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(54) **Title**: IMPROVED CPOX FUEL PEFORMER AND SOFC SYSTEM

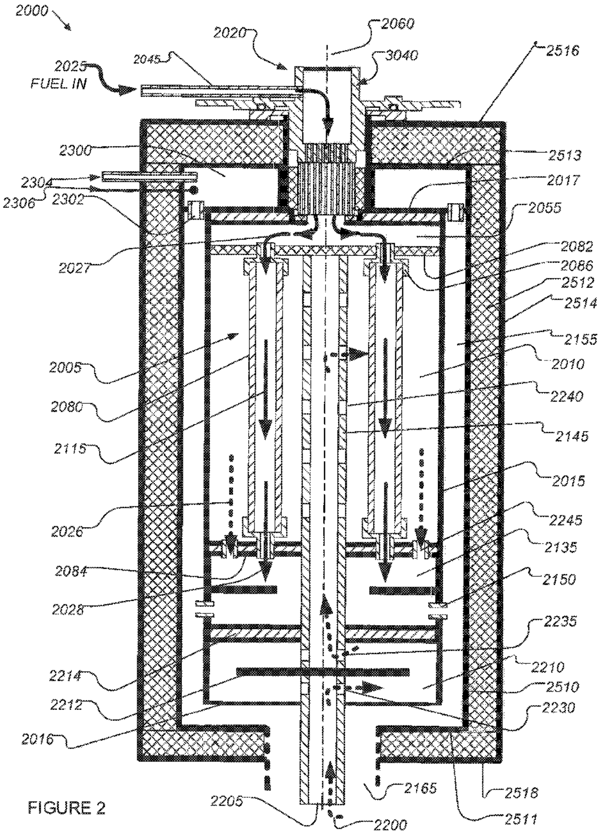

FIGURE 2

(57) **Abstract**: A solid oxide fuel cell (SOFC) system includes hot zone enclosure walls formed as a substantially continuous thermally conductive path each comprising materials having a coefficient of thermal conductivity of greater than 100 W/nr'iv. The SOFC further includes a CPOX reactor that includes a fuel reactor body formed as a thermally conductive path comprising materials having a coefficient of thermal conductivity of greater than 100 W/m°K. The fuel reactor body conducts thermal energy generated by CPOX reaction out of the system to a heat dissipating flange supported in ambient air. The flange is configured to dissipate sufficient thermal energy from the fuel reactor body to maintain the fuel reactor body in a range of about 100°C to 250°C. A fan is optionally provided to cool the heat dissipating flange.

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PATENT APPLICATION

OF

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FOR

IMPROVED CPOX FUEL REFORMER AND SOFC SYSTEM

IMPROVED CPOX FUEL REFORMER AND SOFC SYSTEM

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2 Background of the Invention

2.1 Field of the Invention

[0002] The exemplary, illustrative technology described herein relates to Solid Oxide Fuel Cell (SOFC) systems and particularly to structural features and operating methods of fuel processor reactors usable to reform hydrocarbon fuels by partial or catalyzed partial oxidation. More specifically the technology relates to thermal energy management as a means of improving fuel processor performance.

2.2 The Related Art

[0003] Solid oxide fuel cell (SOFC) systems used to generate electrical energy by an electrochemical process typically include a fuel processor that is configured to convert any of a variety of incoming hydrocarbon fuels (*e.g.* propane, methane, kerosene) into fuel components that more readily react with solid oxide fuel cell electrodes in the electrochemical reaction that produces electrical current. Ideally, the fuel processor is operable to convert various hydrocarbon fuel air mixtures into a mixture of hydrogen and carbon monoxide using flameless combustion or preferably flameless catalytic combustion.

Advantages of flameless combustion techniques include the ability to reform a larger variety of fuel types, a homogeneous temperature distribution in the fuel processor, reduced thermal stress in the structure of the fuel reformer, a longer reformer and gas seal lifetime, and a reduction of undesirable Nitrous Oxide (NOX) emissions in the exhaust gas.

[0004] Example conventional fuel processor reactors include a partial oxidation (POX) and catalyzed partial oxidation (CPOX) reactor which are each used to reform a mixture of hydrocarbon fuel and air into a suitable SOFC fuel through the exothermic process of flameless combustion. A CPOX reactor typically includes a catalyst mounted on a support substrate. In conventional CPOX reactors the support substrate is generally a porous ceramic material formed with internal passages through which the fuel air mixture passes from one external surface of the porous material to an opposing external surface. A catalyst layer is formed on internal surfaces of the internal passages. As the fuel air mixture being processed flows through the porous material the fuel air mixture makes contact with the catalyst layer which leads to flameless combustion occurring inside the porous material. As a result of the flameless combustion, the fuel is converted to the desired mixture of hydrogen and carbon monoxide, e.g. Syngas, with the main by-product being thermal energy being given off during the flameless combustion.

[0005] Another example catalyst support structure includes a wire or woven mesh substrate formed by a plurality of individual screen elements stacked one above another to form a unitary porous substrate. For wire or woven mesh elements, surfaces of each screen or element are over coated with a catalyst layer. As the fuel is flowed through the stacked screen elements the fuel interacts with the catalyst layer which initiates flameless combustion and the fuel is converted to the desired mixture of hydrogen and carbon monoxide with the main by-product being thermal energy being given off during the flameless combustion.

[0006] It is a typical problem with fuel reformers that thermal energy generated by the exothermic reaction (flameless combustion) that occurs inside the porous substrate can heat the temperature of the incoming unprocessed fuel to its auto ignition temperature, causing the fuel to ignite before reaching the catalyst or inside passages of the catalyst support structure. When this occurs the ignited fuel is partially converted to carbon dioxide (CO_2) which reacts with and damages the catalyst layers formed inside the porous substrate, eventually reducing fuel reformer efficiency and ultimately rendering the catalyst layer unusable. While it is known to position a flame arrestor proximate to the entrance of a CPOX reactor to suppress flame ignition of the incoming unprocessed fuel air mixture, the flame arrestor adds cost and increases flow resistance without actually contributing any fuel reforming benefit.

[0007] It is a further problem with conventional CPOX reactors that non-uniform over-heating of the catalytic layers damages the catalyst layer at local hot spots, e.g. proximate to an input end of the catalyst support structure and the hots spots can eventually burn through the catalyst layer, reducing reformer efficiency. However, under-heating the catalytic layer also damages the catalyst and reduces reformer efficiency because under-heating or incomplete combustion of the fuel air mixture inside the catalyst support structure causes carbon powder formation on the catalyst layer. In either case, overheating and under heating and especially non-uniform overheating and under-heating damages the catalyst layers, eventually reducing fuel reformer efficiency and ultimately rendering the catalyst layer unusable.

[0008] It is a still further problem that thermal energy generated by the exothermic reaction (flameless combustion) that occurs inside the porous catalyst support structure can heat the temperature of the reformed fuel exiting from the fuel reformer to its auto ignition temperature causing the fuel to ignite before reaching the fuel cell stack. The result of this problem is that the electrical power output and overall system efficiency is reduced because fuel that is combusted before reaching the fuel call stack is not usable in the SOFC reactor to generate electrical power.

[0009] One problem with conventional CPOX reactor substrates formed by a porous ceramic material substrate is that the ceramic material is a poor thermal conductor, with most ceramic materials having a coefficient of thermal conductivity of less than about 40 W/m°K and more generally less than 20 W/m°K. Thus as compared with thermally conductive metals (*e.g.* aluminum) with a coefficient of thermal conductivity of more than 200 W/m°K, ceramic materials and stainless steel mesh are not good thermal conductors. Thus quickly removing thermal energy from the porous ceramic material substrate of a CPOX reactor by thermal conduction is too slow to effectively remove enough thermal energy from the substrate by thermal conduction to provide active cooling during the fuel reforming process. For the same reason, thermal conduction from one region of a ceramic CPOX reactor substrate to another is too slow to effectively provide a homogeneous temperature over the substrate volume which is part of the reason why hot and cold areas persist during normal fuel processing.

[0010] With respect to woven metallic screens, used in conventional catalytic substrates they suffer the same deficiency because they are generally made from high temperature metal alloys such as austenitic stainless steel or other high temperature metal alloys such as Hastelloy, Monel, or Inconel because these metal alloys are suitable for continuous operation at temperatures above about 800°C. However, the specialty high temperature metal alloys actually provide a coefficient of thermal conductivity that is less than that of most ceramic materials. In particular, the coefficient of thermal conductivity of austenitic stainless steel, Hastelloy, Monel, and Inconel are all less than about 25 W/m°K.

[0011] In operation, without any form of active cooling or thermal energy management, the temperature of conventional catalyst support structures and the temperature of the fuel air mixture passing through the conventional catalyst support structure eventually increase to the steady state CPOX reaction temperature which is estimated to be between 800 and 1200°C. However since this is above the auto ignition or auto combustion temperature of desirable fuels such as propane, methane, or kerosene, which have approximate auto ignition temperatures of 470°C, 580°C, and 295°C respectively the problem has conventionally be solved using a flame arrestor positioned at the input side of the catalyst support substrate to prevent ignition. However this solution fails to prevent auto ignition inside or proximate to the output side of a conventional catalyst substrate. Thus their a need in the art to more effectively manage thermal energy in and around the CPOX reactor substrate in a manner that prevents the fuel air mixture from auto igniting at temperatures above about 295°C and up to about 580°C and specifically to prevent fuel auto ignition proximate to the input and output side an inside of the catalyst support substrate.

[0012] Additionally, there is a need in the art to more proactively and reliably control the operating temperature range of conventional CPOX fuel reactors operating in a SOFC system in order to avoid damage to the catalyst layer and to enhance electrical generation efficiency.

Additionally there is a need in the art to more proactively and reliably control the operating temperature range of conventional CPOX fuel reactors in order to avoid auto ignition of unprocessed fuels entering the CPOX fuel reactor and also to avoid auto ignition of process fuels passing through and exiting from the CPOX reactor.

3 Summary of the Invention

[0013] The present technology solves the above described problems with conventional fuel reformer systems and methods that utilize an exothermic chemical reaction to reform a hydrocarbon compound into a fuel comprising hydrogen gas (H_2) and carbon monoxide (CO). In particular the present technology provides an improved fuel reformer module incorporated into a Solid Oxide Fuel Cell (SOFC) system.

[0014] The fuel reformer module includes a fuel reactor body enclosing a hollow fuel chamber. The hollow fuel chamber is bounded by a perimeter wall disposed to surround a chamber longitudinal axis. A cap wall is attached to the perimeter wall and disposed to enclose a top end of the fuel chamber. A reactor shield base wall is attached to the perimeter wall and disposed to enclose a bottom end of the fuel chamber. The reactor shield base wall and permitted wall are preferably a single element, e.g. a metal casting.

[0015] The reactor shield base wall includes a base wall top surface facing into the hollow fuel chamber and a substantially parallel and opposing base wall bottom surface facing out of the hollow fuel chamber. A plurality of substantially identical base wall fuel passages extend through the reactor shield base wall from the base wall top surface to the base wall bottom surface and the base wall fuel passages provide the only exit through which fuel can flow out of the hollow fuel chamber.

[0016] Each base wall fuel passage has a substantially constant cross-sectional area along its longitudinal length and is axially centered by a passage longitudinal axis that is substantially parallel with the chamber longitudinal axis. A catalyzing body formed from a solid non-porous ceramic substrate includes a catalyzing body top surface and a substantially parallel and opposing catalyzing body bottom surface and a cylindrical side wall. The catalyzing body top surface is disposed proximately opposed to the base wall bottom surface across an interface. The interface defines a separation between an exit port of each base wall fuel passage and an input port of each catalyst fuel passage. The separation across the interface may be very small, e.g. when the bottom surface of the reactor shield base wall is in mating contact with the top surface of the catalyzing body, or the interface may include an air gap separating the bottom surface of the reactor shield base wall from the top surface of the catalyzing body. In addition to separating the exit port of each base wall fuel passage from the input port of each catalyst fuel passage, the interface separates an exothermic chemical reaction occurring inside each catalyst fuel passage from incoming fuel. More specifically thermal energy emitted by the exothermic chemical reaction reaches the bottom surface of the reactor shield base wall and inside surfaces of the plurality of base wall fuel passages across the interface and is at least partially absorbed by those surfaces.

[0017] The catalyzing body includes a plurality of substantially identical catalyst fuel passages with each catalyst fuel passage extending from the catalyzing body top surface to the catalyzing body bottom surface. Each of the plurality of catalyst fuel passage is formed with the same cross-sectional area along its longitudinal length and a catalyst layer is coated onto inside surfaces of each catalyst fuel passage. Each of the plurality of base wall fuel passages is longitudinally aligned with one of the plurality of catalyst fuel passages. Accordingly there is a one to one relationship between each base wall fuel passage and a corresponding catalyst fuel passage with each of the plurality of base wall fuel passages sharing a substantially coaxial longitudinal axis with its corresponding catalyst fuel passage.

[0018] The cross-sectional area of each of the plurality of base wall fuel passage is substantially identical and the cross-sectional area of each of the plurality of catalyst fuel passage is substantially identical however the cross-sectional area of the bases wall passages is smaller than the cross-sectional area of the catalyst fuel passages in order to expose an area of the bottom surface of reactor shield base wall to each catalyst fuel passage. This is done to allow thermal radiation emitted from inside each catalyst fuel passage to impinge on the bottom surface of reactor shield base wall for absorption. In a non-limiting example embodiment, the ratio of the cross-sectional area of a base wall fuel passage to the cross-sectional area of a catalyst fuel passage is less than 0.9 or between 0.6 and 0.9. In a non-limiting example embodiment, each of the plurality of base wall fuel passages has a circular cross-section having a diameter in the range of 0.65 to 2.6 mm and each of the plurality of catalyst fuel passages has a square cross-section with a side dimension ranging between, the diameter of the base wall fuel passage and about 1.26 times the diameter of the base wall fuel passages. In further a non-limiting embodiment, the diameter of a circular base wall fuel passage is in the range of 0.65 to 2.6 mm and its longitudinal length is between 10 and 20 times the diameter and the side dimension of a square fuel passage is in the range of 0.65 to 2.6 mm and its longitudinal length is between 5 to 40 times the side dimension.

[0019] The base wall fuel passages are arranged in an array pattern. The array pattern has a solid material area, where no holes exist, and a hole pattern area wherein holes exist. In a non-limiting example embodiment the ratio of the solid material area to hole pattern area is between 0.75 and 0.9.

[0020] A portion of fuel reactor body is exposed to ambient air in order to provide a surface area exposed to ambient air to dissipate thermal energy from. The entire fuel reactor body is formed from materials having a coefficient of thermal conductivity greater than 100 W/m°K in order to provide rapid thermal conductivity through the fuel reactor body and the fuel reactor body is formed to provide a substantially continuous thermally conductive path extending from the bottom surface of the reactor shield base wall to the portion of the fuel reactor body that is exposed to ambient air. The portion of the fuel reactor body that is exposed to ambient air includes a disk shaped heat dissipating flange extending radially out from the perimeter wall. A temperature sensing element in communication with a system controller is provided on a surface of the heat dissipating flange and an air moving device is provided to cool the heat dissipating flange by flowing ambient air over surfaces thereof.

[0021] The present technology further includes a fuel reforming method. The method includes delivering a flow of gaseous hydrocarbon compound into a hollow fuel chamber enclosed within by a fuel reactor body and then delivering the flow of gaseous hydrocarbon compound out of the hollow fuel chamber through a reactor shield base wall. The reactor shield base wall is formed by the fuel reactor body and includes plurality of substantially identical base wall fuel passages passing there through with each base wall fuel passage acting as an exit port.

[0022] The method includes receiving the flow of gaseous hydrocarbon compound exiting from each one of the plurality of base wall fuel passages into a plurality of corresponding catalyst fuel passages. Each catalyst fuel passage passes through a non-porous catalyzing body such as a ceramic structure. Each of the plurality of base wall fuel passages shares a substantially coaxial longitudinal axis with its corresponding catalyst fuel passage. Each of the plurality of catalyst fuel passages is coated on its inside surface or surfaces with a catalyzing layer. The catalyzing layer is suitable for reforming the gaseous hydrocarbon compound by catalyzed partial oxidation (CPOX) and the CPOX reaction emits thermal radiation.

[0023] The reactor shield base wall includes a top surface facing into the hollow fuel chamber and a substantially parallel and opposing bottom surface facing away from the hollow fuel chamber. The catalyzing body includes a top surface positioned opposed to the bottom surface of the reactor shield base wall across an interface.

[0024] A portion of the fuel reactor body is exposed to ambient air and the fuel reactor body is formed from materials having a coefficient of thermal conductivity greater than 100 W/m°K and provides a substantially continuous thermally conductive pathway extending from the reactor shield base wall bottom surface to the portion of the fuel reactor body is exposed to ambient air.

