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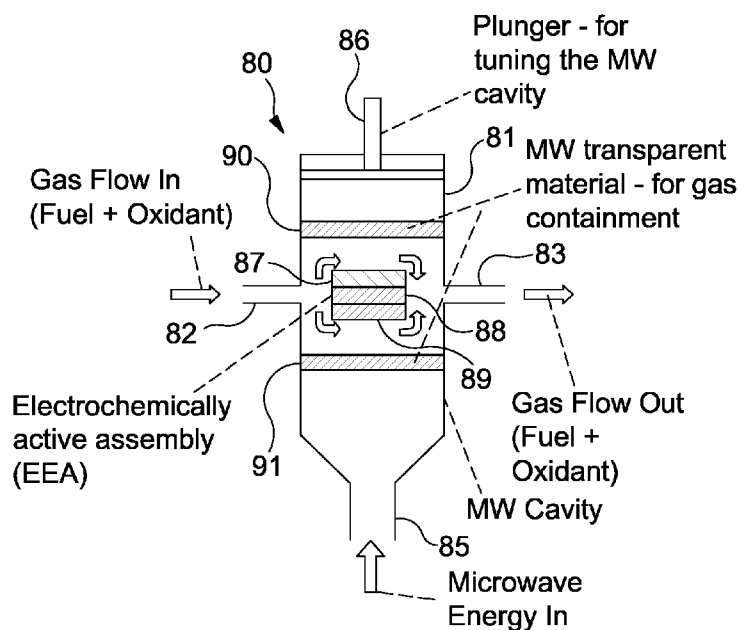
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(54) **Title:** FUEL CELL



**Single Chamber Microwave
Tunable Fuel Cell**

Figure 8

(57) **Abstract:** A fuel cell comprising: a cavity; an electrochemically active assembly located within the cavity, at least a portion of the electrochemically active assembly being capable of absorbing microwave radiation; a microwave applicator comprising a source of microwave radiation and a waveguide arranged to transmit microwave radiation generated by the source of microwave radiation into the cavity; wherein the cavity is configured such that, in use, for a given microwave frequency, a desired microwave field configuration is produced within the cavity, the desired microwave field configuration being selected such that at least a portion of the electrochemically active assembly is selectively heated.



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Fuel Cell

The present invention relates to fuel cells, systems comprising fuel cells, uses of fuel cells and methods of manufacture of fuel cells.

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A fuel cell is a device that converts chemical energy from a fuel directly into electrical power by oxidising the fuel. Typically, a fuel cell comprises an anode and a cathode separated by an electrolyte. The anode and cathode are connected to an external load via a circuit. In use, a fuel is supplied to the anode and an oxidant is supplied to the cathode. The fuel undergoes an electrochemical reaction (oxidation) at the interface between the anode and the electrolyte and the oxidant undergoes an electrochemical reaction (reduction) at the interface between the cathode and the electrolyte. If the fuel is hydrogen and the oxidant is oxygen, then the by-product of the electrochemical reactions at the point of use will be water. Oxygen anions pass through the electrolyte, while electrons flow around the circuit from the anode to the cathode, thereby producing an electric current.

The merit of fuel cell technologies (FCTs) to help achieve a sustainable and secure energy future is now recognized worldwide. Institutional R&D support and market incentives are being provided by the US, UK, Germany, Japan, and South Korea governments for developing and commercializing FCTs for civilian and for military use (see, for example, The Business Case for Fuel Cells 2012; and 2011 Fuel Cell Technologies Market Report, US Department of Energy, http://www1.eere.energy.gov/hydrogenandfuelcells/market_publications.html.)

25

Table 1 below presents a non-exhaustive snapshot of some advantageous features of FCTs [source: Lowering the temperature of solid oxide fuel cells, Eric D Wachsman et al., Science 334, 935 (2011)].

#	Advantageous Feature of FCTs	Explanatory / Qualifying Notes
1	High efficiency	200% of “combustion” technologies;

		Not limited by the Carnot Theorem
2	Low to zero carbon and sulphur footprint, fuel flexibility	Dependent on fuel type and history, balance of plant, FCT; H ₂ , natural gas, biogas, CO, hydrocarbons;
3	Electricity grid independence, decentralization	Energy and cyber security; Speedily refuellable -- within few minutes
4	Scalable, modular, robust	<~ kW for handheld electronics, to ~ megawatts for residential or industrial applications; Stationary, transport, or portable sectors;

Table 1

FCTs may be categorized on the basis of operating temperature (OT), into “low” (50-
 5 200 °C) and “high” (>~ 650 °C) OT technologies. Acceptably sized FC units based on high OT technologies can provide power outputs sufficient for residential or industrial purposes (kilowatts to megawatts).

An example of a high operating temperature fuel cell technology is a solid oxide fuel
 10 cell (SOFC). In an SOFC, the electrolyte is made from a solid oxide material, e.g. yttria-stabilised zirconia (YSZ). Solid oxide fuel cells typically operate at temperatures of around 800°C or more. Solid oxide fuel cells have several advantageous attributes including: high efficiency, particularly when used in combined heat and power generation; size flexibility, making them potentially suitable for a range of mobile and
 15 stationary applications; good environmental performance; and fuel flexibility, in that the electrolyte may not be overly sensitive to the fuel that is used.

However, fuel cells technologies have yet to achieve widespread application, despite their potential benefits and despite considerable research and commercial interest.

Three outstanding disadvantages holding back the widespread application of fuel cell technologies are: high initial system costs; high operating costs, due to corrosion and materials degradation; and long start-up (and shut-down) durations.

- 5 The long start-up duration of high OT fuel cells arises due to the fact that the fuel cell is initiated by heat conducted to it from an external source – consequently, a present day high OT fuel cell may take several tens of minutes before being able to deliver its full rated power. Such a delay may be unacceptably long for many applications.
- 10 Two examples of high operating temperature fuel cell technologies are: solid oxide fuel cell (SOFC), and molten carbonate fuel cell technologies (MCFC). The high operating temperature requirement ($>\sim 650\text{ }^{\circ}\text{C}$ for MCFC, $>\sim 800\text{ }^{\circ}\text{C}$ for SOFC), is currently achieved through conventional (conductive, non-selective) heating, and constrains the construction materials choices of the fuel cell and balance of plant (BOP), and the
- 15 operation of the fuel cell. For instance, construction materials must have simultaneously high electrical and mechanical performances which are not easy to engineer for these elevated temperatures. On the operational front, useful power output is obtainable only after the requisite (uniformly high) operating temperature is achieved, which results in inordinately high start-up (and shut-down) durations of tens of minutes
- 20 or longer. At present, the long start-up duration limitation severely limits the sectors within which fuel cell technology is deployable. For instance, in spite of the fact that SOFCs can deliver power sufficient for an automobile drive-train from an acceptable form-factor, the long start-up time disadvantages this technology from being widely adopted in the automotive sector.
- 25 A first aspect of the invention provides a fuel cell comprising:
- a cavity;
 - an electrochemically active assembly typically comprising an anode, an electrolyte and a cathode located within the cavity, at least a portion of the
- 30 electrochemically active assembly being capable of absorbing microwave radiation;

a microwave applicator comprising a source of microwave radiation and a waveguide arranged to transmit microwave radiation, generated by the source of microwave radiation, into the cavity;

5 wherein the cavity is configured such that, in use, for a given microwave frequency, a desired microwave field configuration is produced within the cavity, the desired microwave field configuration being selected such that at least a portion of the electrochemically active assembly is selectively, and preferably controllably, heated.

10 It will be appreciated that the invention therefore provides for microwave-assisted dielectric heating of a fuel cell.

The desired microwave field configuration may comprise a multi-mode or a single-mode, e.g. resonant, microwave field configuration. The desired microwave field configuration may comprise a transverse electromagnetic (TEM) mode, a transverse electric (TE) mode or a transverse magnetic (TM) mode.

In an embodiment, the desired microwave field configuration may selectively heat an internal region of the electrochemically active assembly.

20 In an embodiment, the desired microwave field configuration may selectively heat an interfacial region between the anode and the electrolyte and/or an interfacial region between the cathode and the electrolyte.

In an embodiment, the microwave applicator may be capable of delivering up to 10 kW, up to 5 kW or up to 2kW of power to the cavity.

Any suitable source of microwave radiation may be employed. For instance, the source of microwave radiation may comprise a magnetron, a klystron or a solid-state source.

30 The fuel cell is tuned to produce the desired microwave field configuration. In an embodiment, the fuel cell may be tuneable so that the desired microwave field configuration can be controlled and/or modified and/or optimised during operation of

the fuel cell. The optimum microwave field configuration may change during operation of the fuel cell. Accordingly, the microwave field configuration may be controlled and/or modified such that it conforms substantially to a desired, e.g. optimum, microwave field configuration for a given set of operational conditions, parameters and objectives at a given time.

