. A process comprising:
introducing one or more reactants into the reactor of claim 16;
contacting the catalyst with the reactants to facilitate a reaction of the reactants to produce at least one desired product and at least one by-product;
selectively passing the desired product and the by-product through the membrane;
adsorbing the by-product with the adsorbent; and
withdrawing the desired product from the reactor.
34. The process of claim 33, wherein the process is carried out at 275-700° C.
35. A process comprising:
introducing one or more reactants into each reactor of the apparatus of claim 18;
contacting the catalyst with the reactants to facilitate a reaction of the reactants to produce at least one desired product and at least one by-product in the reactor;
selectively passing the desired product and the by-product through the membrane in the reactor;
adsorbing the by-product with the adsorbent with the adsorbent in the reactor;
and withdrawing the desired product from the reactor.
wherein the reactors of the apparatus are offset in point of time such that, at all times, the desired product is being withdrawn from at least one of the reactors.
36. The process of claim 35, wherein the process is carried out at 275-700° C.
37. A process comprising:
introducing one or more reactants into the reactor of claim 19;
contacting the catalyst with the reactants to facilitate a reaction of the reactants to produce at least one desired product and at least one by-product;
selectively passing the desired product and the by-product through the membrane;
adsorbing the by-product with the adsorbent; and
withdrawing the desired product from the reactor.
38. The process of claim 37, wherein the process is carried out at 275-700° C.
39. A process comprising:
introducing one or more reactants into each reactor of the apparatus of claim 20;
contacting the catalyst with the reactants to facilitate a reaction of the reactants to produce at least one desired product and at least one by-product in the reactor;
selectively passing the desired product and the by-product through the membrane in the reactor;
adsorbing the by-product with the adsorbent in the reactor;
and withdrawing the desired product from the reactor.
wherein the reactors of the apparatus are offset in point of time such that, at all times, the desired product is being withdrawn from at least one of the reactors.
40. The process of claim 39, wherein the process is carried out at 275-700° C.

* * * * *