0025] The method further includes reforming the gaseous hydrocarbon compound inside each of the catalyst fuel passages by the CPOX reaction. As thermal energy is emitted from inside the catalyst fuel passages the thermal energy is absorbed by the reactor shield base wall bottom surface and by inside surfaces of any one of the plurality of base wall fuel passages. Once the thermal energy is absorbed by surfaces of the reactor shield base wall, thermal engery is thermally conducted through the fuel reactor body to the portion of the fuel reactor body exposed to ambient air. The method further includes monitoring a temperature of the portion of the fuel reactor body is exposed to ambient air and operating an air moving device to direct an ambient air flow across surfaces of the heat dissipating flange. The method further includes configuring the fuel reactor body with sufficient thermal mass and sufficient thermal energy dissipating surface area to maintain the fuel reactor body at a steady state operating temperature of less than 250°C.

4 Brief Description of the Drawings

[0026] The features of the present technology will best be understood from a detailed description of examplary embodiments thereof selected for the purposes of illustration and shown in the accompanying drawings in which:

[0027] Figure 1 depicts a schematic view of a non-limiting exemplary SOFC system embodiment according to the present technology.

[0028] Figure 2 depicts a schematic side section view taken through a non-limiting exemplary solid oxide fuel cell stack assembly according to the present technology.

[0029] Figure 3 depicts a schematic side section schematic view taken through a anon-limiting exemplary fuel reformer module of according to the present technology.

[0030] Figure 4 depicts a schematic side section view of a non-limiting exemplary catalyzing body embodiment of a SOFC system according to the present technology.

[0031] Figure 4A is a schematic diagram depicting surface area of the reactor base wall that is available to absorb thermal energy being radiated from catalyst fuel passages according to the present technology.

[0032] Figure 5 depicts a schematic top section view taken through a non-limiting exemplary cathode chamber according to the present technology.

[0033] Figure 6 depicts a bottom schematic section view taken through a non-limiting exemplary fuel reformer module according to the present technology.

4.1 Definitions

[0034] The following definitions are used throughout, unless specifically indicated otherwise:

[0035]

TERM	DEFINITION
Hastelloy	A group of alloys comprising predominantly metal nickel plus molybdenum, chromium, cobalt, iron, copper, manganese titanium, zirconium, aluminum and tungsten in varying percentages including zero in some alloys. Hastelloy alloys are primarily used for effective survival under high temperature and or high stress in moderate to severely corrosive environments. Available from Haynes International Inc. of Kokomo IN, USA.
Monel	A group of alloys comprising up to 67% metal nickel and about 30% copper with smaller amounts of iron, manganese, carbon and silicon. Monel is used for its resistance to corrosion. Available from Special Metals Corp. of New Hartford NY, USA.
SOFC	Solid Oxide Fuel Cell

Inconel	A family of austenitic nickel-chromium alloys comprising nickel 40-70%, chromium 14-30%, iron 3-9%, manganese 0.3-1%. plus silicon, carbon, sulfur, and other elements used for its resistance to oxidation and corrosion and strength over a wide range of temperatures. When heated, Inconel forms a thick stable passivating oxide layer protecting the surface from further attack. Attractive for high temperature applications to reduce creep. Available from Special Metals Corp. of New Hartford NY, USA
Cermet	Any of a class of heat-resistant materials made of ceramic and sintered metal. Often formed and sintered as a ceramic oxide mixture and converted through the reduction from an oxide ceramic to the metallic phase. (NiO-YSZ →Ni-YSZ)
Perovskite	A ternary material with the general structure $A^{[12]}B^{[6]}X_3^{[6]}$ same type of crystal structure as calcium titanium oxide ($CaTiO_3$).

5 Item Number List

[0036] The following item numbers are used throughout, unless specifically indicated otherwise.

[0037]

ITEM NUMBER	DESCRIPTION	ITEM NUMBER	DESCRIPTION
100	SOFC system	2200	Incoming air
105	Hot zone	2205	Air input port
110	Cold zone	2210	Recuperator chamber
115	Hot zone enclosure walls	2212	Flow barrier
120	Hot zone cavity	2214	Disk shaped separator wall
125	Anode gas	2230	Recuperator input ports
125a	Spent anode gas	2235	Recuperator output port
126	Cathode gas	2240	Air exit ports
126a	Spent cathode gas	2245	Cathode chamber exit port
127	Combustion exhaust gases	2300	Cold start combustion chamber
127a	Spent exhaust gas	2302	Cold start exit port
130	Thermal insulation	2304	Fuel inlet
132	Outer enclosure walls	2306	Ignitor
135	Fuel cell stack	2510	Intermediate cylindrical sidewall

140	DC power output module	2514	Outer cylindrical sidewall
145	Solid electrolyte layer	2516	Disk shaped outer top wall
150	Solid oxide anode electrode	2518	Disk shaped outer bottom wall
155	Solid oxide cathode electrode	3000	Fuel reformer system
157	Hot zone thermocouple/ temperature sensor	3005	Cylindrical fuel chamber
160	Incoming fuel	3010	Annular perimeter wall
165	Fuel reformer module	3015	Reactor shield base wall
167	Catalyst support structure	3017	Fuel chamber cap
170	Incoming air	3020	Fuel reformer module
175	Recuperator module	3025	Incoming fuel air mixture
180	Combustor module	3030	Cylindrical catalyzing body
185	Exhaust port	3032	Catalyzing body input end
190	Electronic controller	3034	Catalyzing body output end
195	Cold start module	3035	Cylindrical catalyzing cavity
197	Fuel input module	3040	Fuel reactor body
198	Air input module	3055	Fuel inlet manifold

		3060	Annular enclosure wall
2000	SOFC fuel cell stack assembly	3065	Catalyzing body support flange
2005	SOFC fuel cell stack	3070	Circular aperture
2010	Cathode chamber	3075	First annular washer
2015	Longitudinal cylindrical side wall	3080	Annular thermally insulting element
2016	Disk shaped bottom end wall	3085	Catalyst fuel passage
2017	Disk shaped top end wall	3088	Catalyst fuel passage (larger square)
2020	Fuel reformer module	3090	Catalyst layer
2025	Incoming fuel air mixture	3095	Base wall fuel passages
2026	Spent cathode gas	3100	Heat dissipating flange
2027	Reformed fuel/ syngas	3105	Annular seal plate
2028	Spent fuel	3110	O-ring seal element
2045	Fuel input conduit	3115	O-ring seal element
2055	Fuel inlet manifold	3120	Fasteners
2060	Longitudinal axis	3125	Array of fuel passages

2080	Tubular fuel cells	3130	Air moving element
2082	Disk shaped top tube support wall	3135	Temperature sensing element
2084	Disk shaped bottom tube support wall	3140	Communication pathway
2086	Tube holding flange	5000	SOFC system
2115	Anode gas flow	5002	Cathode chamber
2135	Combustion chamber	5010	Circumferential edge
2145	Cathode feed tube	5015	Inner shaded area
2150	Combustor exit port	5020	Outer shaded area
2155	Air gap	5025	Cathode feed tube
2165	System exit port	5030	Longitudinal central axis
2511	Disk shaped intermediate bottom end wall	5035	Inner circular pattern
2512	Layer of thermal insulation	5040	Tubular fuel cell
2513	Disk shaped intermediate top end wall	5045	Outer circular pattern

6 Detailed Description of the Invention:

6.1 Solid Oxide Fuel Cell System

[0038] Referring to Figure 1, a schematic diagram of a first exemplary non-limiting embodiment of the present technology depicts a Solid Oxide Fuel Cell (SOFC) system (100). The system (100) includes a hot zone (105) enclosed within hot zone enclosure walls (115) which in the present embodiment enclose a cylindrical hot zone cavity (120). The hot zone enclosure walls (115) are further enclosed by a layer of thermal insulation (130) which is further enclosed by outer enclosure walls (132). The hot zone enclosure walls (115) and the outer enclosure walls (132) each include a separate cylindrical side wall with each sidewall mechanically interfaced with a different pair of opposing disk shaped end walls described further below.

[0039] The hot zone enclosure walls (115) enclose a fuel cell stack (135). The fuel cell stack (135) includes at least one SOFC fuel cell but preferably includes a plurality of SOFC fuel cells each electrically interconnected in series or in parallel with a DC power output module (140). The DC power output module receives electrical power generated by the fuel cell stack and delivers output power to an external power load, (not shown). Each fuel cell comprises a solid oxide cathode electrode (155) which is oriented for exposure to cathode gas present inside the hot zone cavity (120). The hot zone cavity (120) is filled with a cathode gas (air) (126) during operation and the cathode gas in the hot zone cavity (120) chemically reacts with surfaces of the solid oxide cathode electrode (155). Each fuel cell further comprises a solid oxide anode electrode (150) which is not exposed to the hot zone cavity (120) or to the cathode gas contained therein but instead is oriented for exposure to an anode gas (reformed fuel) (125) such that during operation the anode gas is passed over the solid oxide anode electrode (150) in order to chemically react with the solid oxide anode electrode (150). The SOFC fuel cell further comprises a solid electrolyte layer (145) disposed to separate the solid oxide cathode electrode (155) from the solid oxide anode electrode (150). The solid electrolyte layer (145) is an oxygen ion conducting layer provided as an ion exchange medium for ion exchange between the solid oxide anode electrode (150) and the solid oxide cathode electrode (155).

[0040] The fuel cell stack (135) is maintained at a high operating temperature (*e.g.* ranging from 350 to 1200°C), depending on the composition of the solid material layers of the fuel cell stack and the characteristics of the anode and cathode gases. A preferred operating temperature is selected to support efficient electro-chemical energy generation. Electrical energy is generated by the fuel cell stack (135) when anode gas (125) comprising hydrogen is reacted with the solid oxide anode electrode (150) and cathode gas (126) comprising oxygen is reacted with the solid oxide cathode electrode (155).

[0041] The hot zone (105) further encloses a combustor module (180), or tail-gas combustor, which comprises a combustion chamber configured to receive spent anode gas (125a) and spent cathode gas (126a) after each of the spent anode gas and the spent cathode gas has reacted with the corresponding solid oxide anode electrode (150) and solid oxide cathode electrode (155). Upon mixing in the combustor module (180) the spent anode gas (125a) and the spent cathode gas (126a) are combusted. Thermal energy generated by combustion taking place inside the combustion module (180) is used to heat the hot zone enclosure walls (115) as well as the hot zone cavity (120).

[0042] The hot zone cavity (120) further encloses a recuperator module (175). The recuperator module (175) is in fluid communication with the combustor module (180) and receives combustion exhaust gases (127) exiting therefrom. The combustion exhaust gases (127) pass through the recuperator module (175) and transfer thermal energy therefrom to incoming air (170) when each of the combustion exhaust gases (127) and the incoming air (170) pass through separate gas conduits of a gas counter flow heat exchanger (not shown). Thereafter, spent combustion exhaust gas (127a) exits the recuperator module (175) and is delivered out of the hot zone through an exhaust port (185). The incoming air (170) after exiting from the recuperator module (175) comprises the cathode gas (126) which is delivered into the hot zone cavity (120).

[0043] The system cold zone (110) includes a fuel input module (197). Various hydrocarbon fuels such as propane, methane, or kerosene, and other suitable fuels, are received into the fuel input module (197) from various fuel sources (not shown). The fuel input module (197) is operable to modulate incoming fuel (160) delivered from the fuel source and deliver a desired volume or mass flow rate of incoming fuel (160) to the fuel reformer module (165). The fuel reformer (165) is operable to reform the fuel in a manner that makes the incoming fuel more suitable for the desired chemical reaction with the solid oxide anode electrode (150).

[0044] The incoming fuel (160) comprises a liquid or gaseous hydrocarbon compound from which hydrogen can be extracted. The incoming fuel (160) may be mixed with air and may be atomized or otherwise vaporized. The fuel reformer module (165) of the present technology comprises a Catalytic Partial Oxidation (CPOX) reactor which provides a catalyst support structure (167) having some of its surfaces coated by a catalytic layer, described below. As the incoming fuel is passed over the catalyst layer, the fuel is combusted or partially combusted inside the catalyst support structure (167). The heat generated by the combustion reforms the incoming fuel (160) into hydrogen gas (H_2) and carbon monoxide gas (CO). The reformed fuel exits the fuel reformer module (165) as anode gas (125) which is reacted with the solid oxide anode electrode (150) of each fuel cell in the SOFC fuel cell stack (135).

[0045] The system cold zone (110) includes an air input module (198) for incoming air (170) or another oxygen rich source gas into the recuperator module (175). Air or any other oxygen rich source gas is received into the air input module (198) from various air sources, (not shown), or the air comprises room air which is pumped into the recuperator module (175) by a fan. The air input module (198) is operable to modulate air flow into the recuperator module (175). The recuperator module (175) heats the incoming air (170) with combustion exhaust gases (127) by passing the combustion exhaust gases through a gas counter flow heat exchanger (not shown). The heated air exits the recuperator as the cathode gas (126).

[0046] The system cold zone (110) includes an electronic controller (190) in electrical communication with the fuel input module (197) and the air input module (198). The electronic controller (190) includes a digital data processor and associated digital data memory with various operating programs and or digital logic control elements operating thereon to manage operation of the SOFC system (100). The electronic controller (190) is in electrical communication with the DC power output module (140) to monitor and modulate DC power output to a load. The electronic controller is also in electronic communication with the fuel input module (197) to monitor and modulate incoming fuel (160) and further is in electronic communication with the air input module (198) to monitor and modulate incoming air (170) and further is in electronic communication with the at least one temperature sensors (157) to monitor the temperature of one or more surfaces of the hot zone enclosure walls (115), the outer enclosure walls (132), the fuel reformer module (165) and other surfaces as may be required to monitor temperature of various surfaces of the SOFC system (100).

[0047] Each of the fuel input module (197) and the air input module (198) may include one or more gas pressure regulators, gas flow actuator valves, mass or volume gas flow rate controllers and or mass flow rate sensors, or the like, gas pressure sensors, or the like, and temperature sensors, or the like, each operable by or otherwise in electrical communication with the electronic controller (190) to modulate incoming fuel (160) into the fuel reformer module (165) or incoming air (170) into the recuperator module (175). More specifically the fuel input module (197) in cooperation with the electronic controller (190) is operable to regulate input fuel pressure, to variably regulate incoming fuel mass or volume flow rates and to stop incoming fuel (160) from entering the SOFC system (100) as required. Similarly, the air input module (198) in cooperation with the electronic controller (190) may also be operable to regulate input air pressure, to variably regulate incoming air mass or volume flow rates and to stop incoming air (170) from entering the SOFC system (100) as required. In some operating environments the air input module (198) may comprise a simple fan running at constant angular velocity without any further air input control sensors or elements.

[0048] According to the present technology the fuel reformer module (165) is configured to cause an exothermic reaction between the incoming fuel (160) and catalyst layers provided on surfaces of the ceramic catalyst support structure (167) in order to reform the fuel into hydrogen gas (H_2) and carbon monoxide (CO). Further, according to the present technology an improved fuel reformer module (165) comprises a ceramic catalyst support structure (167) comprising a plurality of longitudinal fuel flow passages, described below, with each longitudinal fuel flow passage being coated on internal surfaces thereof with a catalyst layer. In addition, the fuel reformer module (165) is configured to prevent auto ignition of unprocessed fuels entering the ceramic catalyst support structure (167) in part by providing the longitudinal fuel flow passage as a means of transferring thermal energy generated by the exothermic reaction taking place inside the ceramic catalyst support structure (167) out of the ceramic catalyst support structure (167) along the longitudinal pathways toward the incoming fuel. As can be seen in Figure 1, the fuel reformer module (165) is disposed in part between the outer enclosure walls (132) and in part outside the outer enclosure walls (132) and is further configured to provide a thermally conductive pathway that passes through the outer enclosure walls (132). In addition the SOFC system (100) optionally includes one or more cooling devices (*e.g.* air fans, water pumps, or the like) to cool portions of the fuel reformer module (165) that are disposed outside the outer enclosure walls (132).

[0049] The SOFC system (100) may optionally include a cold start module (195). The cold start module (195) is configured to receive and combust a portion of the incoming fuel (160) which is redirected into the cold start module (195). Operation of the cold start module (195) is initiated by the electronic controller (190) when the temperature of the incoming fuel (160) or the temperature of the hot zone enclosure walls (115) or the temperature of the fuel cell stack (135) is below a desired operating or reaction temperature. In operation, a portion of the incoming fuel (160) is diverted to a combustion chamber associated with the cold start module (195). A controllable fuel ignitor is provided inside a combustion chamber of the cold start module (195) and fuel inside the combustion chamber is ignited and combusted to heat the incoming fuel (160), the fuel reformer module (165) and the hot zone enclosure walls (115) during a cold start. Once the SOFC system (100) reaches its desired operating temperature, operation of the cold start module (195) is terminated.

[0050] During operation, the electronic controller (190) is in communication with other electronic elements such as one or more cooling fans, one or more electrically operable gas flow valves, gas flow rate detectors, and or gas modulators, associated with the fuel input module (197), the air input module (198) and electrical power output detectors, or the like, and other elements as may be required to control various operating parameters of the SOFC (100). The electronic controller (190) monitors DC current/power output as well as temperature measured by one or more thermocouples, or the like, and further operates to vary the mass flow rate of incoming fuel and optionally of incoming air as a means of increasing or decreasing DC current/power output.