In an embodiment, the impedance of the cavity may be tuneable, in order to obtain and/or maintain effective coupling of the microwave field with the electrochemically active assembly.

In an embodiment, the shape and dimensions of the cavity may be controllably variable in order to modify and/or optimise the desired microwave field configuration.

The volume of the cavity may be controllably variable. In use, the volume of the cavity may be continuously or periodically controlled or varied. For instance, the fuel cell may comprise at least one plunger movable to vary the volume of the cavity. Technically, the or each plunger may be named a sliding-short.

In an embodiment, the cavity may contain one or more bodies, e.g. grains, particles or discs, made at least partially from alumina.

For instance, alumina bodies, e.g. discs, may be stacked or otherwise arranged within the cavity, in order to help produce the desired microwave field configuration.

Alternatively or additionally, the cavity may contain a ceramic oxide, e.g. alumina, powder to help produce the desired microwave field configuration. Tubing, typically made from quartz, may be utilised in order to pass gases through the powder.

The shape, dimensions, number and arrangement of the one or more bodies comprising alumina may vary depending upon the desired microwave field configuration for the fuel cell. Changing the number or arrangement of the alumina-comprising bodies

during operation of the fuel cell or between periods of operation of the fuel cell may provide a further means of tuning the fuel cell.

Advantageously, the body or bodies comprising alumina may guide the microwave radiation within the cavity. Other specific materials may be used instead of or as well as alumina, e.g. another ceramic oxide. The material(s) from which the one or more bodies, e.g. grains, particles or discs, are made should have a high permittivity, be very low loss, carry the microwave field and be temperature stable. However, alumina may be preferred on economic and operational grounds, since it is readily available and relatively easy to machine in appropriate configurations.

Advantageously, having close control of the microwave field configuration may enable a user to significantly influence or control the rate of catalytic reactions and/or electrochemical transport processes which occur within the interior, or across interfacial regions of the electrochemically active assembly.

The fuel cell may be of any configuration, e.g. planar, tubular or coaxial.

The electrochemically active assembly may be known as a puck or a plate.

The fuel cell may be a high operating temperature fuel cell or a low operating temperature fuel cell. Typically, the fuel cell or the electrochemically active assembly may have an operating temperature of 50°C or higher.

The electrolyte may comprise a solid oxide material, e.g. yttria-stabilised zirconia (YSZ) or gadolinium-stabilised ceria.

A power density of about 0.2 W/cm² to about 0.4 W/cm² may be generated by the fuel cell when it is operational and the electrolyte is yttria-stabilized zirconia (YSZ). A solid oxide fuel cell comprising a YSZ electrolyte typically has an operating temperature of around 1000 °C.

A power density of about 0.4 W/cm^2 to about 0.8 W/cm^2 may be generated by the fuel cell when it is operational and the electrolyte is gadolinium-doped ceria (GDC). A solid oxide fuel cell comprising a GDC electrolyte typically has an operating temperature of around 650°C .

5

The power density that can be delivered to the electrochemically active assembly can be varied and may depend on the fuel cell materials within the electrochemically active assembly. The power dissipated is proportional to the square of the E-field in a given material, which can be whatever a user wants it to be (that is, until the field reaches the dielectric breakdown strength for the given material).

10

In an embodiment, the cavity may be provided with at least one inlet and at least one outlet. A fuel, an oxidant and/or a mixture of a fuel and an oxidant may be supplied to the electrochemically active assembly via the inlet(s). In use, reaction by-products and/or unused fuel and/or oxidant may leave the cavity via the outlet(s).

15

The fuel cell may comprise a gas flow system to controllably and/or independently deliver one or more gas streams to the inlet(s).

Typically, the microwave radiation may have a government specified frequency, e.g. 2.45 GHz or 915 MHz . In practice, the given microwave frequency typically may have a tolerance of $\pm 25 \text{ MHz}$.

20

The cavity may be within a metal housing or casing. A housing or cavity made of metal will constrain microwaves within it. Accordingly, in use, microwave radiation may not escape from the cavity to any significant amount. This may improve safety of the fuel cell. Additionally, it may be possible to use microwave radiation having any frequency, rather than just government specified frequencies.

25

The fuel cell may comprise one or more chokes or self-cancelling steps to prevent microwave radiation from escaping from the cavity. The or each inlet and/or outlet may comprise a choke.

30

In an embodiment, the fuel cell may comprise an electrical wiring system capable of transporting electrical current from the anode to an external load and delivering electrons to the cathode. The fuel cell may be connected or connectable to a network or
5 grid for supplying electricity or to any device requiring electrical power.

In an embodiment, the cavity may comprise one or more chambers. For instance, the cavity may comprise two chambers. The fuel cell may comprise a gas impermeable and microwave transparent separator between the two chambers.

10

In an embodiment, the separator between the two chambers may comprise the electrochemically active assembly.

In an embodiment, the fuel cell may further comprise a temperature sensor capable of
15 determining, in use, the temperature of the electrochemically active assembly or a portion thereof. For instance, the temperature sensor may comprise an IR sensor or a Pt thermometer.

The fuel cell may be configured such that, in use, a portion of the electricity generated
20 may be used to power the source of microwave radiation.

In an embodiment, the fuel cell may be adapted such that at least a portion of the waste heat from the fuel cell may be used to power the source of microwave radiation, e.g. via a thermoelectric process.

25

The fuel cell may further comprise a monitoring-processing-control unit capable of monitoring, e.g. continuously or periodically monitoring, the electric power output of the fuel cell as a function of time. The monitoring-processing-control unit may also be capable of optimizing the operational parameters of the fuel cell, e.g. according to a pre-
30 programmed algorithm, in order to deliver a desired net electric power output performance.

The net electric power output from a fuel cell is equal to the power generated by the fuel cell minus the power consumed by the source of microwave radiation.

- 5 The monitoring-processing-control unit may be configured to receive inputs about operational parameters such as incoming oxidant gas composition/flow-rate/etc., and/or the incoming fuel gas composition/flow-rate/etc., and/or the temperature of the electrochemically active assembly, and/or the actual power output of the fuel cell, and/or the desired power output of the fuel cell.
- 10 In response to the one or more inputs, the monitoring-processing control unit may determine control actions sufficient, e.g. for a given, pre-programmed algorithm, to deliver a given operational goal. Example operational goals may include: maximizing the net electric power output; minimizing fuel consumption while delivering a desired power output level; and/or delivering a desired amount of power irrespective of fuel
- 15 and/or oxidant composition. Example control actions may include: switching on/off the microwave field; changing the dimensions of the cavity to switch between microwave field configurations or modes; changing the flow rates or compositions of the gas stream(s) supplied to the fuel cell; and/or pulse-width modulation of the microwaves.
- 20 The present invention may be applicable to a range of fuel cell applications and types of fuel cell. For instance, the fuel cell of the invention may be used: to generate power; to produce hydrogen or another industrially useful chemical; for carbon dioxide separation, e.g. from a flue gas stream; to generate combined heat and power; and/or to generate combined heat, hydrogen and power. The fuel cell may be a solid oxide fuel
- 25 cell, a polymer electrolyte membrane fuel cell, a direct methanol fuel cell, an alkaline fuel cell, a phosphoric acid fuel cell, a molten carbonate fuel cell or a regenerative fuel cell. The fuel may comprise hydrogen, carbon monoxide, natural gas, biogas or a hydrocarbon.
- 30 The invention may have applicability in enabling a hydrogen economy.

A second aspect of the invention provides a fuel cell system comprising at least one fuel cell according to the first aspect of the invention and a balance of plant.

5 The fuel cell system may comprise a plurality of fuel cells according to the first aspect of the invention. The operation of each fuel cell may be controllable independently of the other fuel cell(s), e.g. in response to changes in demand.

10 A third aspect of the invention provides a use of a fuel cell according to the first aspect of the invention or a fuel cell system according to the second aspect of the invention: to generate power (electricity); to produce hydrogen; to produce an industrially useful chemical; for carbon dioxide separation, e.g. from a flue gas stream; to generate combined heat and power; and/or to generate combined heat, hydrogen and power.

15 The output of the fuel cell may then be transmitted or transported to a site of use. For instance, generated electricity may be transmitted via a grid or a network to a remote location.

20 The output, e.g. generated electricity or produced hydrogen, of the fuel cell may be stored for future use.

A fourth aspect of the invention provides a mobile or stationary structure comprising a fuel cell according to the first aspect of the invention or a fuel cell system according to the second aspect of the invention. The mobile structure may comprise a land, sea or air vehicle. The stationary structure may be a permanent or temporary structure and may
25 comprise a commercial, industrial or residential building.