6.2 Solid Oxide Fuel Cell Stack Side Section

[0051] Turning now to Figure 2, a second non-limiting exemplary embodiment of an improved SOFC fuel cell stack assembly (2000) according to the present technology is shown in side section view. In particular the SOFC fuel cell stack assembly (2000) includes a SOFC fuel cell stack (2005) comprising a plurality of tubular fuel cells (2080) each longitudinally extended along a substantially cylindrical hot zone cavity or cathode chamber (2010).

[0052] The cylindrical cathode chamber (2010) is bounded by cylindrical hot zone enclosure walls which include an open ended longitudinal cylindrical side wall (2015) that is mechanically interfaced with a disk shaped bottom end wall (2016) and with an opposing disk shaped top end wall (2017). The cylindrical cathode chamber (2010) is formed as a gas tight chamber and each wall thereof comprises materials having a high coefficient of thermal conductivity, *e.g.* between 100 and 300 W/(m°K), and preferably above 200 W/(m°K). Accordingly, the longitudinal cylindrical side wall (2015), disk shaped bottom end wall (2016) and disk shaped top end wall (2017) are fabricated from one or more of copper, molybdenum, aluminum copper, copper nickel alloys, or a combination thereof, and each wall is preferably nickel coated on surfaces that face the cathode chamber (2010) or on any surfaces that may be exposed to an oxygen rich environment. The nickel coating is provided in order to prevent surface oxidation due to contact with oxygen rich gases. Specifically each of the hot zone enclosure walls (2015, 2016, 2017) is configured to provide a thermally conductive pathway for rapid conduction of thermal energy by thermal conduction from one area of the hot zone to another in order to more rapidly reduce temperature gradients and maintain the entire hot zone enclosure wall structure substantially at the same temperature. Additionally disk shaped bottom end wall (2016) and disk shaped top end wall (2017) are each preferably formed with a copper core having sufficient thermal mass to rapidly absorb thermal energy from the cold start combustion chamber (2300) and the combustion chamber (2135) and to rapidly distribute the absorbed thermal energy to the side wall (2015) by thermal conduction.

[0053] In the present example embodiment, the disk shaped bottom end wall (2016) also forms a bottom wall of a recuperator chamber (2210). As described above the recuperator chamber (2210) is provided to heat incoming air (2200) entering the fuel cell stack assembly through a cathode feed tube (2145). The incoming air (2200), or cathode gas, flows into the recuperator chamber (2210) through recuperator input ports (2230) and out of the recuperator chamber (2010) returning back to the cathode feed tube (2145) through recuperator output ports (2235). One or a plurality the recuperator input ports (2230) and the recuperator output port (2235) may be disposed around the circumference of the cathode feed tube (2145). A flow barrier (2212) directs air flow toward peripheral walls of the recuperator chamber (2210) thereby increasing thermal energy exchange between air passing through the recuperator chamber and its peripheral walls. The recuperator chamber (2210) is bounded on a top side thereof by a disk shaped separator wall (2214) disposed between a combustion chamber (2135) and the recuperator chamber (2210). The disk shaped separator wall (2214) is configured to absorb thermal energy as spent anode and spent cathode gas is combusted inside the combustion chamber (2135) such that the absorbed thermal energy is reemitted into the recuperator chamber (2210).

[0054] An intermediate cylindrical enclosure surrounds the hot zone enclosure walls. The intermediate cylindrical enclosure is bounded by an open ended longitudinal intermediate cylindrical side wall (2510) that mechanically interfaces with a disk shaped intermediate bottom end wall (2511) and an opposing disk shaped intermediate top end wall (2513). The intermediate cylindrical enclosure is sized to form an air gap (2155) substantially surrounding the longitudinal cylindrical side wall (2015) and the disk shaped top end wall (2017). The air gap (2155) provides a fluid flow passage proximate to portions of the hot zone enclosure walls and the fluid passage is in fluid communication with a system exit port (2165). The air gap (2155) is further in fluid communication with the combustion chamber (2135) through one or more combustor exit ports (2150) and is in fluid communication with a cold start combustion chamber (2300) through one or more cold start exit ports (2302). Accordingly exhaust gas exiting each the combustion chamber (2135) and the cold start combustion chamber (2300) flows over outside surfaces of the hot zone enclosure walls before exiting the fuel cell stack assembly (2000) through the system exit port (2165). In one non-limiting example embodiment the dimension of the air gap (2155) from an exterior surface of wall (2015) to an interior surface of wall (2510) ranges from 1 to 4 mm.

[0055] An outer cylindrical enclosure surrounds the intermediate cylindrical enclosure. The outer enclosure is bounded by an open ended outer cylindrical side wall (2514) that mechanically interfaces with a disk shaped outer bottom wall (2518) and an opposing disk shaped outer top wall (2516). Each of the walls (2514), (2518) and (2516) preferably comprises aluminum or an aluminum alloy preferably having a coefficient of thermal conductivity above 140 W/m°K to support rapid thermal energy conduction in order to provide a substantially homogeneous temperature of the outer cylindrical enclosure during operation. A layer of thermal insulation (2512) is disposed between outside surfaces of the intermediate enclosure walls and the inside surfaces of outer enclosure walls and the layer of thermal insulation (2512) impedes thermal energy being radiated across the air gap (2155) or being carried through the air gap by exhaust gases exiting the SOFC system from reaching surfaces of the outer cylindrical side wall (2514) and the disk shaped outer bottom wall (2518). Preferably, the layer of thermal insulation (2512) is constructed to ensure that surfaces of the outer cylindrical side wall (2514) and the disk shaped outer bottom wall (2518) remain within operational parameters, *e.g.* the layer of thermal insulation (2512) is configured to prevent the temperature of the outer cylindrical side wall (2514) and the disk shaped outer bottom wall (2518) from reaching more than about 110°C.

[0056] A plurality of tubular fuel cells (2080) also known as fuel rods or rods are longitudinally supported inside the cathode chamber (2010) between disk shaped top tube support wall (2082) and opposing disk shaped bottom tube support wall (2084). Each tubular fuel cell (2080) comprises a solid oxide anode electrode support structure that forms the inside diameter of the tube. A solid ceramic electrolyte layer is formed over the outside diameter of the solid oxide anode electrode support layer and a solid oxide cathode electrode layer is formed over the outside diameter of the solid electrolyte layer. Each tubular fuel cell (2080) is open at both ends thereof and provides a cylindrical fluid conduit for anode gas, also referred to herein as reformed fuel or syngas, to flow through. A plurality of tube holding flanges (2086) are optionally provided to support tube ends with respect to the top tube support walls (2082) and the bottom tubular support wall (2084). Each tube holding flange (2086) also includes an electrically conductive terminal electrically interfaced to the DC power output module (140).

[0057] The solid anode electrode used to form the support layer of each tubular fuel cell (2080) may comprise a cermet material such as nickel and doped zirconia, nickel and doped ceria, or copper and ceria. Alternately the solid anode electrode may comprise a perovskite such as Sr2Mg1-xMnxMoO6-δ or La 0.75Sr0.25Cr0.5Mn0.5O3-δ. In either case the inside surface of each of the tubular fuel cells (2080) comprises the solid oxide anode electrode and anode gas flow (2115) passes through each disk shaped top tube support wall (2082) such that only anode gas flow (2115) enters each of the tubular fuel cells (2080) through a fuel inlet manifold (2055) to react with the solid anode electrode.

[0058] The solid oxide cathode electrode may comprise any one of Lanthanum Strontium Cobalt Oxide (LSC), Lanthanum Strontium Cobalt Iron Oxide (LSCF) or Lanthanum Strontium Manganite (LSM). The solid oxide cathode electrode forms an outside surface of each tubular fuel cell (2080). As the cathode chamber (2010) is filled with the incoming air (2200) (*i.e.* cathode gas), the cathode gas reacts with the solid oxide cathode electrode formed on the outside surface of each tubular fuel cell (2080).

[0059] The electrolyte layer is disposed between the anode layer and the cathode layer. The preferred electrolyte layer comprises an ion conducting ceramic medium and preferably comprises an oxygen ion conductor such as yttria doped zirconia or gadolinium doped ceria. Alternately, the electrolyte layer is a proton conducting ceramic such as barium cerates or barium zirconates. Ideally, the electrolyte layer is formed with sufficient thickness so as to provide a near hermetic barrier between the anode electrode and the cathode electrode to prevent anode and cathode gas from crossing the electrolyte layer.

[0060] The improved SOFC fuel cell stack assembly (2000) optionally includes a cold start combustion chamber (2300). The cold start combustion chamber (2300) is housed within the intermediate chamber walls and is bounded by the intermediate longitudinal cylindrical side wall (2510), the intermediate top wall (2513) and the disk shaped top end wall (2017) of the cathode chamber. The cold start combustion chamber (2300) forms an annular chamber volume that partly surrounds the fuel reformer module (2020). When starting the SOFC system from a cold start, a portion of the incoming fuel air mixture (2025) is diverted to the cold start chamber (2300) through a fuel inlet (2304) and ignited by an ignitor (2306). Thus during a cold start a portion of the incoming fuel air mixture (2025) is combusted in the cold start combustion chamber (2300). The thermal energy generated by combustion in the cold start combustion chamber (2300) is radiated into the surrounding walls thereof, which includes the disk shaped top end wall (2017), that is specifically configured with a copper core provided to rapidly absorb thermal energy. Once absorbed by the disk shaped top end wall (2017) thermal energy is rapidly conducted through the hot zone enclosure walls which all comprise highly thermally conductive materials. Exhaust from combustion taking place inside the cold start chamber (2300) exits the chamber through exhaust ports (2302) and passes through the air gap (2155) to the system exit port (2165). During the passage through the air gap (2155) the combustion exhaust transfers thermal energy to the hot zone enclosure walls (2015) and (2016) by radiation and convection to further aid in heating the system to a desired steady state operating temperature.

[0061] The incoming fuel air mixture (2025) enters the improved SOFC fuel cell stack assembly (2000) through a fuel reformer module (2020). In the present preferred embodiment the fuel reformer is a Catalytic Partial Oxidation (CPOX) reactor. The fuel reformer module (2020) receives the incoming fuel air mixture (2025) through the fuel input conduit (2045) and reforms the incoming fuel air mixture (2025) to provide reformed fuel or syngas (2027) which is used as the anode gas to react with the solid oxide anode electrode formed on the inside wall of each of the tubular fuel cells (2080). The reformed fuel or syngas (2027) exits from the fuel reformer module (2020) and enters a fuel inlet manifold (2055). The fuel inlet manifold (2055) is configured to distribute anode gas into a top or input end of each of the plurality of tubular fuel cells (2080). At the bottom or output end of each tubular fuel cell (2080), spent fuel (2028) comprising hydrogen depleted anode gas exits the tubular fuel cell to the combustion chamber (2135) where is it mixed with spent cathode gas (2026) or oxygen depleted air and combusted.

[0062] Incoming air (2200), or cathode gas, shown by dashed lines, enters the improved SOFC fuel cell stack assembly (2000) through the cathode feed tube (2145), passes through the recuperator chamber (2210) where it is heated by surfaces thereof and then reenters the cathode feed tube through recuperator output ports (2235). The heated air then passes through the combustion chamber (2135) while flowing through the cathode feed tube (2145) where the air is further heated by thermal energy being generated by combustion and being transferred to and through the wall of the cathode feed tube (2145) before entering the cathode chamber (2010). A plurality of air exit ports (2240) pass through the cathode feed tube (2145), inside the cathode chamber (2010) and the heated air enters the cathode chamber (2010) through the air exit ports (2240). Once inside the cathode chamber, the heated air or cathode gas reacts with the solid oxide cathode electrode formed on the outside surface of each tubular fuel cell (2080). Spent cathode gas (2026) exits the cathode chamber through cathode chamber exit ports (2245) to the combustion chamber (2135) where it is mixed with spent anode gas (2028) and combusted. Exhaust gas exits from the combustion chamber (2135) to the air gap (2155) through the combustor exit ports (2150) to heat the walls of the recuperator chamber (2210) as the exhaust gas flows toward the system exit port (2165).

6.3 Solid Oxide Fuel Cell Stack Top Section View

[0063] The schematic diagram of Figure 2 depicts a schematic side section view of an improved SOFC fuel cell stack assembly (2000) that shows only two tubular fuel cells (2080) to simplicity the description. However a preferred stack comprises more than two tubular fuel cells (2080) with the fuel cells arranged within the cathode chamber (2005) in a manner that provides efficient use of space, promotes efficient gas flow patterns and provides the desired power output at the desired voltage.

[0064] Referring now to Figure 5 the figure depicts a non-limiting exemplary schematic top section view taken through a non-limiting exemplary cathode chamber of an improved SOFC stack (5000) of one example of the present technology. The cathode chamber (5002) is bounded by an open ended longitudinal cylindrical side wall, *e.g.* longitudinal cylindrical side wall (2015) shown in Figure 2 which defines a circumferential edge (5010). The inner shaded area (5015) represents the longitudinal intermediate cylindrical side wall (2510) and the air gap (2155) shown in Figure 2. The outer shaded area (5020) represents the layer of thermal insulation (2512) and the outer cylindrical side wall (2514) shown in Figure 2.

[0065] A cathode feed tube (5025) is positioned at the center of the cathode chamber (5002) to distribute cathode gas into the cathode chamber through a plurality of radially disposed air exit ports, *e.g.* (2240) shown in Figure 2. A longitudinal central axis (5030) centers the cathode feed tube (5025) and the circumferential edge (5010).

[0066] The improved SOFC stack (5000) includes a plurality of substantially identical tubular fuel cells (5040) each comprising a solid oxide anode electrode that structurally forms the inside diameter of each tubular fuel cell (5040) and with a solid oxide cathode electrode formed on the outside diameter of each tubular fuel cell (5040). A first plurality of tubular fuels is arranged in an inner circular pattern (5035) with the center of each of the first plurality of tubular fuels at the same radial distance from the longitudinal central axis (5030) as shown by the inner circular pattern (5035). The inner circular pattern (5035) may be a symmetrical circular pattern wherein the inner tubular fuel cells are equally spaced apart around the inner circular pattern (5035) or the first plurality of tubular fuel cells may be positioned around the inner circular pattern (5035) with unequal angular distribution or angular separation.

[0067] A second plurality of tubular fuel cells is arranged in an outer circular pattern (5045) with the center of each of the second plurality of tubular fuel cells at the same radial distance from the longitudinal central axis (5030) as shown by the outer circular pattern (5045). The outer circular pattern (5045) may be a symmetrical circular pattern wherein the second plurality of fuel cells is equally spaced apart around the outer circular pattern (5045) or the second plurality of fuel cells may be positioned around the outer circular pattern (5045) with unequal angular distribution of angular separation. In the present example embodiment the total number of fuel cells is twenty two (22). Other patterns of fuel cell distribution with other total number of fuel cells are usable without deviating from the present technology.

6.4 Improved CPOX Fuel Reformer

[0068] Referring now to Figures 2-4 a fuel reformer system (3000) according to the present technology is shown in a schematic side section view in Figure 3 and partially in exploded side section view in Figures 4 and 4A. The fuel reformer system (3000) comprises a fuel reformer module (3020) mounted above a fuel inlet manifold (3055). The fuel reformer module (3020) includes a fuel reactor body (3040) configured to receive an incoming fuel air mixture (3025), *i.e.* unreformed fuel, into a cylindrical fuel chamber (3005) which is bounded by an annular perimeter wall (3010), by a reactor shield base wall (3015) and a by a fuel chamber cap (3017). In a preferred embodiment, fuel chamber cap (3017) is welded to the annular side wall (3010). The fuel reformer system (3000) further includes a cylindrical catalyzing body (3030). Each of the fuel reactor body (3040) and the cylindrical catalyzing body (3030) is installed into a cylindrical catalyzing cavity (3035) with the cylindrical catalyzing body (3030) positioned just above the fuel inlet manifold (3055) and the fuel reactor body (3040) position just above the cylindrical catalyzing body (3030). Each of the fuel reactor body (3040) and the cylindrical catalyzing body (3030) is configured to provide fluid communication between the cylindrical fuel chamber (3005) and the fuel inlet manifold (3055).

[0069] A preferred reactor body material has a coefficient of thermal conductivity greater than 100 W/(m°K) and sufficient mass to rapidly conduct thermal energy away from the interface between the fuel reactor body (3040) and the catalyzing body (3030). A preferred catalyzing body material comprises a ceramic substrate having a coefficient of thermal conductivity of less than about 40 W/m°K in order to discourage thermal conduction through the ceramic substrate, either longitudinally or radially. Ideally the present technology is configured to allow the catalyzing body (3030) to reach a state of thermal equilibrium during operation.

More specifically the thermal equilibrium prevents or reduces thermal gradients along the radial axis of the catalyzing body which helps to prevent local hot spots that can burn through the catalyzing layers (3090).