A fifth aspect of the invention provides a fuel cell or a system comprising a fuel cell, comprising:
an electrochemically active assembly having an operating temperature of 50°C
30 or higher; and
a source of energy;

wherein, in use, the source of energy is operable to activate a heat generation process within the electrochemically active assembly, thereby providing the heat needed to realise the operating temperature of the electrochemically active assembly.

- 5 The source of energy may comprise a source of electromagnetic energy, e.g. a source of microwave energy. Accordingly, microwave energy may be used to activate the heat generation process.

The electrochemically active assembly may comprise at least one electrochemical cell.

- 10 In an embodiment, the electrochemically active assembly may comprise at least two or at least three electrochemical cells, which electrochemical cells may be connected in electrical series.

- The or each electrochemical cell may comprise three functional portions. The
15 functional portions may comprise a cathode, an electrolyte and an anode.

In an embodiment, the electrochemically active assembly may be located within an electromagnetic cavity, e.g. a microwave cavity.

- 20 In an embodiment, one or more bodies comprising a dielectric material may be located within the electromagnetic cavity.

The source of electromagnetic energy may be coupled to the electromagnetic cavity.

- 25 The fuel cell or system may further comprise a tuning mechanism to tune the electromagnetic cavity to support, within the cavity, electromagnetic energy received from the source of electromagnetic energy in at least one electromagnetic mode. For instance, the electromagnetic mode may be selected from a transverse electromagnetic (TEM) mode, a transverse electric (TE) mode and a transverse magnetic (TM) mode.

30

The fuel cell or system may further comprise electromagnetic circuitry to transport electromagnetic energy to or from the electrochemically active assembly.

The fuel cell or system may further comprise a fuel and oxidant handling system configured to bring a fuel and/or oxidant into or out of electrochemical contact with the electrochemically active assembly.

5

The output from the fuel cell or system may comprise one or more of electromagnetic energy, heat, hydrogen, carbon dioxide and an industrially useful chemical.

10 A sixth aspect of the invention provides a use of a fuel cell or system according to the fifth aspect of the invention: to generate power (electricity); to produce hydrogen or another industrially useful chemical; for carbon dioxide separation, e.g. from a flue gas stream; to generate combined heat and power; and/or to generate combined heat, hydrogen and power.

15 A seventh aspect of the invention provides a mobile or stationary structure comprising a fuel cell or system according to the fifth aspect of the invention.

The present invention may enable a significant advancement of fuel cell technologies, by using a non-conventional dielectric heating scheme typically based on the use of
20 microwaves to provide start-up energy to the fuel cell. Advantageously, the invention may address one or more of the outstanding disadvantages of fuel cell technologies, in particular high operating temperature fuel cell technologies, which could result in their rapid commercialization across sectors.

25 Advantageously, the present invention may effectively address the problem of start-up duration, and may also have the associated advantage of economical and distinctly spatially controlled delivery of start-up energy to the fuel cell, which in turn may enable the use of cheaper construction materials for the balance of plant. It is envisaged that the invention could have a positive step-change transformative effect on the market
30 prospects of FCTs, especially (but not exclusively) high OT FCTs, in the near future.

Advantageously, the present invention uses microwave radiation to bring about a volumetric (that is, of the entire volume) temperature rise of the fuel cell via directed controllable dielectric heating. In an embodiment, resonant microwave modes may be used to obtain the desired dielectric heating precisely at the location of the
5 electrochemically active assembly or a portion thereof.

In order that the invention may be well understood it will now be described by way of example only with reference to the accompanying drawings, in which:

10 Figure 1 is a schematic diagram comparing the present invention with a conventional fuel cell system;

Figure 2 shows a first example embodiment of a fuel cell according to the invention;

15 Figure 3 shows a second example embodiment of a fuel cell according to the invention;

Figure 4 shows a third example embodiment of a fuel cell according to the invention;

Figure 5 shows a fourth example embodiment of a fuel cell according to the invention;
20

Figure 6 shows a fifth example embodiment of a fuel cell according to the invention;

Figure 7 shows a sixth example embodiment of a fuel cell according to the invention;

25 Figure 8 shows a seventh example embodiment of a fuel cell according to the invention;

Figure 9 shows an eighth example embodiment of a fuel cell according to the invention;
and

30 Figure 10 shows a finite element model of time averaged electromagnetic power dissipated in a fuel cell according to the invention.

Referring to Figure 1, there is shown a fuel cell assembly 1, comprising a fuel cell 2 and a balance of plant 3. The balance of plant 3 includes a start-up energy source. In use, start-up energy is delivered from the balance of plant 3 to the fuel cell 2 as indicated by arrow 4. Various system channels 5 indicated by a dashed two-headed arrow also run
5 between the balance of plant 3 and the fuel cell 2.

The fuel cell 2 is connected to a load 7 via an external circuit 6. In use, electricity generated by the fuel cell 2 flows around the external circuit 6, thereby delivering electrical energy to the load 7.

10

In a conventional fuel cell assembly, start-up energy (heat) is typically delivered to the fuel cell 2 via conduction through at least a portion of the balance of plant 3. Accordingly, the extent of heating necessary to bring the fuel cell to its operating temperature is relatively large, as indicated by large dashed oval 8. The delivery of
15 start-up energy is not focused within the fuel cell. Other parts of the fuel cell assembly are also heated and need to be made able to withstand higher temperatures.

In the present invention, the start-up energy is provided by focused microwave radiation. The invention relies on volumetric heating of the fuel cell via heat received
20 radiatively and directly at the fuel cell. Consequently, the extent of heating, as indicated by small dashed oval 9, is much less than in the conventional fuel cell assembly (as indicated by the large dashed oval 8).

As illustrated in Figure 1, in the conventional scheme at least a portion of the balance of
25 plant is also heated -- the heating energy and start-up duration requirements are therefore inordinately high. In stark contrast, the present invention may enable rapid fuel cell start-up (heating rates upwards of 100°C per second may be achievable). Furthermore, heating of the fuel cell is selective, and therefore economical. Selective heating of the fuel cell in accordance with the invention may also enable simplifications
30 and/or cost savings to be made in the balance of plant. Accordingly, it will be appreciated that the invention may help to increase the commercial viability and competitiveness of fuel cell technology.

In some embodiments, microwave heating may only be applied during initial start-up of the fuel cell.

5 Figure 2 shows in cross-section an embodiment of a fuel cell 20 according to the invention. The fuel cell 20 comprises a metal tubular casing 21, which defines a cavity. At one end of the casing 21 there is an inlet 22 and at the opposite end of the casing 21 there is an outlet 23. The cavity is divided into an upper chamber and a lower chamber by a separator 24. The separator 24 also divides in two the inlet 22 and the outlet 23.
10 The separator is impermeable to gases and is transparent to microwave radiation. Centrally within the cavity there is located an electrochemically active assembly 27 (sometimes known as a puck or a plate). The electrochemically active assembly 27 comprises a porous cathode 28 and a porous anode 30 with a solid oxide electrolyte layer 29 between the cathode 28 and the anode 30. The cathode 28 is located in the
15 upper chamber of the cavity while the anode 30 is located in the lower chamber of the cavity. The cathode 28 and the anode 30 are electrically connected to an external circuit (not shown). There is a gas tight seal (not shown) between the separator 24 and the electrochemically active assembly 27. The casing 21 comprises a microwave transparent window (not shown) through which, in use, microwave radiation from a
20 microwave applicator (not shown) is transmitted into the cavity.

In use, gas flows to the inlet 22 as indicated by arrow 25. An oxidant gas stream, typically comprising oxygen, is supplied to the cathode 28 and a fuel gas stream such as hydrogen or natural gas is supplied to the anode 27. Gases exit the cavity via the outlet
25 23 as indicated by arrow 26 after the fuel and oxidant have interacted with the electrochemically active assembly 27.

Figure 3 shows in cross-section a second example embodiment of a fuel cell 31 according to the invention. The fuel cell 31 comprises a metal casing 32 defining a
30 cavity. An inlet 33 is provided at one end of the cavity and an outlet 34 is provided at the opposite end of the cavity. Within the cavity, there is an electrochemically active assembly 37. The electrochemically active assembly 37 comprises a solid oxide

electrolyte layer 39 adjacent an inner wall of the casing 32. On the opposite side of the solid oxide electrolyte layer 39 from the inner wall of the casing 32, an anode 40 and a cathode 38 are arranged, the anode 40 and the cathode 38 being spaced apart from each other. The cathode 38 and the anode 40 are electrically connected to an external circuit
5 (not shown). The casing 32 comprises a microwave transparent window (not shown) through which, in use, microwave radiation from a microwave applicator (not shown) is transmitted into the cavity.

In use, a first mixed gas stream 35 comprising a fuel and an oxidant is supplied to the
10 fuel cell via the inlet 33. A second mixed gas stream 36 exits the cavity via the outlet 34 after the fuel and the oxidant have interacted with the electrochemically active assembly 37.

Figure 4 shows in cross-section a third example embodiment of a fuel cell 41 according
15 to the invention. The fuel cell 41 comprises a casing 42 having the form of an open ended tube and defining a cavity. The top end of the casing 42 provides an inlet 43, while the bottom end of the casing 42 provides an outlet 44. An electrochemically active assembly is located within the casing 42 and extends substantially across the cavity within the casing. The electrochemically active assembly comprises a porous
20 cathode 47 and a porous anode 49 with a porous solid oxide electrolyte layer 48 between the cathode 47 and the anode 49. The cathode 47 and the anode 49 are electrically connected to an external circuit (not shown). The casing 42 comprises a microwave transparent window (not shown) through which, in use, microwave radiation from a microwave applicator (not shown) is transmitted into the cavity.

25

In use, a first mixed gas stream 45 comprising a fuel and an oxidant is supplied to the fuel cell via the inlet 43. A second mixed gas stream 46 exits the cavity via the outlet
44 after the fuel and the oxidant have interacted with the electrochemically active assembly. It will be appreciated in this arrangement that, in order to get from the inlet
30 43 to the outlet 44, gases flow through the electrochemically active assembly.

Figure 5 shows in cross-section a fourth example embodiment of a fuel cell 50 according to the invention. The fuel cell 50 comprises a metal casing 51 defining a cavity. At one side of the casing 51 there is an inlet 52 and at an opposite side of the casing 51 there is an outlet 53. The cavity is divided into an upper chamber and a lower chamber by a separator 54. The separator 54 also divides in two the inlet 52 and the outlet 53. The separator 54 is impermeable to gases and is transparent to microwave radiation. Within the cavity there is located an electrochemically active assembly (sometimes known as a puck or a plate). The electrochemically active assembly comprises a porous cathode 57 and a porous anode 59 with a solid oxide electrolyte layer 58 between the cathode 57 and the anode 59. The cathode 57 is located in the upper chamber of the cavity while the anode 59 is located in the lower chamber of the cavity. The cathode 57 and the anode 59 are electrically connected to an external circuit (not shown). There is a gas tight seal (not shown) between the separator 54 and the electrochemically active assembly. Accordingly, the upper chamber and the lower chamber are sealed from each other. The casing 51 comprises a microwave transparent window (not shown) in its base through which, in use, microwave radiation from a microwave applicator 55 located below the casing 51 is transmitted into the cavity. The microwave applicator 55 comprises a magnetron operable to generate microwaves and a waveguide configured to transmit the generated microwaves from the magnetron into the cavity. The microwave applicator 55 is a resonant microwave applicator capable of delivering up to 2kW of power to the cavity.

In use, gases flow to the inlet 52. An oxidant gas stream, typically comprising oxygen, is supplied to the cathode 57 and a fuel gas stream such as hydrogen or natural gas is supplied to the anode 59. Gases exit the cavity via the outlet 53 after the fuel and the oxidant have interacted with the electrochemically active assembly.

The fuel cell 50 further comprises a plunger 56, which can be moved linearly to change the volume of the cavity defined by the casing 51. Changing the volume of the cavity by moving the plunger can change the microwave field configuration produced within the cavity. Accordingly, the fuel cell has a cavity with a controllably variable volume and consequently may be tuneable to produce a desired microwave field configuration

within the cavity and/or to vary the microwave field configuration within the cavity during operation of the fuel cell.

Figure 6 shows in cross-section an embodiment of a fuel cell 60 according to the invention. The fuel cell 60 comprises a metal tubular casing 61, which defines a cavity. At one end of the casing 61 there is an inlet 62 and at the opposite end of the casing 61 there is an outlet 63. The cavity is divided into an upper chamber and a lower chamber by a separator 64. The separator 64 also divides in two the inlet 62 and the outlet 63. The separator is impermeable to gases and is transparent to microwave radiation. Within the cavity there is located an electrochemically active assembly 67 (sometimes known as a puck or a plate). The electrochemically active assembly 67 comprises a porous cathode 68 and a porous anode 70 with a solid oxide electrolyte layer 69 between the cathode 68 and the anode 70. The free surface of the cathode 68 is located in the upper chamber of the cavity while the free surface of the anode 70 is located in the lower chamber of the cavity. The cathode 68 and the anode 70 are electrically connected to an external circuit (not shown). There is a gas tight seal (not shown) between the separator 64 and the electrochemically active assembly 67. The casing 61 comprises a microwave transparent window (not shown) through which, in use, microwave radiation from a microwave applicator (not shown) is transmitted into the cavity.

In use, an oxidant gas stream 65a, typically comprising oxygen, is supplied in to the upper chamber and a fuel gas stream 65b, typically comprising hydrogen or natural gas, is supplied in to the lower chamber. Gases exit the cavity via the outlet 63 as indicated by arrow 66 after the fuel and oxidant have interacted with the electrochemically active assembly 67.

Figure 7 shows an embodiment of a fuel cell 71 according to the invention. The fuel cell 71 has the form of a closed ended tube. The closed ended tube comprises an outer layer formed mainly of an anode 74. Beneath the anode 74 there is an electrolyte 73 and a cathode 72, the electrolyte 73 being located between the anode 74 and the cathode 72. The inner surface of the closed ended tube is formed mainly of the cathode 72. An

interconnection provided by a contact layer 75 passes through the electrolyte to the outer surface of the tube. The contact layer 75 does not come into contact with the anode 74. There is a gap between the portion of the outer surface of the tube that is formed by the contact layer 75 and the major portion of the outer surface of the tube that is formed by the anode 74. An air feed tube 77 extends into the interior volume of the tube through the open end of the tube. The air feed tube 77 is located coaxially within the closed ended tube. There is an annular gap 76 between the air feed tube 77 and the cathode 72.

As indicated by arrow 78, in use, fuel is brought into electrochemical contact with the anode 74 by being caused to flow around the outside of the closed ended tube. As indicated by arrow 79a, in use, air is supplied to the cathode 72 via air feed tube 77. Air passes from the air feed tube 77 into the closed ended tube and then flows through the annular gap 76 and out of the open end of the closed ended tube (as indicated by arrow 79b). When the air is flowing within the annular gap 76, the air can interact electrochemically with the cathode 72.

Figure 8 shows in cross-section an embodiment of a fuel cell 80 according to the invention. The fuel cell 80 is a single chamber microwave tuneable fuel cell. The fuel cell 80 comprises a housing or casing 81, within which is located an electrochemically active assembly. The electrochemically active assembly contains three functional portions: a cathode 87, an anode 89 and an electrolyte 88 between the cathode 87 and the anode 89. The housing or casing 81 defines a microwave cavity. As indicated by the solid black arrow, microwave energy from a source of microwave energy (not shown) is transmitted into the cavity via a waveguide 85. The waveguide 85 is connected to the bottom of the cavity. A chamber within the cavity is located between an upper wall 90 and a lower wall 91. The upper wall 90 and the lower wall 91 extend substantially horizontally across the cavity and are both made from a gas impermeable and microwave transparent material. Hence, in use, microwaves can pass through the chamber, but gas cannot escape from the chamber. The electrochemically active assembly is located within the chamber. An inlet 82 leads into the chamber from one side and an outlet 83 leads out of the chamber from the opposite side. In use, a mixture

of fuel and oxidant is supplied to the chamber via inlet 82. Gases flow out of the chamber via outlet 83 after having interacted electrochemically with the electrochemically active assembly. The volume of the cavity is controllably variable using a plunger 86, which can be moved up and down within the portion of the cavity
5 above the upper wall 90. Accordingly, the fuel cell is tuneable.