[0070] In the present non-limiting exemplary embodiment the cylindrical catalyzing cavity (3035) has a side wall formed by an inside diameter of the annular enclosure wall (3060) which is formed with its longitudinal central axis coaxial with the central longitudinal axis (2060), shown in Figure 2. The cylindrical catalyzing cavity (3035) includes two open ends each forming a circular aperture with one circular aperture passing through the disk shaped outer top wall (2516) of the outer enclosure and the other circular aperture passing through the disk shaped top end wall (2017) of the hot zone enclosure.

[0071] In a preferred embodiment the annular enclosure wall (3060) is formed to be less thermally conductive that the fuel reactor body (3040) in order to discourage thermal conduction between the annular enclosure wall (3060) and the fuel reactor body (3040). In a preferred embodiment, the annular enclosure wall (3060) comprises Hastelloy or Monel which each have a high nickel content to resist oxidation damage and which each have suitable service temperatures ratings, *e.g.* exceeding 400°C, and which each have a coefficient of thermal conductivity of less than about 25.0 W/(m°K). Additionally the annular enclosure wall (3060) is thin walled, *e.g.* between 0.02 and 0.1 inches thick to further disclosure thermal conduction there through.

[0072] A catalyzing body support flange (3065) extends from or is formed by the disk shaped top end wall (2017). The catalyzing body support flange (3065) is sized to define a diameter of a circular aperture (3070) which is small enough to prevent the cylindrical catalyzing body (3030) from passing through the circular aperture (3070). A first annular washer (3075) is disposed between the catalyzing body support flange (3065) and a bottom surface of the cylindrical catalyzing body (3030). The first annular washer (3075) provides a gas seal between the cylindrical catalyzing cavity (3035) when a longitudinal downward pressure is applied to the cylindrical catalyzing body (3030). Additionally the first annular washer (3075) is configured as a thermal insulator to thermally isolate the catalyzing body support flange (3065) from the disk shaped top end wall (2017). Preferably, first annular washer (3075) comprises alumina formed with sufficient thickness and with appropriate outer edge diameter dimension to provide the desired gas sealing and thermal insulating properties. More generally, the first annular washer (3075) preferably comprises a very low thermal conductivity non-porous material, *e.g.* having a coefficient of thermal conductivity of less than 40 W/m°K, which includes most ceramic materials.

[0073] A diameter of the cylindrical catalyzing cavity (3035) is sized to receive an annular thermally insulating element (3080) into the cylindrical catalyzing cavity (3035) surrounding the cylindrical catalyzing body (3030). The annular thermally insulating element (3080) is provided to thermally isolate the cylindrical catalyzing body (3030) from the annular enclosure wall (3060). Additionally the annular insulating element (3080) is configured to precisely center the cylindrical catalyzing body (3030) with respect to a central longitudinal axis of the cylindrical catalyzing cavity (3035) and may be further configured to angularly orient the cylindrical catalyzing body (3030) for precise angular alignment with one or more features of the fuel reactor body (3040). Both the first annular washer (3075) and the annular insulating element (3080) are provided to prevent thermal conduction from the enclosure walls, *e.g.* the annular enclosure wall (3060) and the top end wall (2017), to the catalyzing body (3030) which is preferably operating with a higher temperature than the cylindrical catalyzing body.

[0074] The cylindrical catalyzing body (3030) comprises a solid non-porous ceramic substrate formed to include a plurality of longitudinally disposed catalyst fuel passages (3085) each passing completely through the cylindrical catalyzing body (3030). Each catalyst fuel passage (3085) provides an individual fuel conduit that extends longitudinally through the cylindrical catalyzing body (3030). Accordingly each catalyst fuel passage provides fluid communication between the cylindrical catalyzing cavity (3035) and the fuel inlet manifold (3055). Additionally inside surfaces of each of the catalyst fuel passage (3085) are formed with a catalyst layer (3090) coated thereon. The catalyst layer (3090) comprises a catalyst material usable to reform the incoming fuel air mixture (3025) by catalytic partial oxidation, which is an exothermic reaction that causes partial combustion of the fuel air mixture (3025). In the present non-limiting exemplary embodiment a preferred catalyst layer (3090) comprises a metallic or oxide phase of rhodium (Rh). Other suitable catalyzers usable for the catalyst layer (3090) include Pt, Pd, Cu, Ni, Ru and Ce. The solid non-porous ceramic substrate used to form the cylindrical catalyzing body (3030) preferably comprises alumina or any other non-porous material having a relatively low coefficient of thermal conductive as compared to the coefficient of thermal conductive of the fuel reactor body (3040). In the present non-limiting embodiment wherein a ceramic substrate is used the coefficient of thermal conductive of the catalyzing body is less than 40 W/m°K.

[0075] As will be described further below the incoming fuel air mixture (3025) enters the cylindrical fuel chamber (3005), passes through the reactor shield base wall (3015), enters each of the catalyst fuel passages (3085), where it reacts with the catalyst layer (3090), and then enters the fuel inlet manifold (3055) where it is distributed into each of the tubular fuel cells (2080).

6.5 Fuel Reactor Body

[0076] Referring now to Figures 2, 3, 4 and 4A, the fuel reactor body (3040) is disposed partially within the cylindrical catalyzing cavity (3035) and partially extending through the disk shaped outer top wall (2516) into the cold zone such that at least a portion of the fuel reactor body (3040) is exposed to ambient air. The annular perimeter wall (3010) provides a cylindrical side wall of the cylindrical fuel chamber (3005). The fuel input conduit (2025) passes through the annular perimeter wall (3010) to deliver incoming air fuel mixture (2025/3025) into the cylindrical fuel chamber (3005). As will be recognized, other geometries are usable to form the annular perimeter wall (3010) and fuel chamber (3005) which can have a square, rectangular or other cross-sections in transverse planes thereof.

[0077] The reactor shield base wall (3015) comprises a circular bottom wall of the cylindrical fuel chamber (3005) that is preferably integrally formed with the annular perimeter wall (3010). However, the reactor shield base wall (3015) and annular perimeter wall can be formed as separate parts and joined together, for example by welding, soldering, mechanical fasteners, and or other suitable joining techniques. A plurality of base wall fuel passages (3095) each passes completely through the reactor shield base wall (3015) along a longitudinal axis, *e.g.*

with each base wall fuel passage parallel with the central longitudinal axis (2060). Each base wall fuel passage (3095) provides a fuel conduit that extends longitudinally through the reactor shield base wall (3015). Moreover each base wall fuel passage (3095) is longitudinally aligned with and in fluid communication with a corresponding one of the plurality of catalyst fuel passages (3085) that pass through the cylindrical catalyzing body (3030).

[0078] As shown in Figures 4 and 4A, an interface (3032) is defined by a bottom external surface of the reactor shield base wall (3015) and a top or input surface of the cylindrical catalyzing body (3030). In a non-limiting exemplary embodiment one or the other or both of the two surfaces that form the interface (3032) includes a raised feature or features (3033). The raised features may include a circular ring or a plurality of discreet raised bumps, preferably three, formed at one more locations extending from the bottom surface of the reactor shield base wall (3015) in a position that causes the raised features to contact the opposing surface at the interface (3032) in order to provide a small gap between the two opposing surfaces. More generally the interface (3032) is formed with a gap between the bottom surface of the reactor shield base wall (3105) and the top surface of the cylindrical catalyzing body (3030). The gap is provided to all allow radiant thermal energy exiting from each of the catalyst fuel passages to impinge onto the bottom surface of the reactor shield base wall (3015) so that substantially all of the bottom surface of the reactor shield base wall (3015) is available to absorb thermal radiation impinging thereon.

[0079] At the interface (3032) each base wall fuel passage (3095) is aligned with its corresponding catalyst fuel passages (3085) along a substantially coaxial longitudinal axis. In this arrangement the fuel air mixture (2025) being delivered into the cylindrical fuel chamber (3005) passes out of the cylindrical fuel chamber (3005) through each of the plurality of base wall fuel passages (3095) flows across the gap provided between the surfaces of the interface (3032) and enters each of the corresponding catalyst fuel passage (3085). Once inside the catalyst fuel passages (3085) the fuel air mixture begins to react with the catalyst coated sidewall surfaces (3090) and the fuel air mixture begins the catalyzed partial oxidation reaction used to convert the fuel air mixture into reformed fuel or syngas. According to an aspect of the present technology, thermal energy generated by the CPOX reaction taking place inside the catalyst fuel passages (3085) is radiated onto the bottom surface of the reactor shield base wall (3105) for partial absorption thereby. Additionally thermal energy generated by the CPOX reaction taking place inside the catalyst fuel passages (3085) is radiated onto inside surfaces of the base wall fuel passages (3095) for partial absorption thereby.

[0080] The fuel reactor body (3040) is formed from materials having a relatively high thermal conductivity as compared to the thermal conductivity of the ceramic material used to form the cylindrical catalyzing body (3030). A preferred reactor body material has a coefficient of thermal conductivity greater than 100 W/(m°K). Thus in one non-limiting example embodiment the entire fuel reactor body (3040) is formed from a unitary piece of copper or a copper alloy, from a unitary piece of beryllium or a beryllium alloy, from an unitary piece of aluminum or an aluminum alloy, of a unitary piece of brass or a brass alloy, of a unitary piece of tungsten or a tungsten alloy, wherein the alloys may include molybdenum, nickel, chromium, brass, tungsten or the like. In the present example, unitary means the entire fuel reactor body (3040) is formed from a single piece of metal, e.g. cast or machined. In alternate embodiments the fuel reactor body (3040) can be formed from a plurality of cast or machined elements that assembled together, e.g. weld, brazing or mechanically fastening in a manner that provides a continuous thermally conductive path. In any case a desired material has a coefficient of thermal conductivity that is at least greater than 100 W/(m°K) with some embodiments using materials having a coefficient of thermal conductivity in excess of 300 W/(m°K). Additionally the wall thicknesses and or thermal mass of the fuel reactor body (3040) is sufficient to promote rapid thermal conduction from a high temperature region of the reactor body (3040) proximate to the interface (3032) to a low temperature region of the reactor body (3040), e.g. the region disposed outside the hot zone, and to minimize temperature gradients between the interface (3032) and the elements of the reactor body that are disposed outside the hot zone. An additional characteristic of the reactor body material is that it preferably has a service temperature at least exceeding 200°C and preferably up to 1000°C.

[0081] In the present non-limiting exemplary embodiment, the fuel reactor body (3040) is formed from aluminum, preferably the Aluminum 6061 alloy, with a coefficient of thermal conductivity of approximately 167 W/(m°K). Aluminum and aluminum alloys are preferred because they spontaneously form a stable oxide layer that protects the bulk structure from corrosive oxidative damage and can be used without an additional applied protective coating. Additionally, the aluminum and aluminum alloys can be anodized to prevent or reduce surface oxidation. In a preferred embodiment the entire fuel reactor body (3040) comprises a solid element comprising a single piece of aluminum 6061 alloy; however the fuel reactor body (3040) may comprise an assembly formed by assembling a plurality of individual subassembly elements together using mechanical fasteners, welding or brazing, or using interlocking mechanical features, or the like, without deviating from the present technology.

[0082] More specifically according to an important aspect of the present technology the relative thermal conductivity of each of the cylindrical catalyzing body (3030), the annular enclosure wall (3060) and the fuel reactor body (3040) is selected to promote thermal conduction from the interface (3032) to a heat dissipating flange (3100), disposed outside the hot zone, and to promote absorption of thermal radiation impinging on surfaces of the reactor shield base wall (2015). This is accomplished by configuring the fuel reactor body (3040) as the most thermally conductive element local to the interface (3032) and by configuring the fuel reactor body (3040) to extend outside the hot zone where it is either actively cooled e.g. by moving air passing over the surfaces of the fuel reactor body or passively cooled, e.g. by simply exposing surfaces to the fuel reactor body (3040) to ambient air. Thus the configuration of the fuel reactor body (3040) establishes and maintains a temperature gradient between the interface (3032) and external ambient air, outside the hot zone, by providing a thermally conductive path between the interface (3032) and a cooler portion of the fuel reactor body which are provided by exposing a portion of the fuel reactor body to ambient air. The resulting temperature gradient between the portion of the fuel reactor body exposed to ambient air and the portion of the reactor body proximate to interface (3032) tends to promote substantially continuous thermal energy conduction through the fuel reactor body (3040) from the interface (3032) to the portion of the fuel reactor body that is exposed to ambient air.

[0083] The fuel reactor body (3040) includes a heat dissipating flange (3100), *e.g.* a disk shaped flange radially extending from the annular perimeter wall (3010). The heat dissipating flange (3100) is supported above the disk shaped outer top wall (2516) external to the outer enclosure and exposed to surrounding air. Preferably the heat dissipating flange (3100) is integrally formed with the annular perimeter wall (3010) but the heat dissipating flange (3100) may comprise a separate element attached to the annular perimeter wall (3010) by welding, soldering, mechanical fasteners, or other attaching means.

[0084] An annular seal plate (3105) is disposed between the disk shaped outer top wall (2516) and the heat dissipating flange (3100) to provide a mechanical interface between a top surface of the disk shaped outer top wall (2516) and a bottom surface of the heat dissipating flange (3100). The annular seal plate (3105) includes a centered through hole sized to receive the annular perimeter wall (3010) there through. An O-ring seal element (3110), or the like, is disposed between the annular seal plate (3105) and the heat dissipating flange (3100), *e.g.* in an O-ring groove, and serves to gas seal a top portion of the cylindrical catalyzing cavity (3035). A second O-ring seal element (3115), or the like, may be provided between a top surface of the disk shaped outer top wall (2516) and a bottom surface of the annular seal plate (3105).

[0085] Both the annular seal plate (3105) and the heat dissipating flange (3100) are attached to the disk shaped outer top wall (2516) by fasteners, or the like, in a manner that applies a downward force against the fuel reactor body (3040) in order to seat the bottom surface of the reactor shield base wall (3015) against the top surface of the cylindrical catalyzing body (3030) at the interface (3032), or the raised surfaces (3033) formed thereon, and further in order to compress the O-ring seal element (3110) and the O-ring seal element (3110).

[0086] Referring now to Figure 6, a schematic top section view of the fuel reactor body (3040) depicts the heat dissipating flange (3100) radially extending from the annular perimeter wall (3010). Fasteners (3120) extend through the dissipating flange (3100) and the annular seal plate (3105) to attach the heat dissipating flange (3100) and the annular seal plate (3105) to the disk shaped outer top wall (2516). The annular perimeter wall (3010) extends radially outside the annular enclosure wall (3060) such that the seal plate (3105) seals the cylindrical catalyzing cavity (3035). An array (3125) of base wall fuel passages (3095) is depicted passing through the reactor shield base wall (3015).

[0087] Referring now to Figure 3, the fuel reformer system (3000) may include external cooling and temperature sensing elements readable by the electronic controller (190). In one non-limiting example embodiment, an air moving element (3130), such as a rotary fan blade attached to a rotary motor, operable by the electronic controller (190), is disposed to direct air flow over the heat dissipating flange (3100), thereby increasing convective thermal energy transfer from the flange (3100) to the surrounding ambient air. Additionally a temperature sensing element (3135) in contact with a surface of the heat dissipating flange (3100), or one or more other surfaces of the fuel reactor body (3040) is usable to deliver a temperature signal to the electronic controller (190) over a communication path (3140). Operation of air moving element (3130) may be constant or may be variably triggered by changes in the temperature signal emitted by the temperature sensing element (3135). In one non-limiting operating mode the air moving element (3130) is activated when the temperature sensing element (3135) reports a temperature that is above a desired high temperature limit, e.g. above 50°C, and the air moving element (3130) is deactivated when the temperature sensing element (3135) reports a temperature that is below a desired high temperature limit, e.g. below 45°C.

[0088] Additionally, the temperature signal emitted by the temperature sensing element (3135) is usable to control operation of the cold start combustion chamber (2300) such as to stop fuel flow to the cold start combustion chamber (2300) when the temperature of the heat dissipating flange (3100) reaches a desired steady state temperature range.

[0089] In an example operating mode the electronic controller (190) receives temperature signals from the temperature sensing element (3135) over communication pathway (3140) and determines an instantaneous flange temperature based thereon. The electronic controller (190) then determines whether the flange temperature is within one or more desired temperature ranges and if not carries out various commands such as to operate or stop operating the air moving element (3130) and or to start or stop fuel flow to the cold start combustion chamber (2300) or to cease fuel delivery to the fuel reformer system (3000) by commanding the fuel delivery module (197) to close the fuel valve when the instantaneous temperature indicated by the temperature sensing element (3135) exceeds a safe operating limit. In one non-limiting operating mode the electronic controller (190) is configured to activate the air moving element (3130) when the temperature of the heat dissipating flange (3100) exceeds 50°C. In other example embodiments the air moving element (3130) may have multiple operating modes usable to move more or less air depending on need based on different temperature thresholds.