Figure 9 shows in cross-section an embodiment of a fuel cell 92 according to the invention. The fuel cell 92 is a dual chamber planar microwave tuneable fuel cell. The fuel cell 80 is a single chamber microwave tuneable fuel cell. The fuel cell 92
10 comprises a housing or casing 93, within which is located an electrochemically active assembly. The electrochemically active assembly contains three functional portions: a cathode 98, an anode 100 and an electrolyte 99 between the cathode 98 and the anode 100. The housing or casing 93 defines a microwave cavity. As indicated by the solid black arrow, microwave energy from a source of microwave energy (not shown) is
15 transmitted into the cavity via a waveguide 101. The waveguide 101 is connected to the bottom of the cavity. An upper chamber and a lower chamber within the cavity are located between an upper wall 102 and a lower wall 103. The upper wall 102 and the lower wall 103 extend substantially horizontally across the cavity and are both made from a gas impermeable and microwave transparent material. Hence, in use,
20 microwaves can pass through the upper and lower chambers, but gas cannot escape from the upper chamber through the upper wall 102 or from the lower chamber through the lower wall 103. The electrochemically active assembly extends substantially horizontally across the cavity and separates the upper chamber from the lower chamber. Sealing members 104 are provided to hermetically seal the electrochemically active
25 assembly within the housing or casing 93, thereby preventing gas flowing, in use, from the upper chamber to the lower chamber or vice versa. The free surface of the cathode 98 faces into the upper chamber, while the free surface of the anode 100 faces into the lower chamber. An inlet 94 leads into the upper chamber from one side and an outlet 96 leads out of the upper chamber from the opposite side. In use, oxidant is supplied to
30 the upper chamber via inlet 94 and flows out of the upper chamber via outlet 96 after having interacted electrochemically with the cathode 98. An inlet 95 leads into the lower chamber from one side and an outlet 97 leads out of the lower chamber from the

opposite side. In use, fuel is supplied to the lower chamber via inlet 95 and flows out of the lower chamber via outlet 97 after having interacted electrochemically with the anode 100. The volume of the cavity is controllably variable using a plunger 105, which can be moved up and down within the portion of the cavity above the upper wall 102.

5 Accordingly, the fuel cell is tuneable.

Figure 10 shows the results of a finite element model of time averaged electromagnetic power dissipated in a microwave assisted fuel cell (normalised to maximum power) according to the invention. An electrochemically active assembly comprising a fuel cell

10 material 106 is located within a cavity 107. A WR340 waveguide section 108 transmits microwaves into the cavity 107 from below. As indicated by arrow 109, microwaves enter the cavity 107 from the WR340 waveguide section 108 below and selectively heat the fuel cell material 106, here modelled based upon a YSZ material having a complex permittivity of $\epsilon^* = 7 - j*0.5$ (modelled in an air filled cavity with perfectly conducting

15 walls). This is in stark contrast to conventional heating in which heat must be transferred to the material rather than generated in it.

Alumina discs (not shown) may be stacked within the cavity of any of the example embodiments of the invention. Alternatively or additionally, the cavity of any of the

20 example embodiments of the invention may contain some alumina powder.

Chokes (not shown) may be provided on the inlet and the outlet of any of the example embodiments of the invention, in order to prevent microwave radiation escaping from the cavity.

25

Microwave permittivity measurements have revealed loss tangents which amount to theoretical heating rates of ~ 100 °C per second or higher for solid oxide fuel cell electrolyte materials such as yttria-stabilised zirconia.

30 The desired microwave field configuration may comprise a multi-mode or a single-mode, e.g. resonant, microwave field configuration.

The selectivity and/or controllability which may be provided by the present invention may further improve the efficiency of dielectric heating within the fuel cell. A single-mode microwave field configuration may provide particularly efficient, selective dielectric heating of the electrochemically active assembly.

5

Furthermore, the invention may also make it possible to exploit highly-specific non-thermal effects due to the microwave electromagnetic field to advantageously affect electrical transport within the fuel cell.

10 In some embodiments, the fuel cell may comprise a microwave applicator, e.g. a resonant microwave applicator, capable of delivering up to 2kW of power to a single cavity. The microwave applicator may be arranged to deliver microwave radiation to more than one cavity. The microwave applicator may typically operate at the ISM (Industrial, Scientific and Medical) standard frequency of 2.45 GHz. In an embodiment,
15 the microwave applicator may be operable to provide (in combination with the cavity) a resonant single mode microwave field at the site of fuel cell action (i.e. within the electrochemically active assembly). The impedance of the cavity may be tuneable, in order to obtain and/or maintain effective coupling of the microwave field with the fuel cell.

20

The present invention may provide a specific, targeted, spatially controlled, and economic method of energy delivery, which could advance fuel cell technology, whose penetration within various sectors has been hampered by the inordinately long conventional start-up heating process. Conveniently, the invention may also effectively
25 lower the operating temperature of the system, i.e. the temperature over the fuel cell and the balance of plant. For instance, the invention may reduce system operating temperatures to below 650 °C, which could permit the use of cheaper materials for the balance of plant, thereby lowering system life-time (fabrication, operation, maintenance) costs.

30

Some of the immediately foreseeable impacts of the present invention include:

rapid start-up and faster shut-down duration; reduction in fabrication and maintenance cost of fuel cell systems, especially high OT fuel cell systems; lower system operating temperatures allowing the use of cheaper materials: fuel costs may be lowered since high OT FC systems running at lower OTs are typically more efficient. For example, the maximum theoretical efficiency of a solid oxide fuel cell using CO as a fuel increases from 63% at 900 °C to 81% at 350 °C.

It will be appreciated that the invention may be broadly applicable across the range of fuel cell technologies, and has the ability to set into motion a cascade of improvements within the balance of plant. Accordingly, the invention may represent a “geometric” (qualitative) advancement of the art, as opposed to an “arithmetic” (marginal or quantitative) advancement of the art.

The fuel cell market is growing and the present invention may enable to use of fuel cell technologies in sectors, and for purposes, which are currently outside their domain of serviceability.

Claims

1. A fuel cell comprising:
a cavity;
5 an electrochemically active assembly located within the cavity, at least a portion of the electrochemically active assembly being capable of absorbing microwave radiation;
a microwave applicator comprising a source of microwave radiation and a waveguide arranged to transmit microwave radiation generated by the source of
10 microwave radiation into the cavity;
wherein the cavity is configured such that, in use, for a given microwave frequency, a desired microwave field configuration is produced within the cavity, the desired microwave field configuration being selected such that at least a portion of the electrochemically active assembly is selectively heated, wherein the fuel cell is tuneable
15 so that the desired microwave field configuration can be controlled and/or modified and/or optimised during operation of the fuel cell.
2. A fuel cell according to claim 1, wherein the desired microwave field configuration comprises a multi-mode or a single-mode, e.g. resonant, microwave field
20 configuration.
3. A fuel cell according to claim 1 or claim 2, wherein the desired microwave field configuration selectively heats an internal region of the electrochemically active assembly and/or the electrochemically active assembly comprises an anode, an
25 electrolyte and a cathode and the desired microwave field selectively heats an interfacial region between the anode and the electrolyte and/or selectively heats an interfacial region between the cathode and the electrolyte.
4. A fuel cell according to claim 1, claim 2 or claim 3, wherein the microwave
30 applicator is capable of delivering up to 10 kW, up to 5 kW or up to 2kW of power to the cavity.

5. A fuel cell according to any one of the preceding claims, wherein the source of microwave radiation comprises a magnetron, a klystron or a solid-state source.
6. A fuel cell according to any one of the preceding claims, wherein the impedance of the cavity is tuneable, in order to obtain and/or maintain effective coupling of the microwave field with the electrochemically active assembly.
7. A fuel cell according to any one of the preceding claims, wherein the shape and dimensions of the cavity are controllably variable in order to modify and/or optimise the desired microwave field configuration.
8. A fuel cell according to claim 7, wherein the fuel cell comprises at least one plunger or sliding-short movable to vary the volume of the cavity.
9. A fuel cell according to any one of the preceding claims, wherein the cavity contains one or more bodies, e.g. grains, particles or discs, made at least partially from a ceramic oxide such as alumina.
10. A fuel cell according to any one of the preceding claims, wherein the fuel cell or the electrochemically active assembly has an operating temperature of 50°C or higher.
11. A fuel cell according to any one of the preceding claims, wherein the electrochemically active assembly comprises an electrolyte comprising a solid oxide material, e.g. yttria-stabilised zirconia (YSZ) or gadolinium-doped ceria.
12. A fuel cell according to any one of the preceding claims, wherein the cavity is provided with at least one inlet and at least one outlet.
13. A fuel cell according to claim 12 further comprising a gas flow system to controllably and/or independently deliver one or more gas streams to the inlet(s).

14. A fuel cell according to any one of the preceding claims, wherein the microwave radiation has a frequency of 2.45 GHz or 915 MHz.

15. A fuel cell according to any one of the preceding claims, wherein the cavity is within a metal housing or casing.

16. A fuel cell according to any one of the preceding claims further comprising one or more chokes or self-cancelling steps to prevent microwave radiation from escaping from the cavity.

10

17. A fuel cell according to any one of the preceding claims, wherein the cavity comprises one or more chambers.

18. A fuel cell according to claim 17, wherein the cavity comprises two chambers with a gas impermeable and microwave transparent separator between the two chambers.

19. A fuel cell according to any one of the preceding claims further comprising a temperature sensor capable of determining, in use, the temperature of the electrochemically active assembly or a portion thereof.

20

20. A fuel cell according to any one of the preceding claims, wherein the fuel cell is configured such that, in use, a portion of the electricity generated is used to power the source of microwave radiation.

25

21. A fuel cell according to any one of the preceding claims, wherein the fuel cell is adapted such that at least a portion of the waste heat from the fuel cell is used to power the source of microwave radiation, e.g. via a thermoelectric process.

22. A fuel cell according to any one of the preceding claims further comprising a monitoring-processing-control unit capable of monitoring the electric power output of the fuel cell as a function of time.

30

23. A fuel cell according to claim 22, wherein the monitoring-processing-control unit is also capable of optimizing the operational parameters of the fuel cell, e.g. according to a pre-programmed algorithm, in order to deliver a desired net electric power output.
24. A fuel cell system comprising at least one fuel cell according to any one of claims 1 to 23 and a balance of plant.
25. A fuel cell system according to claim 24, the fuel cell system comprising a plurality of fuel cells according to any one of claims 1 to 23.
26. A fuel cell system according to claim 25, wherein the operation of each fuel cell is controllable independently of the other fuel cell(s), e.g. in response to changes in demand.
27. A use of a fuel cell according to any one of claims 1 to 23 or a fuel cell system according to claim 24, claim 25 or claim 26: to generate power (electricity); to produce hydrogen or another industrially useful chemical; for carbon dioxide separation, e.g. from a flue gas stream; to generate combined heat and power; and/or to generate combined heat, hydrogen and power.
28. The use according to claim 27 further comprising transmitting or transporting the output of the fuel cell or the fuel cell system to a site of use.
29. The use according to claim 27 or claim 28 further comprising storing the output, e.g. generated electricity or produced hydrogen, of the fuel cell or fuel cell system for future use.
30. A mobile or stationary structure comprising a fuel cell according to any one of claims 1 to 23 or a fuel cell system according to claim 24, claim 25 or claim 26.