6.6 The Interface Configuration

[0090] Referring now to Fig. 4 an exploded side section view of the interface (3032) between corresponding pairs of base wall fuel passages (3095) and catalyst fuel passages (3085), shows that each corresponding pair of reactor shield base wall fuel passages (3095) and catalyst fuel passages (3085) is aligned along a common longitudinal axis. Thus each corresponding pair of base wall fuel passages and catalyst fuel passages provides a vertical flow path through which the fuel air mixture passes from the cylindrical fuel chamber (3005) to the fuel inlet manifold (3055). As noted above a gap may be provided between the mating surface of the interface (3032) to expose surfaces of the reactor shield base wall (3015) to thermal radiation being emitted by the CPOX reaction but the gap is not shown in Figure 4 to simplify the disclosure. As indicated by the reference number (3090) a catalyst layer is formed on the sidewall of each catalyst fuel passage (3090). As is further shown in Figure 4, a pointer referring to Fig. 4A indicates that Fig. 4A depicts a schematic view of the interface (3032) as viewed from inside a catalyst fuel passage (3085) looking toward its fuel input end. In the present non-limiting example embodiment the diameter (D) of each of the circular base wall fuel passages (3095) is 1.3 mm and the thickness of the reactor shield base wall is 13 mm such that each fuel passage (3095) is 13 mm long. In a preferred embodiment the ratio of fuel passage longitudinal length to its diameter is at least 5, preferably 10 and up to 20. The side wall dimension of each of the square catalyst fuel passages (3085) is 1.3 mm and the thickness of the cylindrical catalyzing body (3030) is about 25.4 mm such that each catalyst fuel passage (3085) is 25.4 mm long. In a preferred embodiment the ratio of catalyzing passage longitudinal length to its square side dimension is at least 10, preferably 15 – 25 and up to 40.

[0091] The cylindrical catalyzing body (3030) has a circular cross-section and an array of catalyzing fuel passages (3085) is formed within the circular cross-section over a circular region having a diameter of 25.4 mm (1.0 in.) Each of the catalyzing fuel passages of the array has a square cross-section and extends completely through the cylindrical catalyzing body (3030). In the present non-limiting exemplary embodiment each square catalyzing fuel passage has a side dimension of 1.3 mm and a length of 25.4 mm. Alternately, the catalyzing body (3030) and the array of fuel passages can have other non-circular cross-sections without deviating from the present technology.

[0092] The reactor shield base wall (3015) is formed with an array of circular base wall fuel passages (3095) formed within a 25.4 mm (1.0 in.) diameter circular array region opposed to the circular array region of the cylindrical catalyzing body (3030). In the present non-limiting exemplary embodiment each circular base wall fuel passage (3095) has a diameter of 1.3 mm and a length of 13.0 mm. Alternately, the reactor shield base wall (3015) and the array region formed thereon can have other non-circular cross-sections without deviating from the present technology. As described above each circular base wall fuel passage (3095) in the array of base wall fuel passages is coaxial with one of the square catalyst fuel passages (3088) in the array of catalyst fuel passages such that a central longitudinal axis of each base wall fuel passage (3095) is coaxial with a central longitudinal axis of a corresponding catalyst fuel passage (3085).

[0093] Solid material of the reactor shield base wall (3015) surrounds each circular base wall fuel passage and solid material of the cylindrical catalyzing body (3030) surrounds each square catalyst fuel passage. In a non-limiting exemplary array pattern, all the passages are arranged in a plurality of parallel linear arrays. Each linear array is offset from an adjacent linear array by the same pitch dimension of 1.2 times the circular passage diameter. In the present example the pitch dimension is 1.56 mm. Based on this non-limiting exemplary array disposed over a 25.4 mm diameter circle, the total number or circular passages (3095) in the circular array area is approximately 208.

[0094] The combined area of the 208 passages each having a 1.3 mm diameter is 276 mm^2. The total area of the 25.4 mm diameter array area is 507 mm^2. Thus the area of solid material in the circular array area is approximately 231 mm^2 such that the bottom surface of the reactor shield base wall (3015) provides about 231 mm^2 of surface area facing the interface (3032) that is available to absorb radiant thermal energy impinging thereon. In the present example embodiment the ratio of solid surface area to hole diameter area is 0.84. As a percentage of the total area of the circular array about 54% of the total area is circular passage area and about 46% of the total area is solid material area. As will be recognized by those skilled in the art the ratio of surface area to hole diameter area can be increased by decreasing the diameter of the circular base wall fuel passages. Since the surface area at the interface (3032) is impinged by radiate thermal energy emitted by the CPOX reaction, increasing the solid surface area, without a change in temperature, increases thermal energy absorption into the reactor shield base wall (3015). In a preferred embodiment the ratio of solid surface area to hole diameter area ranges between 0.75 to 0.9.

[0095] As noted above radiant thermal energy emitted by the CPOX reaction also enters the circular base wall fuel passages (3095) and at least a portion of the radiate thermal energy impinges onto inside surfaces thereof. While the incident angle of radiant thermal energy impinging on the inside surfaces of circular base wall fuel passages (3095) is nearly grazing, the passages are long compared to the passage diameter and reflected energy, even when reflected at near grazing incidence is scattered and ultimately impinges onto and reflects from the inside surfaces over many reflection cycles as it traverses a fuel passage (3095). The total surface area of inside surfaces of all 208 circular passages is about 11043 mm^2.

[0096] Referring now to Fig. 4A the figure depicts the interface (3032) of a single circular fuel passage (3095) and a single square catalyst fuel passage (3085) as viewed from the fuel inlet manifold (3055). As further shown, according to the present technology, each base wall passage (3095) has a circular cross-section having a diameter (D) along its entire longitudinal length and each catalyst fuel passage (3085) has a square cross-section having a side dimension (S) along its entire longitudinal length. In the non-limiting exemplary embodiment of Fig. 4A, the diameter (D) and the side length (S) are equal and an area (B), shown filled with vertical lines, is an exposed surface area of the bottom surface of the reactor shield base wall (3015). The surface area (B) is located at the interface (3032) proximate to the input end of each catalyst fuel passage (3085) and is specifically provided to absorb thermal radiation being radiated from the catalyzing surface (3090). Additionally when a gap between the opposing surfaces of the interface (3032) is provided, thermal radiation enters the gap in part by reflecting from surface area (B).

[0097] Equation (1) below provides the area of surface area (B):

$$A_s - A_c = S^2 - \pi(D/2)^2 \qquad \text{EQU: 1}$$

- where, A_s is the area of a square (3085) having side length (S)
- A_c is the area of a circle (3095) having diameter (D). In the case where S=D the surface area A_B of the surface area (B) is:

$$(A_B) = S^2\,(1 - \pi/4) = 0.2146\,S^2 \qquad \text{EQU: 2}$$

[0098] In other words the area of surface (B) is about 21% of the area of the square (3085). As will be recognized, the area A_B can be increased to increase exposure of the surface (B) to thermal radiation being generated inside the catalyzing fuel passages e.g. by increasing the square side dimension from (S) to (S1), or by decreasing the diameter (D) of the circular passages (3095). When the side dimension of a catalyst fuel passage is increased from (S) to (S1) the area S_B can be increased to 50% of the area of the square of dimension (S1) when the ratio S1/D is equal to about 1.253.

[0099] The surface area (B) is directly exposed to the CPOX reaction taking place inside the square catalyst fuel passages (3085) and is in the best position to absorb thermal energy radiating out of the catalyst fuel passages. In a non-limiting exemplary embodiment of the present technology even when there is no gap at the interface (3032) the surface (B) as well as the inside surfaces of the base wall fuel passages (3095) provide sufficient surface area of the cooler reactor shield base wall (3015) to absorb sufficient radiant thermal energy emitted by the CPOX reaction to prevent catalyst layer burn through. However, as will be recognized by those skilled in the art, when the gap is provided, additional radiant thermal energy enters the gap and may impinge onto and be reflected from the cooler solid material surface areas of the reactor shield base wall (3015) over many cycles absorb additional thermal energy emitted by the CPOX reaction.

6.7 Thermal Energy Transfer

[00100] Without wishing to be bound by theory, Applicants believe that the exothermic catalyzed partial oxidation reaction is initiated immediately upon contacting the catalyst layer (3090) proximate to the interface (3032). Additionally Applicants believe that the exothermic catalyzed partial oxidation reaction reaches its maximum temperature proximate to the interface (3032) with the maximum temperature approximately between 900 and 1000°C, depending on the fuel material, the ratio of fuel to air mixture, and other factors. In response to the rapid heating proximate to the interface (3032) the temperature of the fuel air mixture rapidly increases and thermal energy is absorbed by the fuel air mixture as well as by the catalyst layers (3090). In response to the temperature increase, the fuel air mixture rapidly expands in volume to fill the catalyst fuel passage (3085) and exit to the fuel inlet manifold. During the gas expansion more of the fuel air mixture comes into contact with the catalyzing layer (3090) distal from the interface (3032) to participate in the exothermic catalyzed partial oxidation reaction thereby further heating and expanding the fuel air mixture. Thus most of the thermal energy generated by the catalyzed partial oxidation reaction is absorbed by the fuel air mixture and carried out of the catalyst fuel passage to the fuel inlet manifold (2055). In an example operating mode the volume of fuel air mixture delivered into the CPOX reactor is believed to generate about 300 watts during the CPOX reaction.

[00101] A portion of the thermal energy generated by the catalyzed partial oxidation reaction is absorbed by the catalyzing layer (3090). In the present example the catalyst layer is metallic (*e.g.* Rh), with a coefficient of thermal conductivity of about 150 W/m°K. Thus thermal energy absorbed by the catalyzing layer (3090) is thermally conducted through the catalyzing layer thickness to the reach ceramic catalyzing body (3030) and is further conducted along the longitudinal length of the catalyzing layer. However since the catalyst

body (3030) is a ceramic material with a coefficient of thermal conductivity of about 45 W/m°K, the heat flux density (W/m^2) entering the ceramic material is low resulting in thermal energy absorbed by the catalyzing layer being reemitted into the catalyzing fuel passages instead of being thermally conducted into the ceramic material. However this result is desirable since the low heat flux density along the radial axis of the ceramic catalyzing body prevents thermal energy from being conducted radially away from the catalyzing fuel passages to the extent that thermal energy is either *a)* transferred to the fuel air mixture inside the fuel passages or *b)* radiated out of the ends of the fuel passages either to the fuel inlet manifold or onto the surface area (B) described above, or *c)* radiated onto other exposed solid material surfaces of the reactor shield base wall, e.g. by entering the gap provided at the interface, or *d)* radiated into the circular base wall fuel passages to either be transferred to the incoming gas air mixture by convective heat transfer or *e)* radiated onto inside surfaces of the base wall fuel passages (3095) to be absorbed thereby.

[00102] Thus thermal energy absorbed by the catalyzing layer is not readily dissipated to the ceramic catalyzing body (3030). Instead the thermal energy is reemitted into the catalyzing fuel passage to further heat the fuel air mixture. Additionally thermal energy emitted or reflected by the catalyzing layer impinges onto other surfaces of the catalyzing layer and is partially absorbed and partially reflected thereby. However without at least one outlet for thermal radiation to exit the catalyst fuel passage the energy absorption rate of the catalyzing layer (3090) may exceed the energy reemission rate thereby causing the temperature of the catalyzing layer to continue to increase until it reaches a temperature that causes the catalyzing layer to burn off causing permanent damage to catalyzing fuel passages.

[00103] As described above Applicants believe that the total power generated by the CPOX reaction is 300 W. Using the Stefan Boltzmann equation listed below as equation 3 the total power that can be absorbed by the collective surface area (B) shown in Figure 4A, *i.e.* based on 208 base wall passages (3095) can be estimated given the surface area and temperature.

$$P=e\sigma AS_f(T_c^4-T_b^4) \qquad \text{EQU. 3}$$

- where, P = net absorbed power (watts);

- e = surface emissivity;
- $\sigma = 5.6703 \times 10^{-8}$ (W/m^2K^4) the Stefan Boltzmann constant;
- A = area onto which radiation is radiated (m^2);
- Sf – a form factor related to the incidence angle at which the radiation impinges on the surface area A;
- T_c = temperature of radiation source (°K); and
- T_b = temperature of the surface area A (°K).

[00104] Of particular importance is the fact that when Tc and Tb are equal, equation 3 shows that the net radiated power absorbed by the reactor shield base wall (3015) is zero. Thus without cooler surface areas provided by the reactor shield base wall (3015) the surface temperatures inside the catalyst fuel passages can continue to increase until the catalyst layer overheats and burns through.

[00105] In a non-limiting example embodiment wherein each square catalyst fuel passage (3085) has a side dimension (S) equal to 1.3 mm (0.0013m) and each circular base wall passage (3095) has a diameter of 1.3 mm, the collective area of all the surface areas (B), denoted A_{Bt} for an array of 208 passages is 7.38×10^{-5} m^2. Assuming that the CPOX reaction temperature is 1000°C (1273°K) and the temperature of each surface area A_B is 100°C (373°K) and using the simplified case where the emissivity e = 1.0, equation 3 predicts that the combined surface area A_{Bt} can absorb about 11 W or about 3.6% of the power generated by the CPOX reaction.

[00106] If a gap is provided at the interface (3032) such that the entire solid surface area of the bottom surface of the reactor shield base wall (3015), denoted A_S is potentially available to absorb thermal energy, the available solid material surface area A_S is 2.31×10^{-4} m^2 and equation 3 predicts that the area A_S can absorb about 34 W or about 11.3% of the power generated by the CPOX reaction.

[00107] If in addition the surface area of the inside surfaces of all 208 circular fuel passages (3095) is potentially available to absorb thermal energy, the available surface area of all the

circular fuel passages, denoted A_P is 1.1043×10^{-2} m^2 and equation 3 predicts that the surface area A_P can absorb about 1632 W or about 211% of the power generated by the CPOX reaction.

[00108] As a practical matter, the above listed thermal energy absorption power values are calculated using a firm factor Sf=1 which is the case when the thermal radiation impinges the surface at normal incidence. While this may be the case for the surface area A_{Bt}, a value of Sf=1 is not realistic for the surfaces areas A_S and A_P. Additionally as a practical matter the surface emissivity (e) of a heavily oxidized aluminum surface is not 1.0 but instead is about 0.25 or less. Accordingly the energy absorption values are more realistically represented when Equation 3 is used with surface emissivity e=0.25 for all three surfaces areas A_{Bt}, A_S and A_P and with the form factor Sf=1 for the surface area A_{Bt}, and Sf=0.1 for the surface areas A_S and A_P. In this case Equ. 3, predicts that the surface area A_{Bt} potentially absorbs about 2.75 W, the surface area A_S potentially absorbs about 0.85 W and the surface area A_P potentially absorbs about 44.6 W. Thus the reactor shield base wall (3015) when maintained at about 100°C potentially absorbs about 16% of the total power emitted by the CPOX reaction.

[00109] Those skilled in the art will recognize that additional thermal energy can absorbed by increasing the available surface area or by lowering the temperature of the reactor shield base wall (3015). As noted above according to the present technology the surface temperature of the heat dissipating flange (3100) is preferably maintained in a range of 50-100°C which due to the high thermal conductivity of the fuel reactor body (3040) likely maintains the temperature of the entire reactor shield body (3040) at nearly the same temperature but provides a thermal graduate between the fuel reactor base wall (3015) and the heat dissipating flange (3100). As noted above this allows thermal energy to be absorbed from the CPOX reaction and prevents the unprocessed fuel passing through the fuel reactor body (3040) from reaching its auto ignition temperature of 295 to 580 °C depending on which fuels are in use.

[00110] Thus maintaining the reactor shield base wall (3015) described above at a temperature of 100°C during operation and providing a small gap, e.g. about 1mm at the

interface (3032) has the potential of absorbing about 43W of thermal energy or about 14% of the total energy being radiated by the CPOX reaction at a temperature of 1000°C. However those skilled in the art will recognize that increasing the shape factor, increasing the surface area and decreasing the temperature of the fuel reactor body (3040) can remove additional thermal energy from each of the catalyst fuel passage (3085).

6.8 Operating Mode

6.8.1 Cold Start

[00111] Referring to Figures 1-3, from a cold start, the fuel input module (197) is operated by the electronic controller (190) to deliver a fuel air mixture into the cold start combustion chamber (2300) through a fuel input inlet (2304) and to ignite the fuel air mixture inside the cold start combustion chamber (2300) with an electric ignitor (2306) operable by the electronic controller (190). At the same time or shortly thereafter the fuel input module (197) also operates to deliver fuel air mixture into the fuel reformer module (3020) through the fuel input conduit (2045) and the fuel air mixture passes through the fuel reformer module (3020) to the fuel input manifold (2055). Preferably the initial flow rate of the fuel air mixture being delivered through the fuel reformer module is very low and is intended to merely fill the SOFC system with a nearly stationary volume of fuel air mixture.

[00112] The ignited fuel inside the cold start combustion chamber (2300) heats walls of the cold start combustion chamber (2300) but the top end wall (2017) is configured to absorb more thermal energy than the other walls of the cold start combustion chamber. As the temperature of the top end wall (2017) increases, thermal energy is thermally conducted from the top end wall (2017) to other regions of the hot zone enclosure walls (115). Additionally the top end wall (2017) and other walls of the hot zone enclosure (115) begin to emit thermal radiation into the fuel inlet module (2055) which is absorbed by the fuel air mixture contained therein, increasing its temperature. Exhaust gas generated by combusting the fuel air mixture inside the cold start combustion chamber (2300) exits from the cold start combustion chamber (2300) through cold start exit ports (2302) and flows through the air gap (2155) to a

system exit port (2165). As the hot exhaust gas flows through the air gap (2010) it radiates thermal energy to outside surfaces of the longitudinal cylindrical side wall (2015) which increase in temperature.

[00113] The top end wall (2017) is attached to the longitudinal cylindrical side wall (2015) which is further attached to disk shaped bottom tube support wall (2084) and disk shaped separator wall (2214). Each of the top end wall (2017), the longitudinal cylindrical side wall (2015), the disk shaped bottom tube support wall (2084) and the disk shaped separator wall (2114), collectively form the hot zone enclosure walls (115). As noted above, each of the hot zone enclosure walls is fabricated from one or more of copper, molybdenum, aluminum copper, copper nickel alloys, or a combination thereof such that the entire hot zone enclosure wall structure (115) forms a continuous thermally conductive path having a coefficient of thermal conductivity between about 100 and 300 W/(m°K), and preferably above 200 W/(m°K). Additionally where surfaces of any of the hot zone enclosure walls are exposed to an oxygen rich environment the wall surfaces are preferably nickel coated to prevent oxidation.

[00114] In the case of the three disk-shaped walls, (2017), (2084) and (2214), each of these walls is configured to provide a thermal mass that is capable of absorbing and redistributing thermal energy to other regions of the hot zone enclosure walls by thermal conduction and by reemitting the absorbed thermal energy to cooler areas surrounding each disk-shaped wall such as into the fuel inlet manifold (2055), the cathode chamber (2010), the combustion chamber (2135) and the recuperator chamber (2210). Thus as the top end wall (2017) is heated by combustion inside cold start combustion chamber (2300) thermal energy is absorbed by the top end wall and rapidly conducted to all regions of the hot zone enclosure walls (2017), (2015), (2084), (2214) until the entire hot zone enclosure wall assembly reaches an equilibrium temperature. Moreover as thermal energy is absorbed or emitted by the hot zone enclosure walls its equilibrium temperature varies substantially uniformly across all regions of the hot zone enclosure walls due to its high thermal conductivity.

[00115] Thus, during the startup period at least a portion of the thermal energy generated by combustion of fuel in the cold start combustion chamber (2300) is absorbed by top end wall

(2017). A further portion is absorbed by the longitudinal cylindrical sidewall (2015) as the hot exhaust gas flows through the air gap (2155) to the system exit port (2165). As the temperature of the top end wall (2017) increases, the top end wall (2017) begins to reemit thermal energy into the cooler fuel inlet manifold (2055) which serves to increase the temperature of whatever fuel air mixture is contained therein and or flowing there through.

[00116] Eventually, the temperature of the fuel air mixture inside the fuel inlet manifold (2055) reaches a reaction temperature suitable for initiating a CPOX reaction. The initial CPOX reaction occurs when the fuel air mixture having been heated to the reaction temperature makes contact with the catalyst layers (3090) proximate to the catalyzing body input or top surface located at the interface (3032) where the catalyzing body interfaces with the back end or bottom surface of the fuel reformer module (3020). Once the CPOX reaction is initiated at the output ends of some or all of the catalyst fuel passages (3085) the temperature inside each catalyst fuel passage (3085) rapidly increases along its longitudinal length spreading the CPOX reaction to the interface (3032) and the CPOX reaction becomes self-sustaining.

[00117] Once a self-sustaining CPOX reaction is achieved, the fuel input module (197) is operated to discontinue the flow of fuel air mixture to the cold start combustion chamber (2300) and to adjust the input rate of the fuel air mixture being delivered though the fuel reformer module (3020) as required to maintain the self-sustaining CPOX reaction and generate electrical power. However combustion inside the cold start combustion chamber (2300) may be continued until full power DC power output is also self-sustaining. The electronic controller (190) can become aware of the self-sustaining CPOX reaction by various sensors including temperature sensors provided on a wall of the hot zone enclosure, by the temperature sensor (3135) provided on the heat dissipating flange (3100), by a temperature sensor provided proximate to the system exhaust port (2165), by detecting a DC power signal at the DC power output module (140) and by various other sensing means.

[00118] To heat the cathode gas, the electronic controller (190) operates the air input module (198) to deliver a flow of air/cathode gas, into the air input port (2205). While this step can be taken simultaneously with igniting the cold start chamber or even before igniting the cold

start chamber, it can also be delayed until a self-sustaining CPOX reaction is achieved. Preferably the initial flow rate of the incoming air being delivered through the recuperator chamber (2210) is very low and is intended to merely fill the SOFC system with a nearly stationary volume of air.

[00119] The flow of incoming air exits the cathode feed tube (2145) through the recuperator input port (2235), passes through the recuperator chamber (2210) to the recuperator output port (2235) and the exits the cathode feed tube (2145) to the cathode chamber (2010) through the plurality of air exit ports (2240). After reacting with the solid oxide cathode electrode formed on outside surfaces of each tubular fuel cell (2080) the air/cathode gas, exits the combustion chamber (2135), passing through the cathode chamber exit ports (2245) to the combustion chamber (2135) where it mixes with spent fuel air mixture and for combustion. Thereafter the combustion byproducts exit the combustion chamber through combustor exit ports (2150) to the air gap (2155) and out of the system through the system exit port (2165).

[00120] The main air heating element is the disk-shaped separator wall (2214) provided inside the recuperator chamber (2210). As described above, the disk-shaped separator wall (2214) is part of the hot zone enclosure and therefore begins to increase in temperature during the start-up phase almost concurrently with increases in temperature of the disk-shape top end wall (2017) that forms the base wall of the cold start combustion chamber (2300). Additionally the disk-shaped separator wall (2214) is thermally conductively coupled to the disk-shaped bottom tube support wall (2084) and both walls are heated by combusting the mixture of spent fuel and spent air inside the combustion chamber (2135). Thus at about the same time that the disk-shape top end wall (2017) begins to radiate enough thermal energy into the fuel input manifold (2055) to raise fuel temperature, the disk-shaped separator wall (2214) begins to radiate enough thermal energy into the recuperator chamber (2210) to raise the temperature of the incoming air. At the same time the hot zone enclosure walls are radiating thermal energy into the cathode chamber (2010) which serves to heat the air contained therein and to heat the walls of the tube shaped fuel cells of the fuel cell stack (2005). Once the CPOX reaction becomes self-sustaining the flow rate of both the incoming

air and the fuel air mixture may be adjusted as required to maintain the self-sustaining CPOX reaction and to generate electrical power at desired power output amplitude.

6.8.2 Initiating an SOFC Reaction

[00121] As described above, the fuel air mixture and the incoming air/cathode gas are heated by the hot zone enclosure walls which are heated by combustion taking place inside the cold start combustion chamber (2300). Eventually a self-sustaining CPOX reaction is initiated inside the catalyst fuel passages (3085) which heats the fuel air mixture to a higher temperature and the fuel is reformed into a syngas which is capable of reacting with the solid oxide anode electrodes formed on the inside surfaces of each of the tubular fuel cells (2080). The higher temperature syngas also radiates thermal energy onto the anode electrode electrodes as it passes through the tubular fuel cells (2080). As the temperature of the anode electrode increases the cathode electrode is heated by thermal energy being radiated into the cathode chamber (2010) by the longitudinal cylindrical sidewall (2015) and heated air/cathode gas entering the cathode chamber (2010) from the recuperator chamber (2210).

[00122] Eventually the anode and cathode electrodes, the syngas and the air/cathode gas inside the cathode chamber reach a reaction temperature where a DC power begins to be generated and output to the DC power terminals. Eventually the gas temperature inside the combustion chamber (2135) reaches a combustion temperature and the thermal energy generated by the combustion occurring inside the combustion chamber increases the incoming air temperature to a steady state operating temperature. In one non-limiting example operating mode, the syngas, the incoming air and the tubular fuel cells (2080) have a steady state operating temperature of between 350 and 1200°C with a preferred operating temperature range of 800 - 1000°C. Meanwhile the hot zone enclosure walls (115) constantly redistribute thermal energy by thermal conduction such that the hot zone enclosure wall temperature increases and decreases substantially uniformly over all regions thereof until a steady state operating temperature is reached and then maintained.

6.8.3 Fuel Reformer Operating Mode

[00123] Referring now to Figures 3-4A, as described above, the fuel reformer module (3020) is at least partially thermally isolated from the cold start combustion chamber (2300) and the hot zone enclosure walls in order to prevent the fuel air mixture inside the fuel chamber (3005) from reaching its auto ignition temperature prior to entering the cylindrical catalyzing body (3030). More specifically depending on the fuel being used the fuel auto ignition temperature range is approximately 295 to 580°C. By comparison the operating temperature range of the SOFC system, again depending on fuel and electrode layer materials, is 350 to 1200°C. Additionally as pointed out above the CPOX reaction temperature range is estimated to be 900 to 1000°C.

[00124] During a cold start, the fuel air mixture (3020) enters the cylindrical fuel chamber (3005) and passes through the reactor shield base wall (3015) and then through the cylindrical catalyzing body (3032) to the fuel input manifold (3055). The fuel air mixture then flows through the tubular fuel cells and eventually out of the system. As described above the present technology manages thermal energy generated by combustion inside the cold start combustion chamber (2300) in a manner that facilitates a greater transfer of thermal energy to the disk shaped top end wall (2017) than is transferred to the other cold start combustion chamber walls (2510) and (2513). This is managed by configuring the disk shaped top end wall (2017) with a greater thermal mass than the combined thermal mass of the other walls (2510) and (2513).

[00125] More specifically, thermal energy transfer (Q) is governed by equation 4:

$$Q = C_{th} \Delta T \qquad \text{EQU. 4}$$

- where Q= thermal energy transfer (J)
- C_{th} = thermal mass of wall (J/°C)
- ΔT = temperature difference between the hot gas and the wall.

[00126] In the present example ΔT is approximately the same for each wall; however the thermal mass of each wall is different. The thermal mass C_{th} is defined as the product of wall material mass (m) in units of (g) and the specific heat capacity (μ) in units of (J/g°C) of the

material, where mass (m) is the product of wall material volume V in units of (cm^3) and material density (ρ) in units of (g/cm^3).

$$C_{th} = \rho\ V\ \mu \qquad \text{EQU. 5}$$

- where ρ = material density (g/cm^3)
- V = material volume (cm^3)
- μ = material specific heat capacity of the material (J/g°C).

[00127] In a non-limiting example embodiment the disk shaped top end wall (2017) comprises mostly copper and the other walls (2510) and (2513) surrounding the cold start combustion chamber (2300) comprises mostly Hastelloy. For copper, the specific heat capacity (μ) is 0.385 J/g°C. For Hastelloy, the specific heat capacity (μ) of Hastelloy is 0.450 J/g°C. For copper, the density (ρ) is 8.96 g/cm^3 and for Hastelloy the density (ρ) is 8.22 g/cm^3. Thus ensuring that the top end wall (2017) absorbs more thermal energy that the other walls combined is accomplished when (Q_t) of the disk shaped top end wall (2017) is greater that (Q_o) of all the other walls combined which when expressed in terms of equation 4 when the term ΔT is the same for each wall simplifies to:

$$C_{th}t > C_{th}o \text{ or } (\rho_c\ Vt\ \mu_c) > (\rho_h\ Vo\ \mu_h)$$

- where $C_{th}t$ = thermal mass of the top end wall
- $C_{th}o$ = thermal mass of the other walls combined
- Vt = volume of the top end wall
- Vo = volume of the other walls combined
- ρ_c = density of copper and ρ_h = density of Hastelloy
- μ_c = specific heat of copper and μ_h = specific heat Hastelloy;

with the result of the present example that:

$$\mathbf{V_t > 1.07\ V_o}$$

[00128] In other words the thermal mass of the top disk shaped top end wall (2017) exceeds the thermal mass of other cold start combustion chamber walls (2510) and (2513) when the volume (V_t) of the disk shaped top end wall (2017) exceeds 1.07 times the combined volume

(V_o) of the other walls (2510) and (2513). Thus according to the present technology the thermal mass of the top disk shaped top end wall (2017) exceeds the thermal mass of other cold start combustion chamber walls (2510) and (2513) combined and preferably by 100% or more or according to the above example when the volume of the disk shaped top end wall (2017) is 2.14 times the combined volume (V_o) of the other walls (2510) and (2513) which can be accomplished simply by increasing the thickness of the wall (2017) to achieve the desired volume ratio.

[00129] As a result, more thermal energy is absorbed by the top end wall (2017) than is absorbed by all the other cold start combustion chamber walls combined. A primary advantage of this embodiment is absorbing the majority of thermal energy generated by the fuel air mixture being combusted inside the cold start combustion chamber (2300) into the top end wall (2017) and then rapidly distributing that energy to other areas of the SOFC system through the thermal conductive path formed by hot zone enclosure walls. In particular during the cold start process combustion energy from the cold start chamber is primarily absorbed by the top end wall (2017) and reemitted into the fuel inlet manifold (2055) to sufficiently heat the fuel air mixture contained therein to a temperature that is high enough to initiate the CPOX reaction at the output end (3034) of the catalyst fuel passages (3085). A secondary advantage of this embodiment is that the majority of thermal energy generated by the fuel air mixture being combusted inside the cold start combustion chamber (2300) is diverted away from the fuel reformer module (3020).

[00130] Once the CPOX reaction is initiated and self-sustaining the fuel reactor body (3040) provides a thermally conductive path and sufficient thermal mass to rapidly conduct thermal energy from the reactor shield base wall (3015) to the heat dissipating flange (3100). In particular since the interface (3032) is proximate to the CPOX reaction which has a temperature of 900 – 1000°C thermal energy reaches the reactor shield base wall (3015) in varying amounts by radiation, thermal conduction, and convection and is absorbed by the exposed surface (B) and the remaining solid material of the bottom surface of the reactor shield base wall (3015), as well as internal surfaces of the circular base wall fuel passages (3095) shown in Fig. 4 and 4A. As a result the initial CPOX reaction proximate to the

interface (3032) is effectively quenched to prevent auto ignition of incoming fuel air mixture. In particular the combined surface area (B) denoted A_{Bt} potentially absorbs about 1% of the total thermal radiation emitted from all the catalyst fuel passage (3085) and the solid surface area of the reactor shield base wall at the interface, denoted A_S above, potentially absorbs about 0.2% of the total thermal radiation emitted from all the catalyst fuel passage (3085) and internal surfaces of the base wall fuel passages (3095) potentially absorb about 13.6% for a combined total of about 15%.

[00131] According to the subject technology the thermal mass of the reactor shield base wall (3015) , *i.e.* its volume, is formed large enough to provide sufficient energy transfer from the catalyst fuel passages (3085) to prevent over heating therein when the reactor shield base wall can be maintained at or below 100°C. Additionally according to the subject technology the thermal mass of the fuel reactor body (3040), *i.e.* its volume, is formed large enough to provide sufficient energy transfer by thermal conduction from the reactor shield base wall (3015) to the heat dissipating flange (3100) to allow the entire fuel reactor body (3040) to be maintained nearly at uniform temperature with a small thermal gradient maintained between the higher temperature reactor shield base wall and the heat dissipating flange (3100). Additionally according to the present technology the surface area of the heat dissipating flange (3100) is sufficiently large that thermal energy is dissipated therefrom at a rate equal to the rate of thermal energy being absorbed by the reactor shield base wall (3015), which as noted above is about 44 W. Additionally according to the present technology the fuel reactor body (3040) is configured to dissipate sufficient thermal therefrom to prevent the fuel air mixture passing through the cylindrical fuel chamber (3005) from exceeding an auto ignition temperature thereof. More specifically the heat dissipating flange (3100) is configured to dissipate enough thermal energy to the surrounding air to maintain the temperature of the fuel reactor body (3040) below about 295°C, equal to the lowest auto ignition temperature of expected fuel air mixtures, and preferably to maintain the temperature of the entire fuel reactor body (3040) between about 100 and 250°C during all operating modes. Also according to the present intention, temperature of the heat dissipating flange (3100) is monitored during all operating phases and if the temperature of the heat dissipating flange

exceeds a desired high temperature limit, in a range of 100 to 250°C, the input fuel air mixture may be stopped by operable elements of the fuel input module (197) to prevent fuel from entering the reformer (167) until further operation or the air moving element (3130) reduces the temperature the heat dissipating flange (3100) to a safe operating temperature.