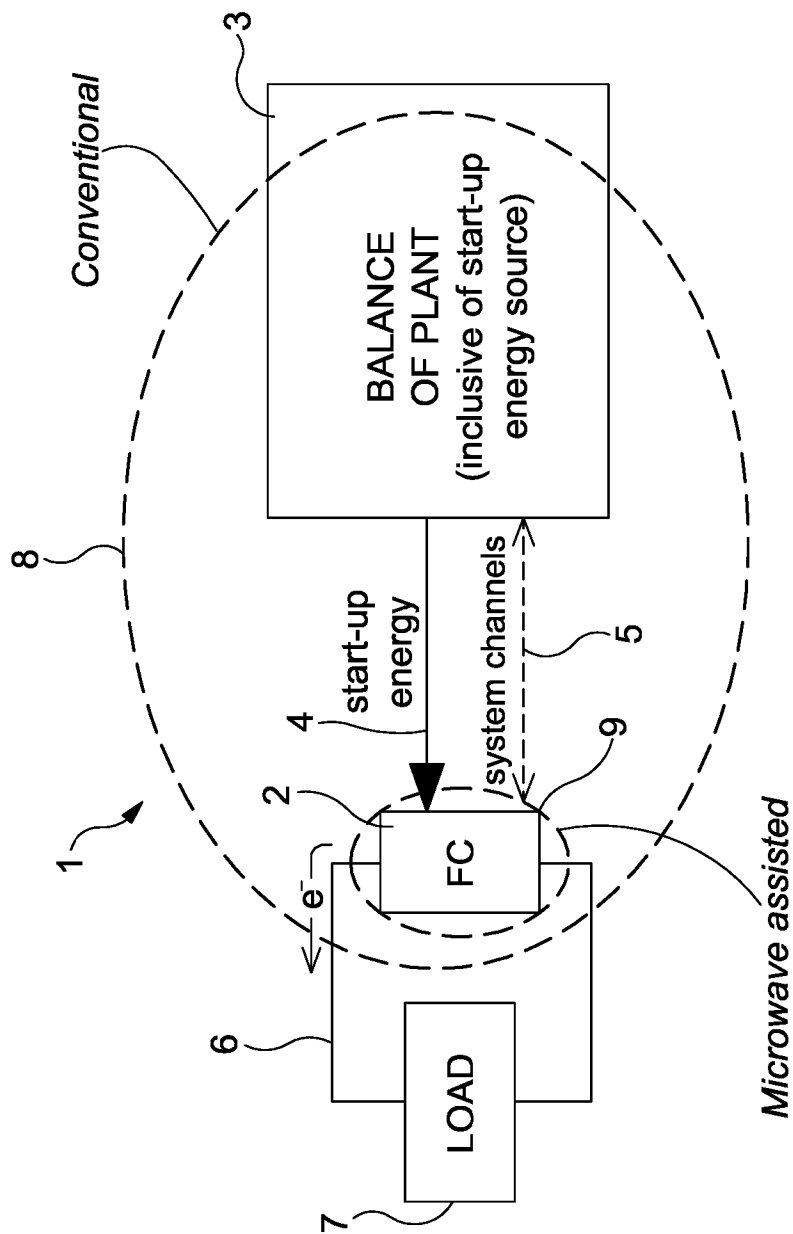


Figure 1

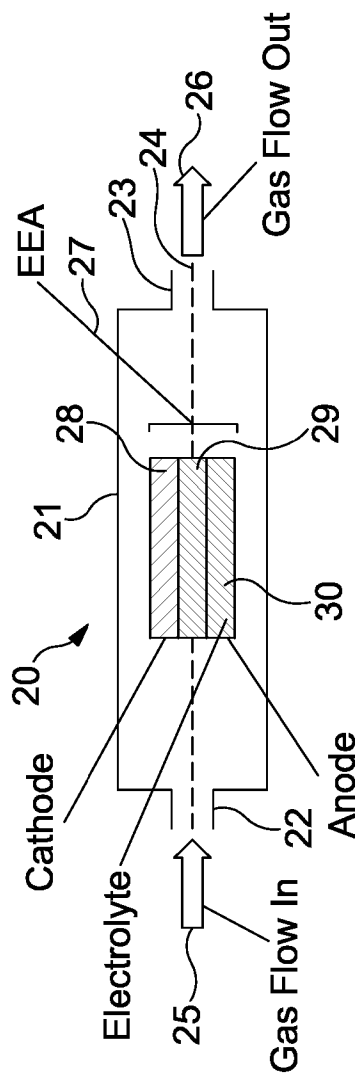


Figure 2

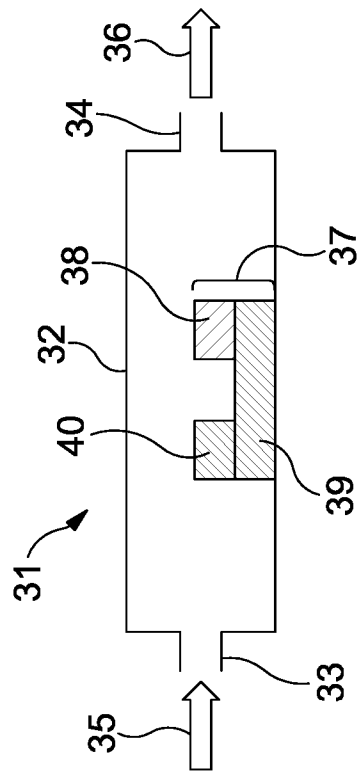


Figure 3

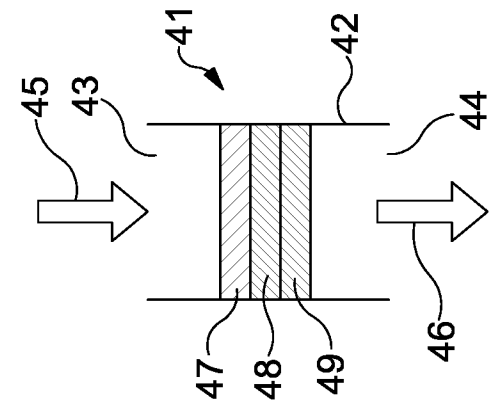


Figure 4

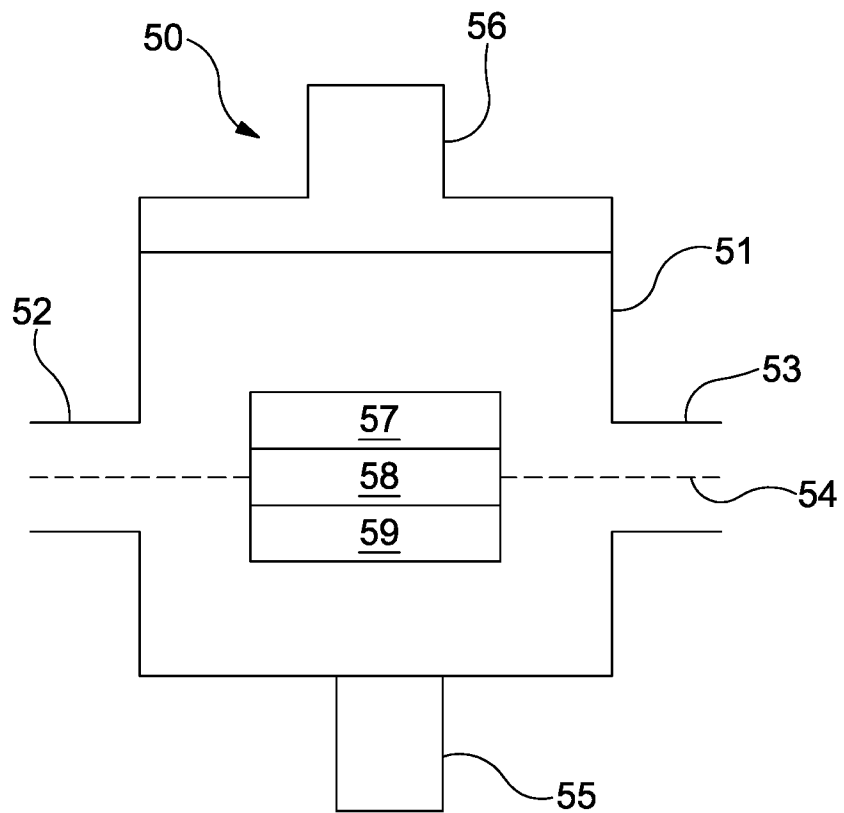


Figure 5

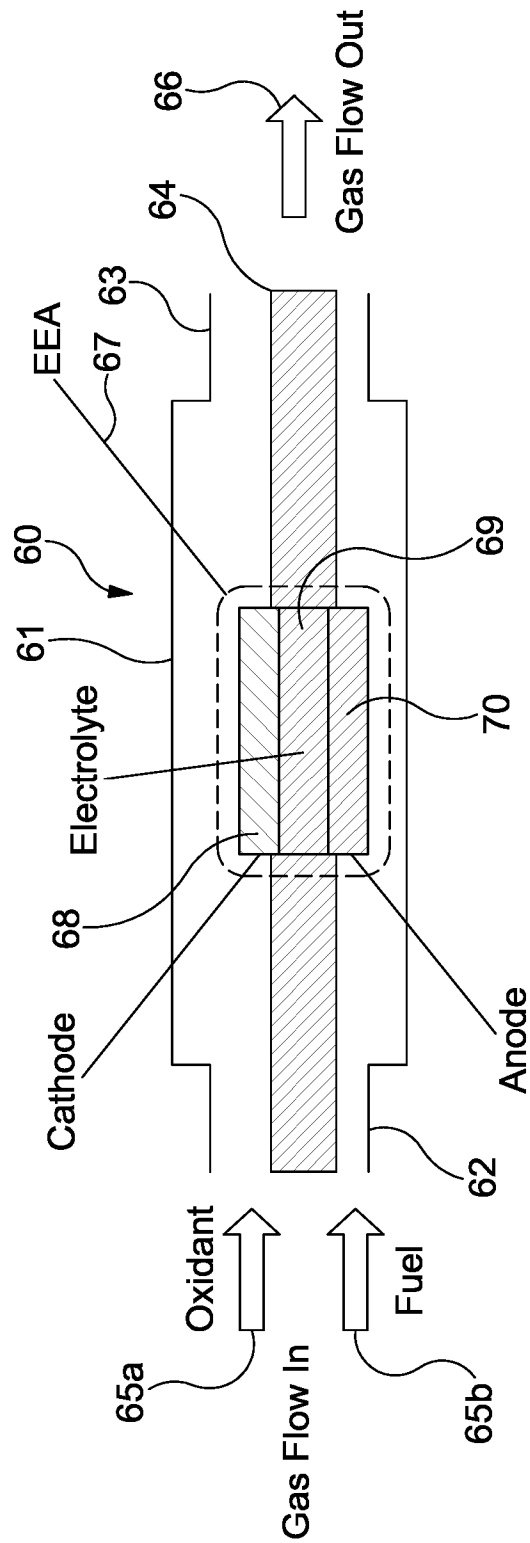


Figure 6

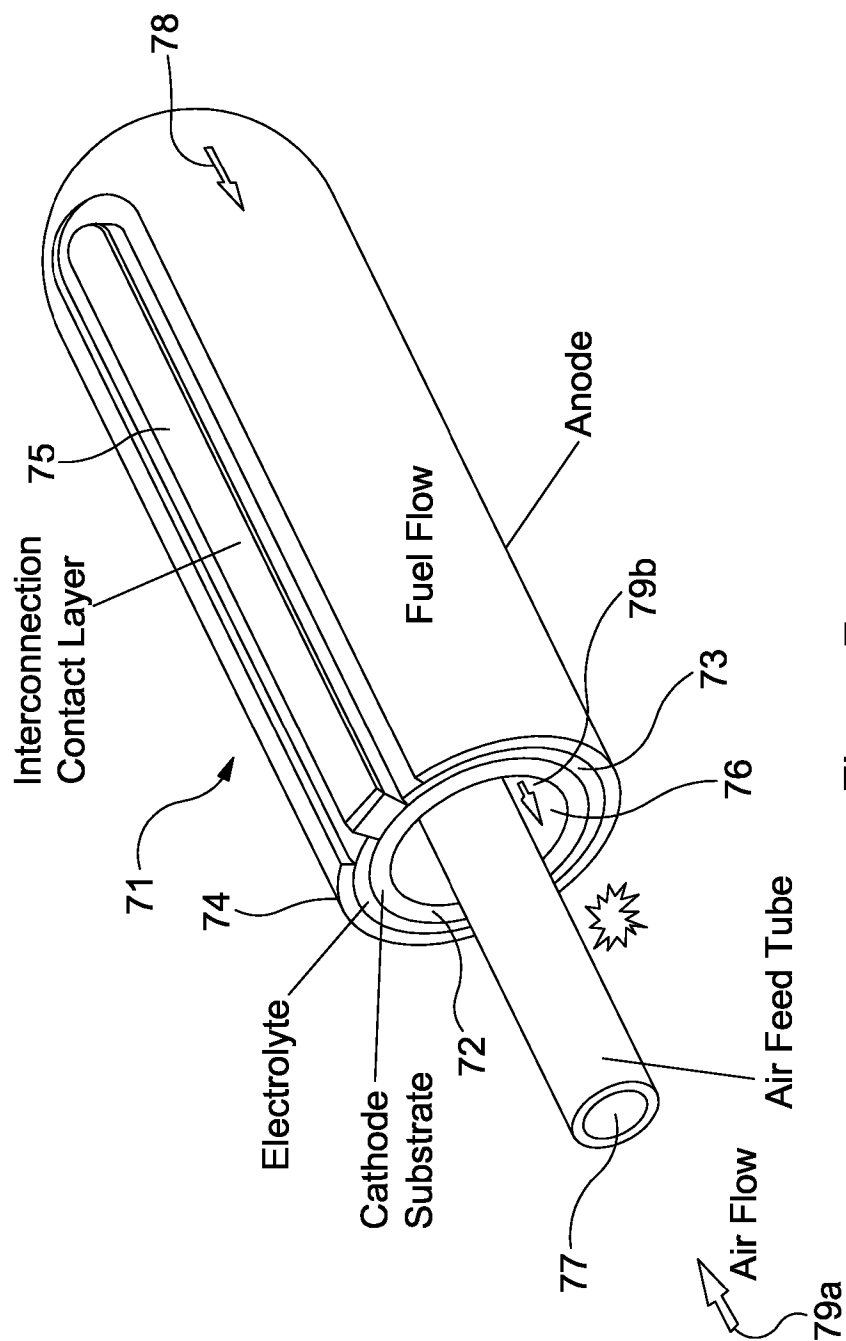


Figure 7

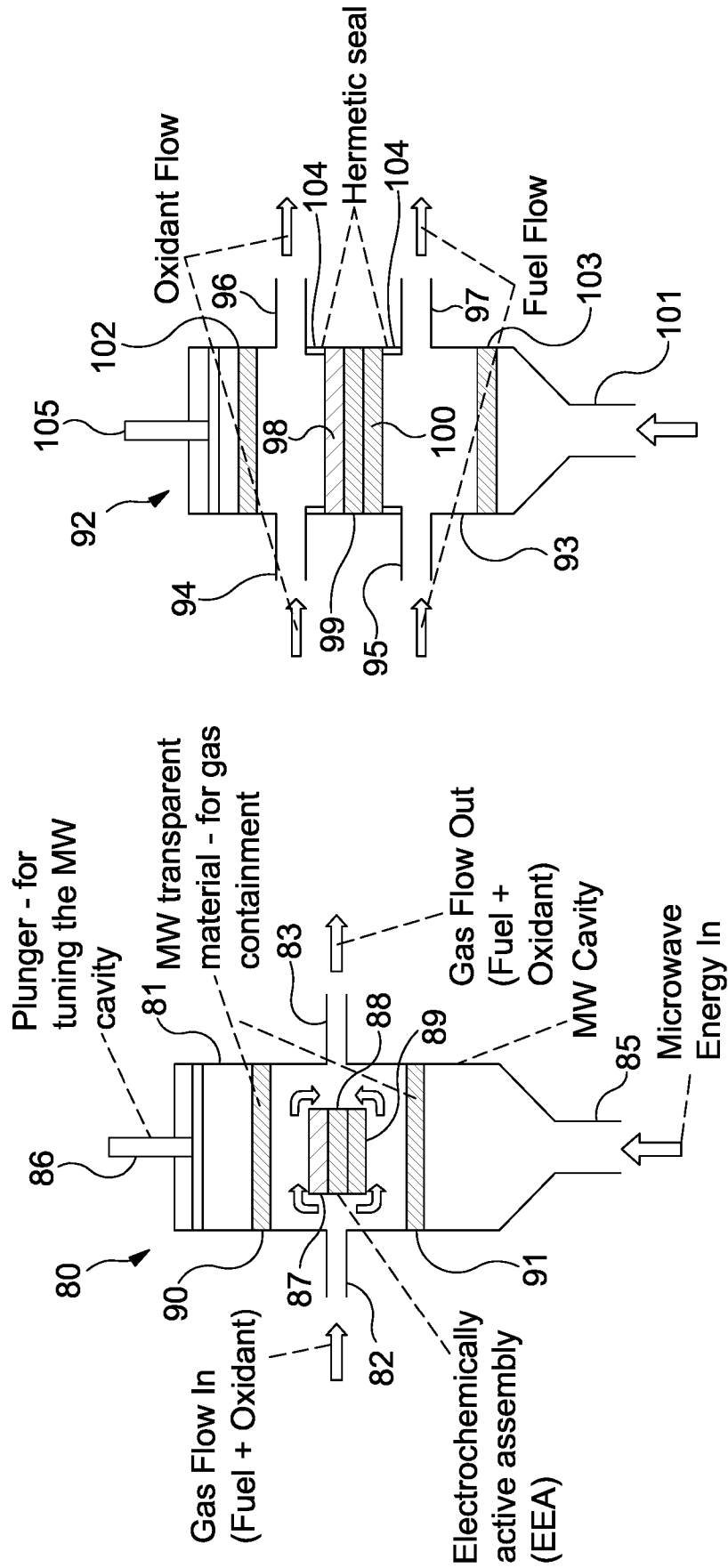


Figure 8

Single Chamber Microwave Tunable Fuel Cell

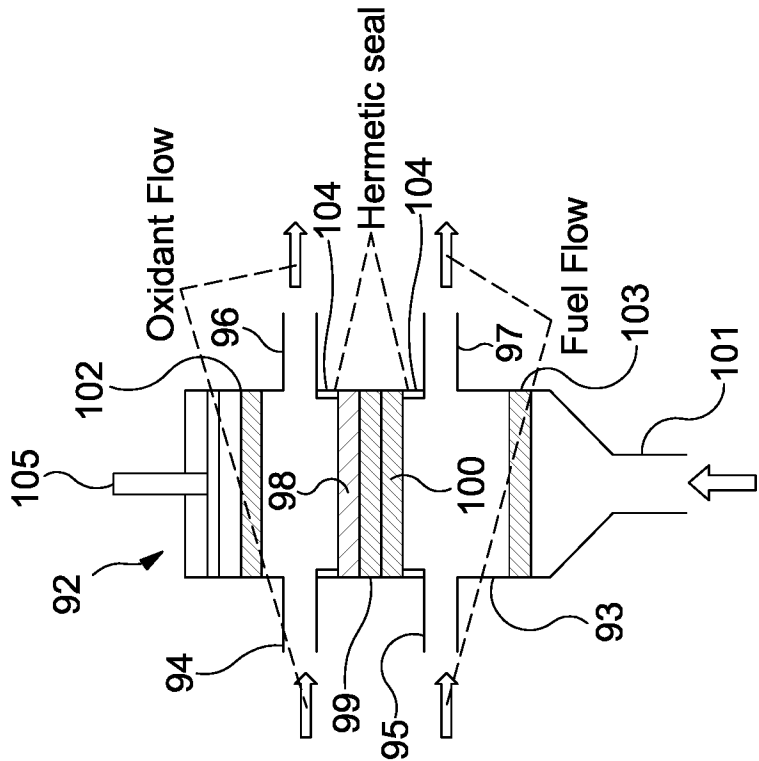


Figure 9

Dual Chamber Planar Microwave Tunable Fuel Cell

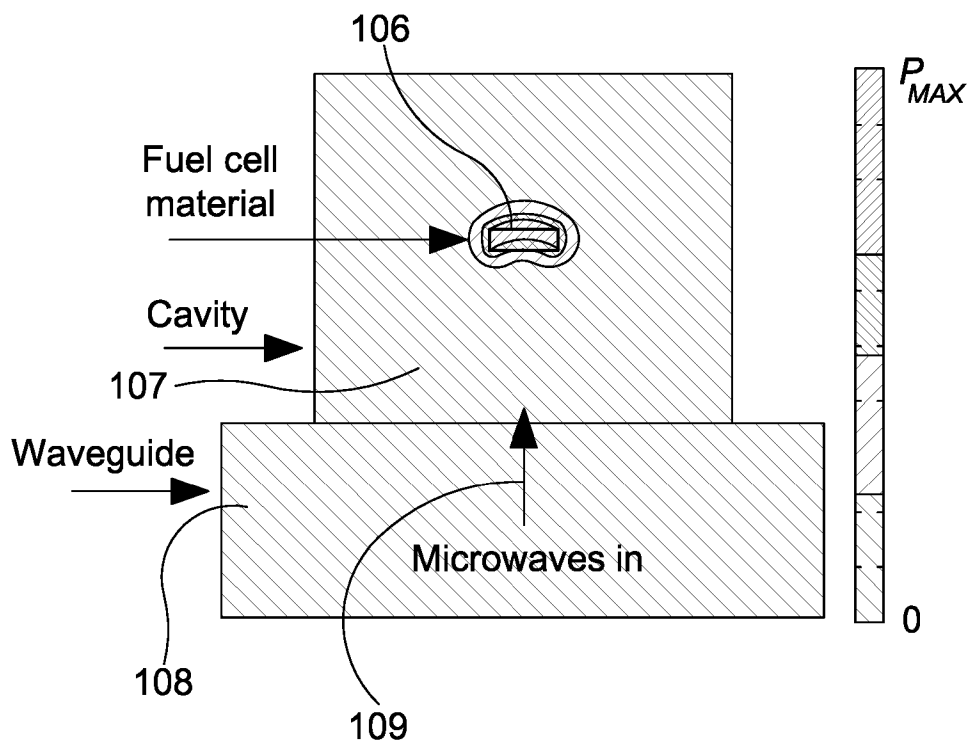


Figure 10

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2014/052990A. CLASSIFICATION OF SUBJECT MATTER
INV. H01M8/04
ADD. H01M8/12

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H01M

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	JP 2011 165516 A (HONDA MOTOR CO LTD) 25 August 2011 (2011-08-25) abstract; figures 1,2,5,8 paragraphs [0021], [0022], [0023], [0025] paragraph [0041] - paragraph [0043] paragraph [0047] - paragraph [0051] ----- -/--	1-4, 6-19,21, 25-28,30



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

12 November 2014

Date of mailing of the international search report

25/11/2014

Name and mailing address of the ISA/

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Authorized officer

Hintermaier, Frank

INTERNATIONAL SEARCH REPORT

International application No

PCT/GB2014/052990

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	GB 2 469 522 A (ENERGY CONVERSION TECHNOLOGY AS [NO]) 20 October 2010 (2010-10-20) figures 3,7,8,9 page 12, line 35 - page 13, line 8 page 9, line 16 - line 24 page 10, line 4 - line 6 page 14, line 9 - line 19 page 13, line 9 - line 32 page 7, line 25 - line 28 page 13, line 29 -----	1-5, 12-15, 17-24, 26-30

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/GB2014/052990

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
JP 2011165516 A	25-08-2011	NONE	

GB 2469522 A	20-10-2010	GB 2469522 A	20-10-2010
		WO 2010120188 A1	21-10-2010