[00132] It will also be recognized by those skilled in the art that, while the subject technology has been described above in terms of preferred embodiments, it is not limited thereto. Various features and aspects of the above described subject technology may be used individually or jointly in any combination. For example, any of the following claims may be re-arranged to have some or all of the limitations in any other claim and the claims may depend from each other or some or all of the other claims in any combination. Further, although the subject technology has been described in the context of its implementation in a particular environment, and for particular applications (*e.g.* fuel reformation by catalytic partial oxidation in a solid oxide fuel cell system), those skilled in the art will recognize that its usefulness is not limited thereto and that the present technology can be beneficially utilized in any number of environments and implementations where it is desirable to manage thermal energy in high temperature corrosive environments where flammable materials are processed. Accordingly, the claims set forth below should be construed in view of the full breadth and spirit of the invention as disclosed herein.

WHAT IS CLAIMED IS:

1. A fuel reformer module comprising:

a fuel reactor body enclosing a hollow fuel chamber wherein the hollow fuel chamber is bounded by a perimeter wall, disposed along a chamber longitudinal axis, a cap wall, attached to the perimeter wall and disposed to enclose a top end of the fuel chamber, and a reactor shield base wall, attached to the perimeter wall and disposed to enclose a bottom end of the fuel chamber,

wherein the reactor shield base wall includes a base wall top surface facing into the hollow fuel chamber and a substantially parallel and opposing base wall bottom surface facing out of the hollow fuel chamber and a plurality of substantially identical base wall fuel passages extending through the reactor shield base wall from the base wall top surface to the base wall bottom surface, and

wherein each base wall fuel passage has a substantially constant cross-sectional area along its longitudinal length and is axially centered by a passage longitudinal axis that is substantially parallel with the chamber longitudinal axis; and

a catalyzing body comprising a solid non-porous ceramic substrate bounded by a catalyzing body top surface and a substantially parallel and opposing catalyzing body bottom surface,

wherein the catalyzing body top surface is disposed proximately opposed to the base wall bottom surface across an interface;

wherein the catalyzing body includes a plurality of substantially identical catalyst fuel passages each extending from the catalyzing body top surface to the catalyzing body bottom surface with each of the plurality of catalyst fuel passage having a substantially constant cross-sectional area along its longitudinal length and a catalyst layer coated onto inside surfaces of each catalyst fuel passage, and

wherein each of the plurality of base wall fuel passages is longitudinally aligned with one of the plurality of catalyst fuel passages such that each of the plurality of base wall fuel passages shares a substantially coaxial longitudinal axis with one of the plurality of catalyst fuel passages.

2. The fuel reformer module of claim 1 wherein the ratio of the cross-sectional area each of the plurality of base wall fuel passages to the cross-sectional area of each of the plurality of catalyst fuel passages is less than 0.9.

3. The fuel reformer module of claim 1 wherein the ratio of the cross-sectional area each of the plurality of base wall fuel passages to the cross-sectional area of each of the plurality of catalyst fuel passages is between 0.6 and 0.9.

4. The fuel reformer module of claim 1 wherein each of the plurality of base wall fuel passages has a circular cross-section having a diameter in the range of 0.65 to 2.6 mm and each of the plurality of catalyst fuel passages has a square cross-section having a side dimension ranging between equal to the diameter of the base wall fuel passages and up to 1.26 times the diameter of the base wall fuel passages.

5. The fuel reformer module of claim 1 wherein each of the plurality of base wall fuel passages has a circular cross-section having a diameter in the range of 0.65 to 2.6 mm with a longitudinal length ranging between 10 and 20 times the diameter.

6. The fuel reformer module of claim 5 wherein each of the plurality of catalyzing fuel passages has a square cross-section having a side dimension in the range of 0.65 to 2.6 mm with a longitudinal length ranging between 5 to 40 times the side dimension.

7. The fuel reformer module of claim 3 wherein the plurality of base wall fuel passages is arranged in an array pattern wherein the array pattern has a solid material area and a hole pattern area wherein the ratio of the solid material area to hole pattern area has a range of 0.75 to 0.9.

8. The fuel reformer module of claim 1:

wherein a portion of the fuel reactor body is exposed to ambient air;

wherein the fuel reactor body is formed from materials having a coefficient of thermal conductivity greater than 100 W/m°K; and

wherein the fuel reactor body is formed to provide a substantially continuous thermally conductive path extending from the bottom surface of the reactor shield base wall to the portion of the fuel reactor body that is exposed to ambient air.

9. The fuel reformer of claim 8 wherein the portion of the fuel reactor body that is exposed to ambient air includes a disk shaped heat dissipating flange extending radially out from the perimeter wall.

10. The fuel reformer module of claim 9 further comprising a comprising temperature sensing element in communication with a system controller provided on a surface of the heat dissipating flange.

11. The fuel reformer module of claim 10 further comprising an air moving device operable to cool the heat dissipating flange by flowing ambient air over surfaces of the heat dissipating flange.

12. A fuel reforming method comprising:

delivering a flow of gaseous hydrocarbon compound into a hollow fuel chamber enclosed within by a fuel reactor body;

delivering the flow of gaseous hydrocarbon compound out of the hollow fuel chamber through a reactor shield base wall formed by the fuel reactor body and formed to include plurality of substantially identical base wall fuel passages passing there through;

receiving the flow of gaseous hydrocarbon compound from each of the plurality of base wall fuel passages into a plurality of catalyst fuel passages, wherein each catalyst fuel passage passes through a non-porous catalyzing body, wherein each of the plurality of base wall fuel passages shares a substantially coaxial longitudinal axis with one of the plurality of catalyst fuel passages;

wherein each of the plurality of catalyst fuel passages is coated on inside surface thereof with a catalyzing layer suitable for reforming the gaseous hydrocarbon compound by catalyzed partial oxidation (CPOX) and wherein the CPOX reaction emits thermal radiation;

wherein the reactor shield base wall includes a top surface facing into the hollow fuel chamber and a substantially parallel and opposing bottom surface facing away from the hollow fuel chamber and the catalyzing body includes a top surface positioned opposed to the bottom surface of the reactor shield base wall across an interface and a substantially parallel and opposing bottom surface;

wherein a portion of the fuel reactor body is exposed to ambient air;

wherein the fuel reactor body is formed from materials having a coefficient of thermal conductivity greater than 100 W/m°K and provides a substantially continuous thermally conductive pathway extending from the reactor shield base wall bottom surface to the portion of the fuel reactor body is exposed to ambient air;

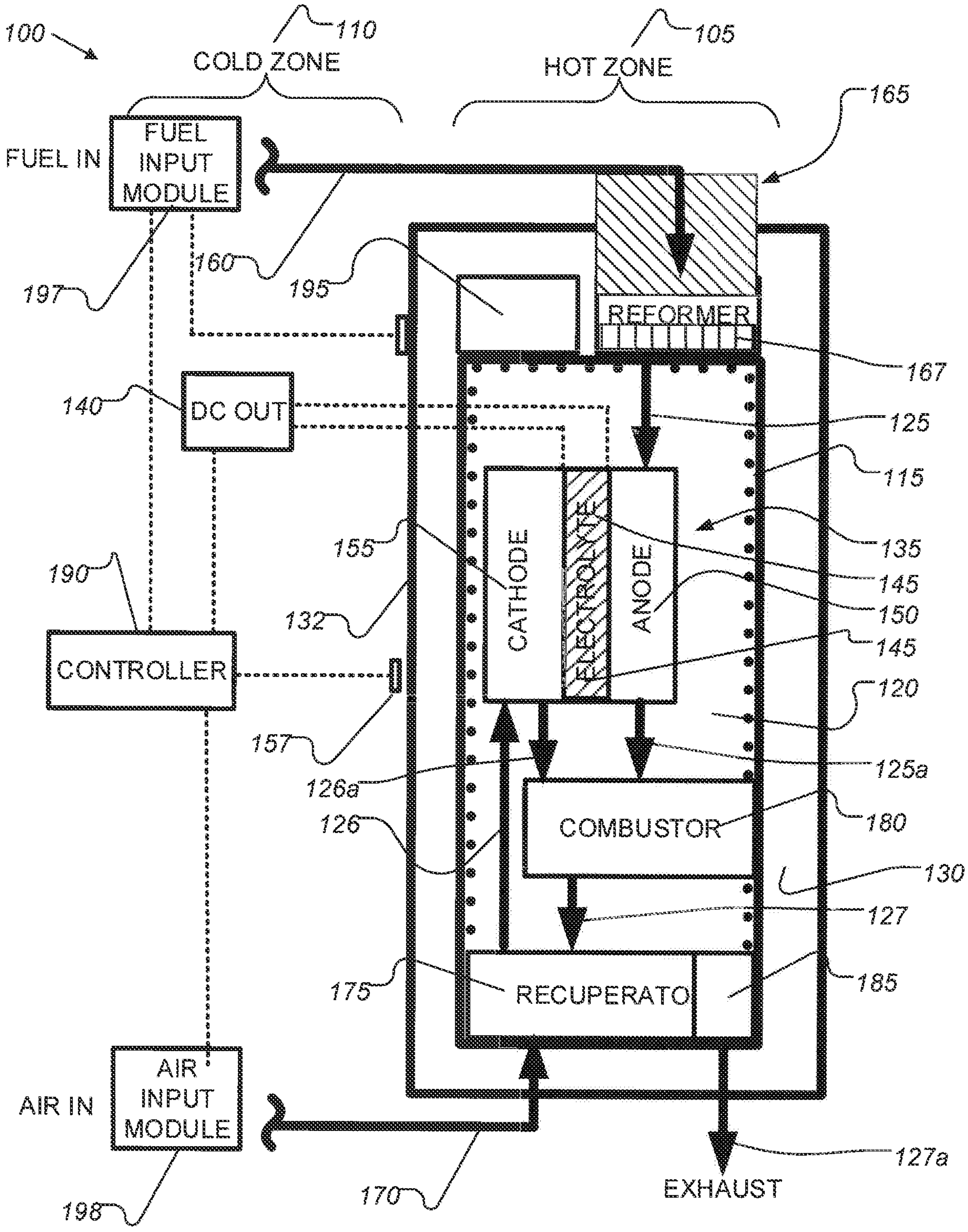
reforming the gaseous hydrocarbon compound inside each of the catalyst fuel passages by the CPOX reaction; and,

absorbing the thermal radiation emitted by the CPOX reaction onto any one of the reactor shield base wall bottom surface and inside surfaces of any one of the plurality of base wall fuel passages wherein the absorbed thermal radiation is thermally conducted through the fuel reactor body to portion of the fuel reactor body exposed to ambient air.

13. The method of claim 12 further comprising monitoring a temperature of the portion of the fuel reactor body is exposed to ambient air.

14. The method of claim 13 further comprising operating an air moving device to direct an ambient air flow across surfaces of the portion of the fuel reactor body is exposed to ambient air.

15. The method of claim 14 further comprising configuring the fuel reactor body with sufficient thermal mass and sufficient thermal energy dissipating surface area to maintain the fuel reactor body at a steady state operating temperature of less than 250°C.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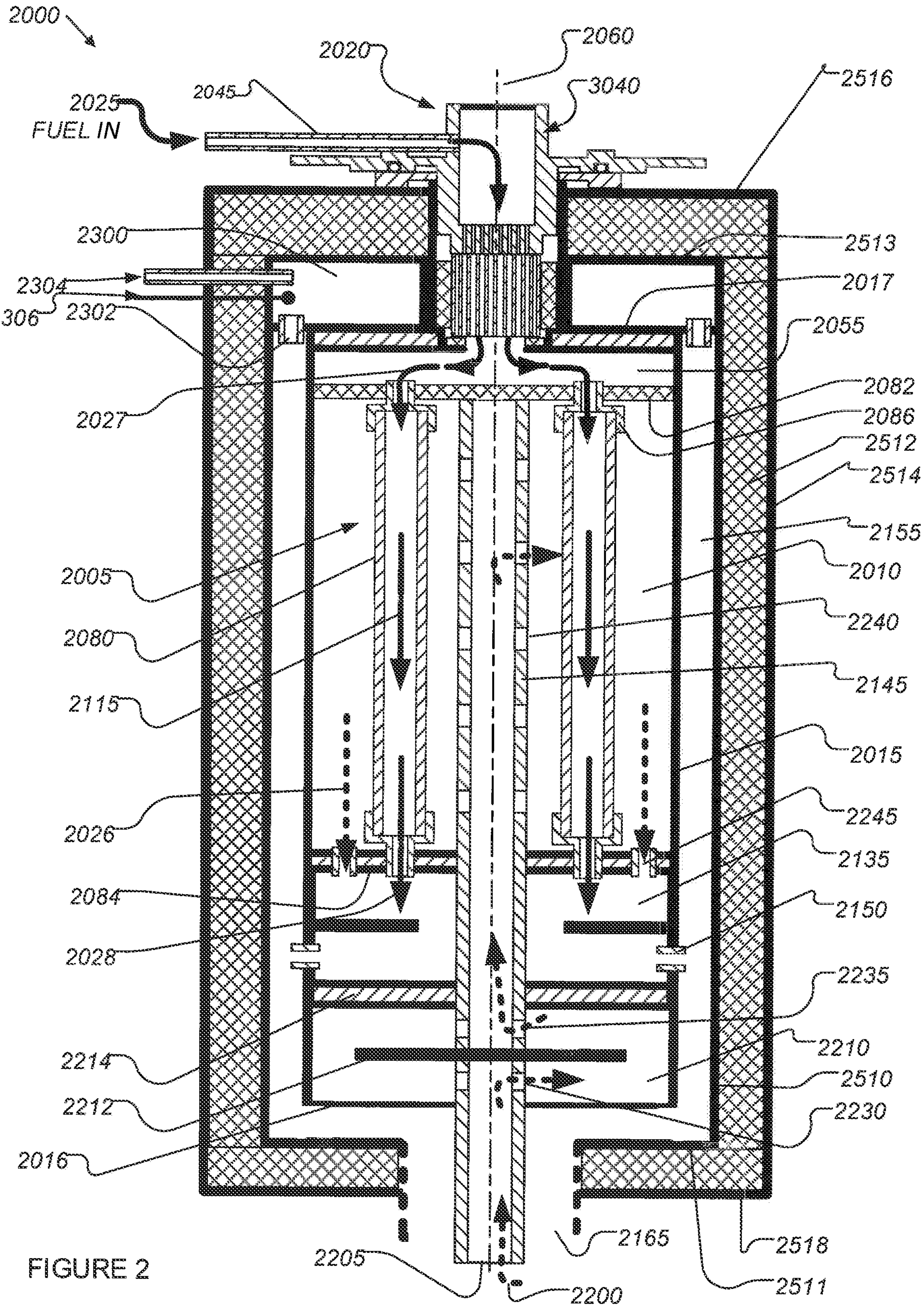
110
COLD ZONE
105
HOT ZONE
165
FUEL IN
FUEL INPUT MODULE
160
195
197
REFORMER
167
140
DC OUT
125
115
135
155
CATHODE
ELECTROLYTE
ANODE
145
150
145
190
132
CONTROLLER
120
157
125a
126a
126
COMBUSTOR
180
130
127
175
RECUPERATO
185
AIR IN
AIR INPUT MODULE
127a
EXHAUST
170
198

FIGURE 1


2000
2020
2060
2516
2045
3040
2025
FUEL IN
2300
2513
2304
2017
2306
2302
2055
2082
2027
2086
2512
2514
2155
2005
2010
2080
2240
2115
2145
2015
2026
2245
2135
2084
2150
2028
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2518
2205
2200
2511

FIGURE 2

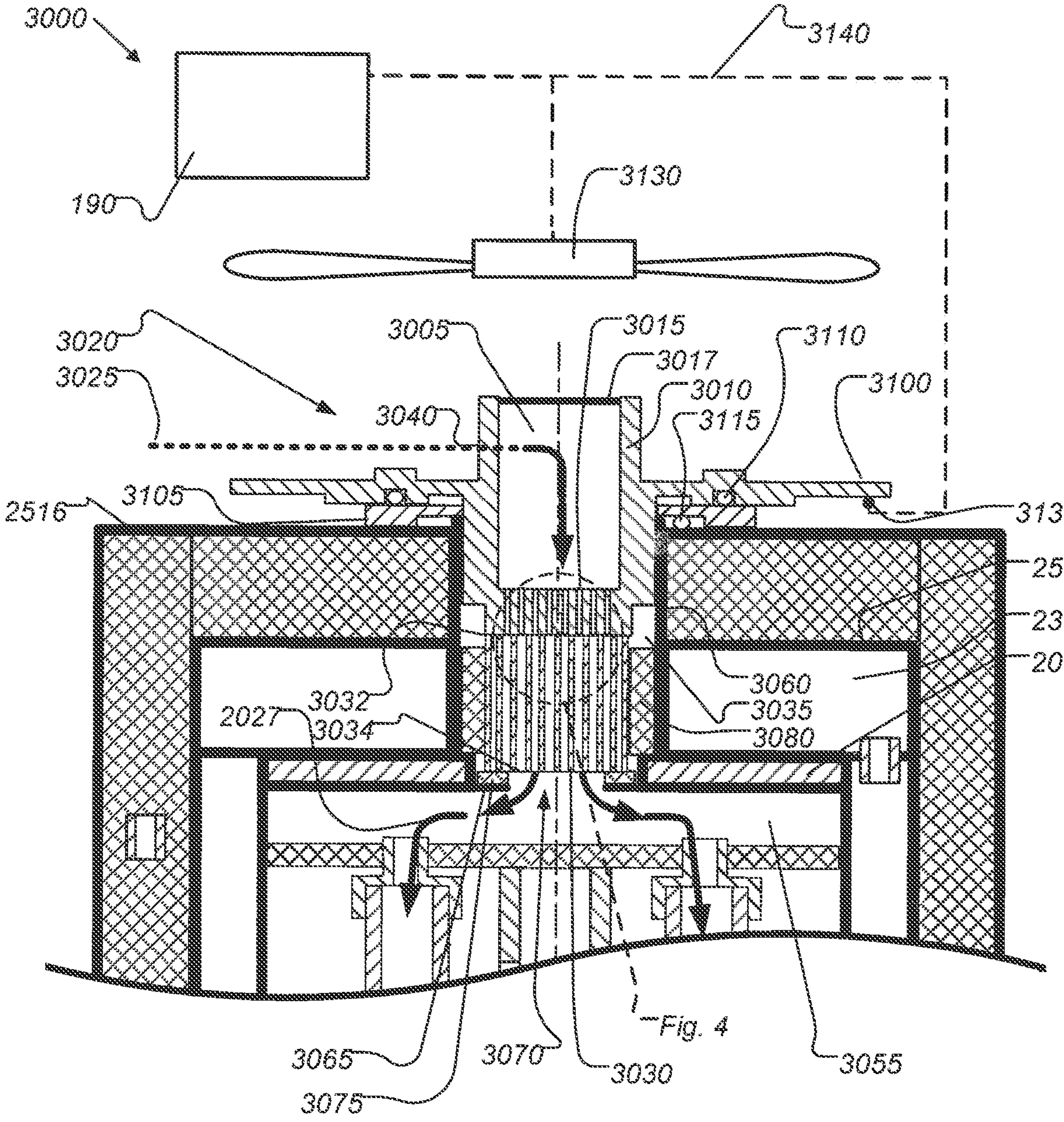
3000
3140
190
3130
3020
3025
3005
3015
3017
3010
3110
3100
3040
3115
2516
3105
3135
2513
2300
2017
3060
3035
3080
3032
2027
3034
Fig. 4
3065
3070
3030
3055
3075

FIGURE 3

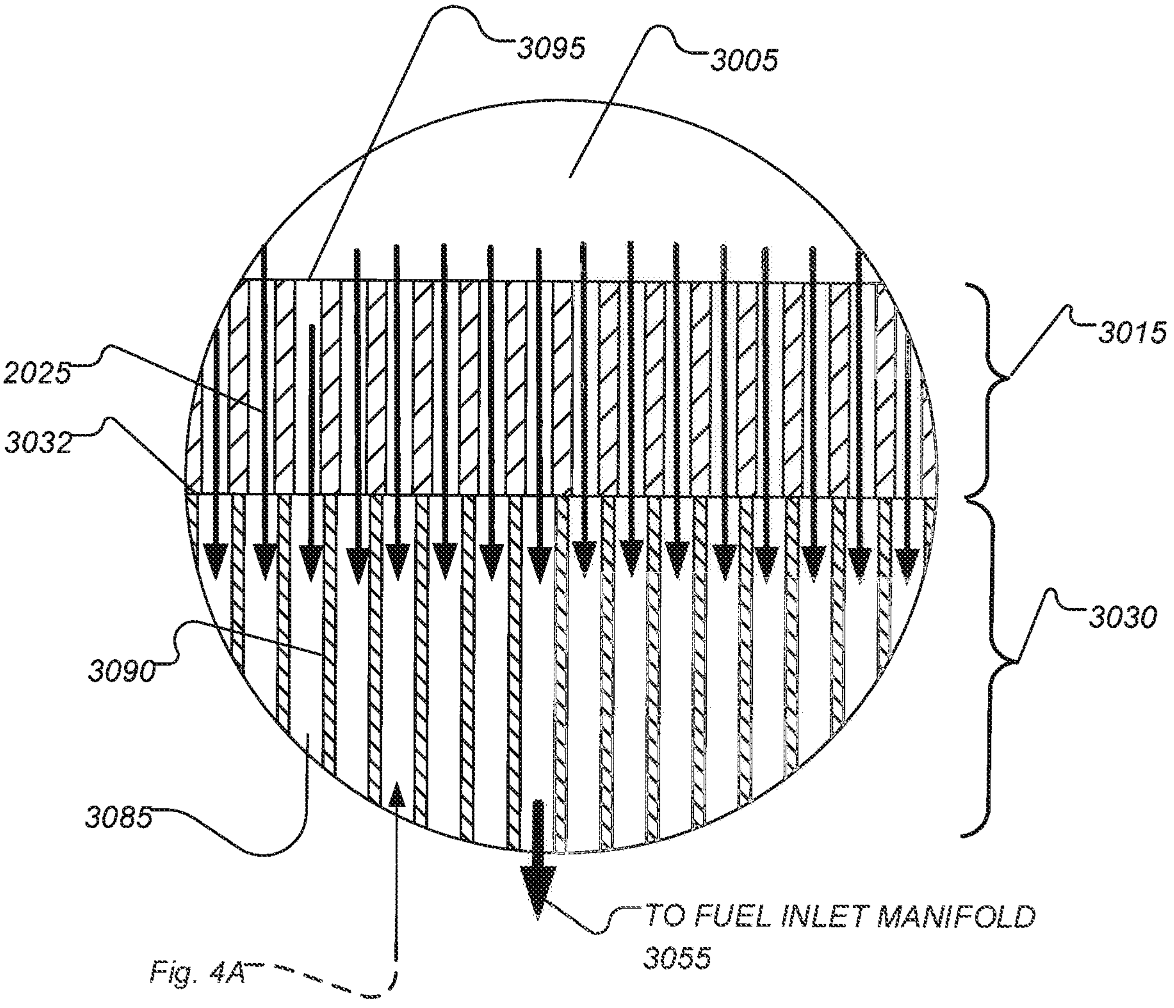
3095
3005
3015
2025
3032
3030
3090
3085
TO FUEL INLET MANIFOLD
3055
Fig. 4A

FIGURE 4

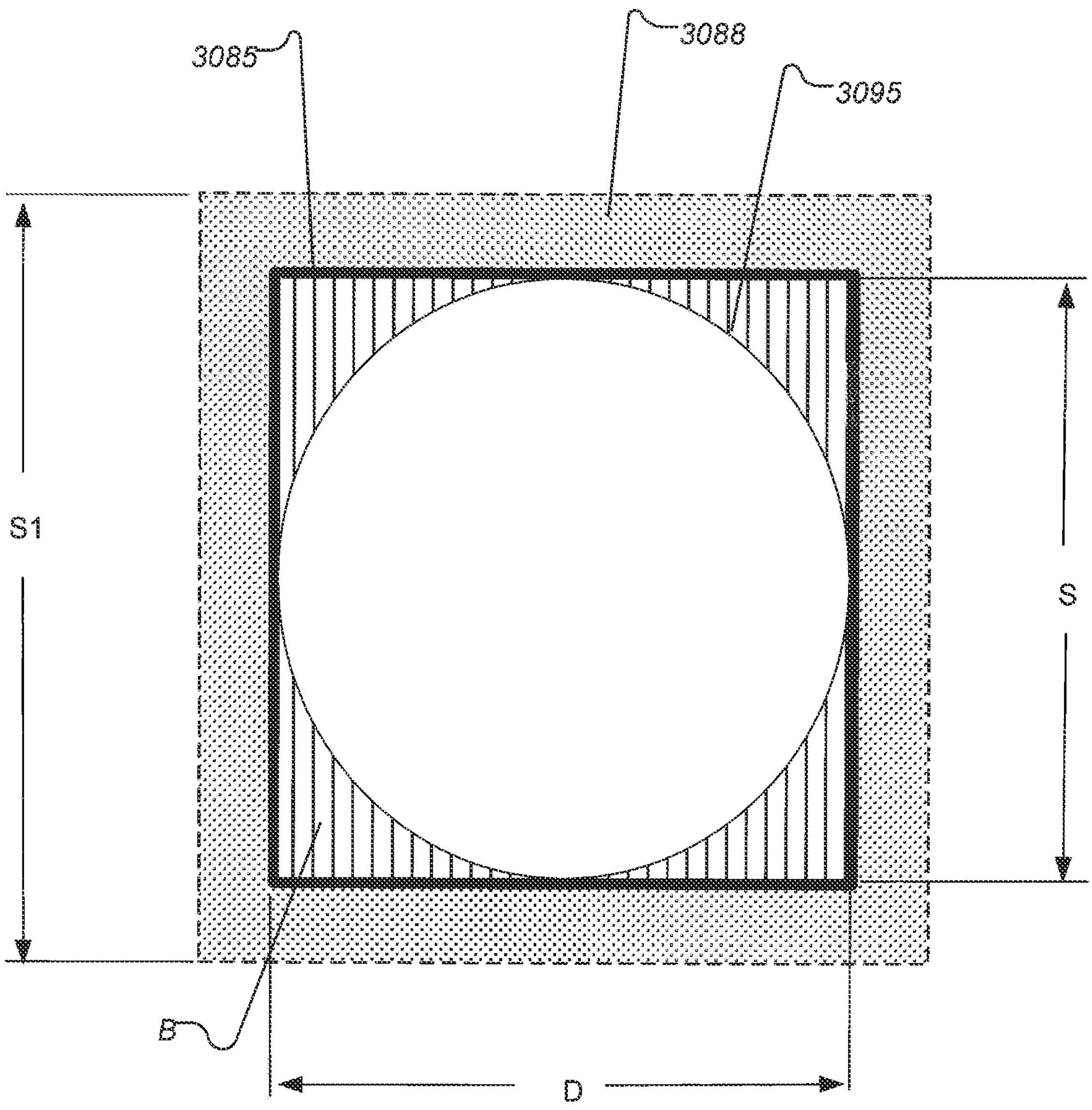

FIGURE 4A

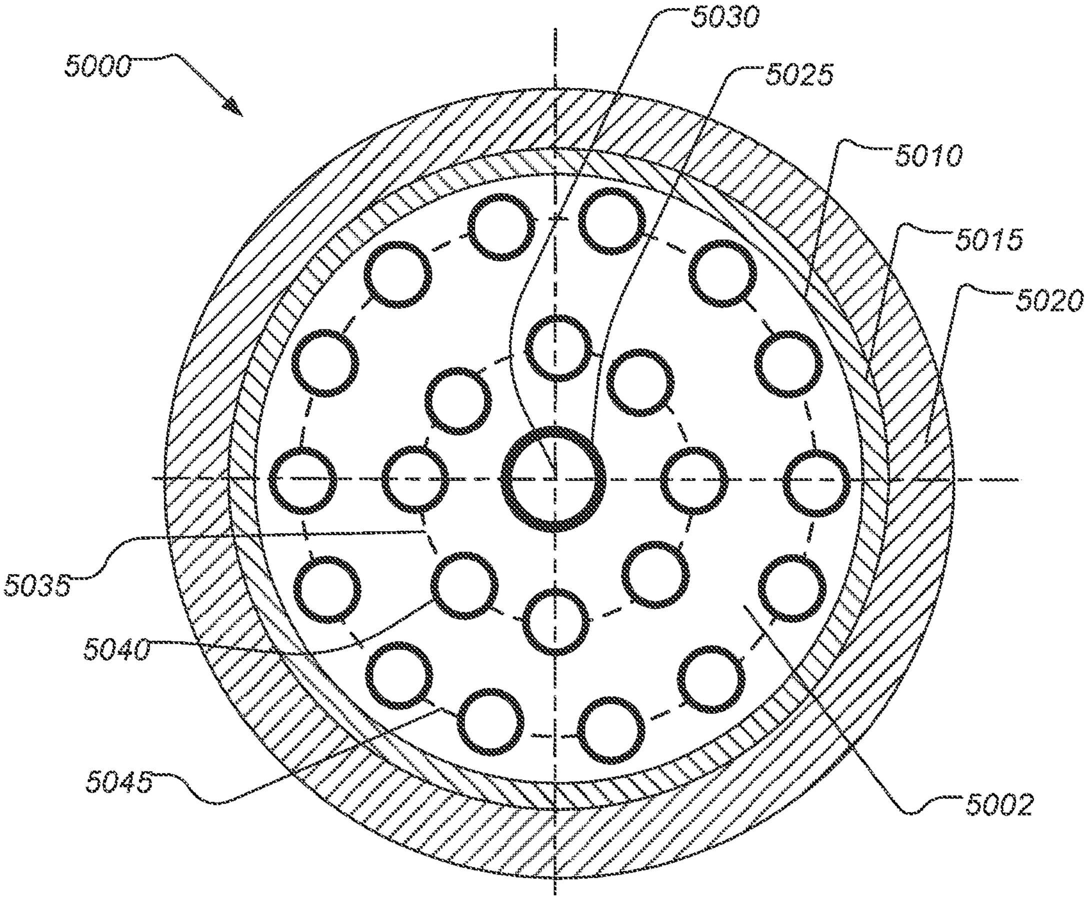

FIGURE 5

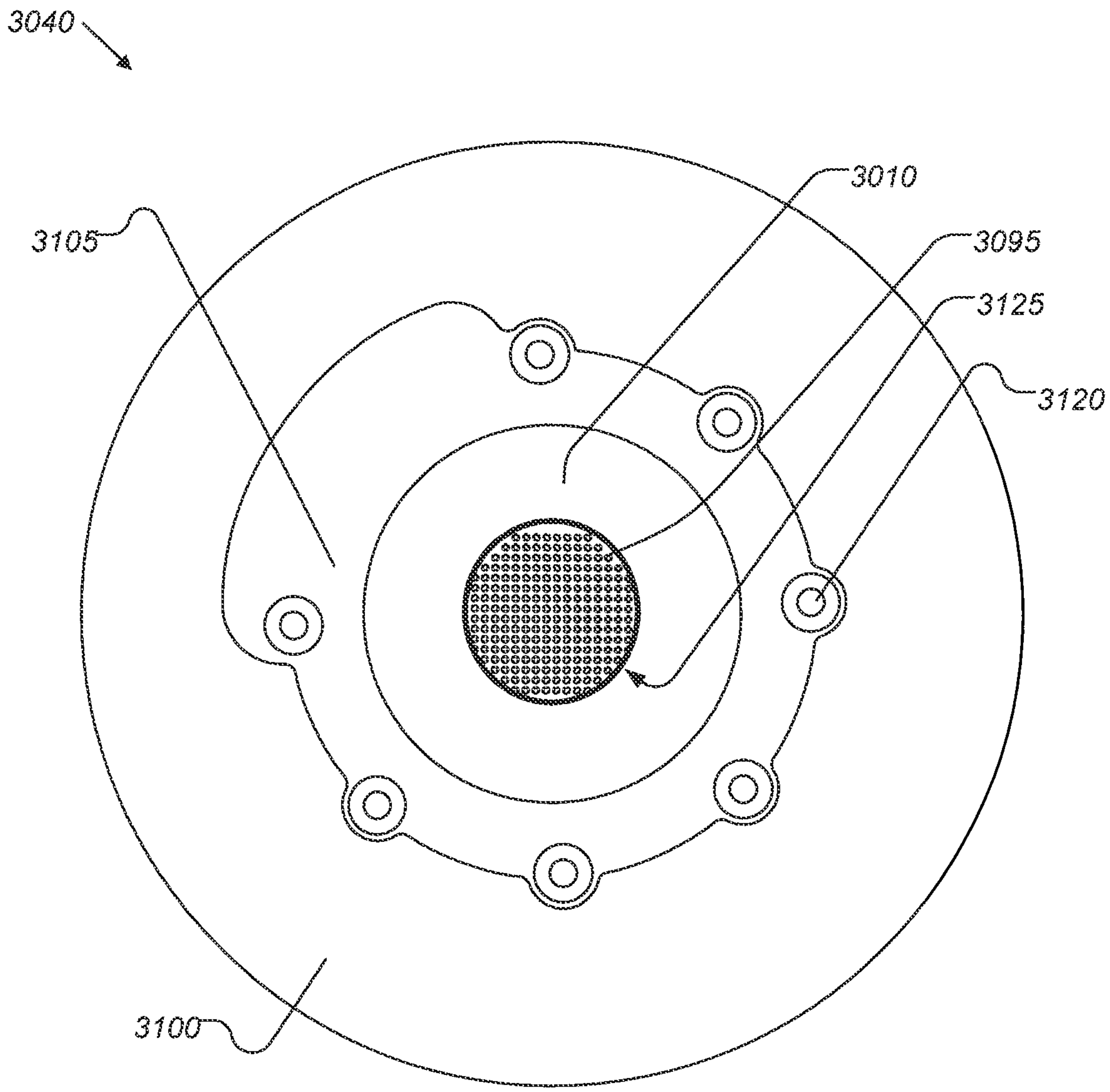

FIGURE 6