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(71) Applicant(s):
ACAL Energy Ltd
The Heath Business and Technical Park, Runcorn, Cheshire, WA7 4QX, United Kingdom

(72) Inventor(s):
Robert J Longman

(74) Agent and/or Address for Service:
WP Thompson
55 Drury Lane, London, WC2B 5SQ, United Kingdom

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EP 2535973 A1 **EP 0517217 A1**
CN 102110830 A **US 20100291429 A1**

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Other: **Online: WPI, EPODOC, INSPEC, XPRD**

(54) Title of the Invention: **Apparatus for cooling a fuel cell**
Abstract Title: **Apparatus for cooling a liquid electrolyte fuel cell**

(57) Apparatus for cooling a liquid electrolyte fuel cell comprises a liquid electrolyte transport arrangement 601 for bringing liquid electrolyte from a fuel cell 201 into thermal communication with a thermal energy transfer medium, and for communicating the liquid electrolyte from thermal communication with the energy transfer medium back to the fuel cell. The apparatus also comprises a thermal energy transfer medium transport arrangement 105, 106, 108 for communicating the thermal energy transfer medium to thermal communication with the liquid electrolyte from a heat sink 107, and for communicating the thermal energy transfer medium from thermal communication with the liquid electrolyte back to the heat sink. The liquid electrolyte and thermal energy transfer medium preferably come together at a heat exchanger, which is most preferably in the form of a reaction (regeneration) chamber 801 for the liquid electrolyte. The liquid electrolyte may be a catholyte. The thermal energy transfer medium is preferably non-conducting, and may be, for example, a water/ethylene glycol mix. Alternatively, an electrically insulating material may be provided between the thermal energy transfer medium and the liquid electrolyte. A method for cooling a liquid electrolyte fuel cell using the apparatus is also disclosed. The apparatus may be used to cool a stack of fuel cells, which fuel cells may be used in electronic and/or automotive equipment, and/or for generating combined heat and power.

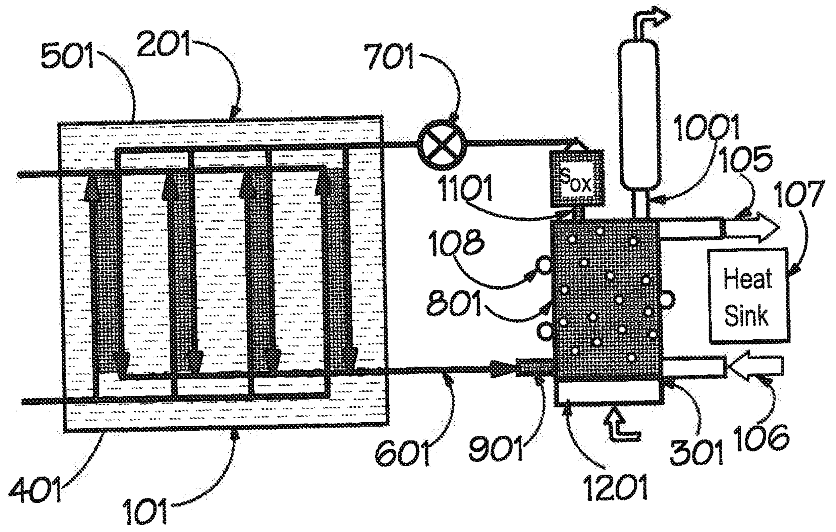

Fig.2.

At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

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24 06 13

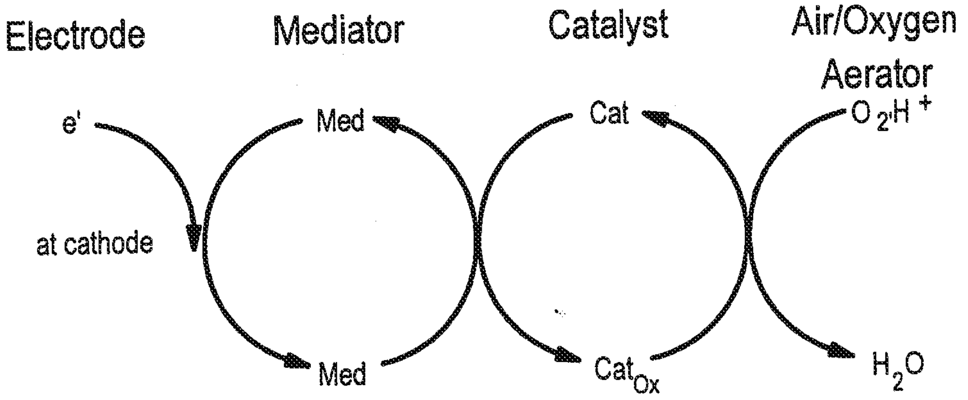


Fig.1.

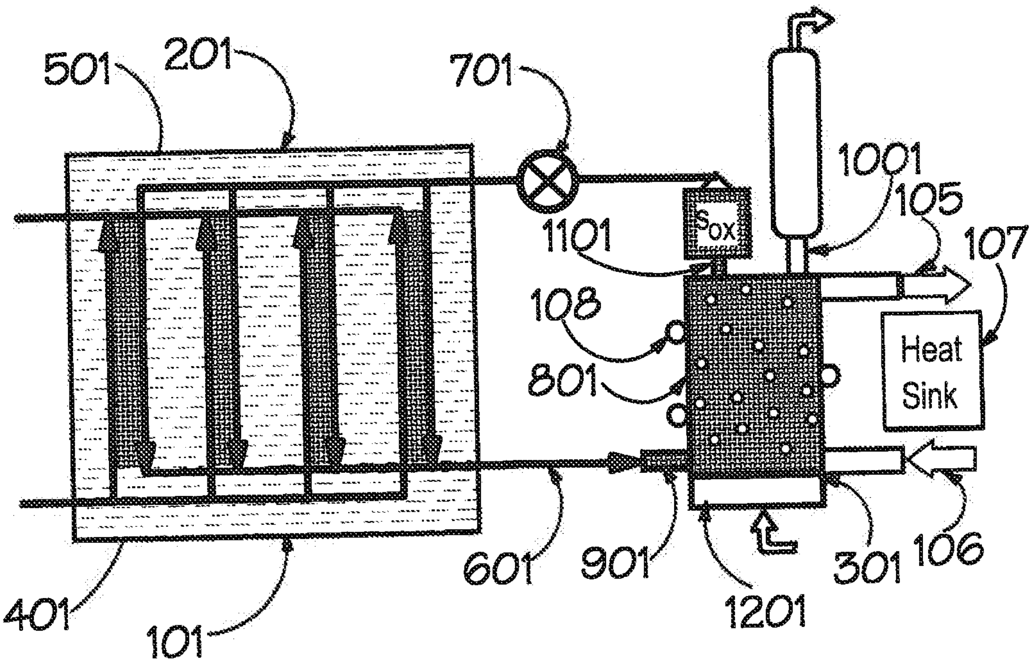


Fig.2.

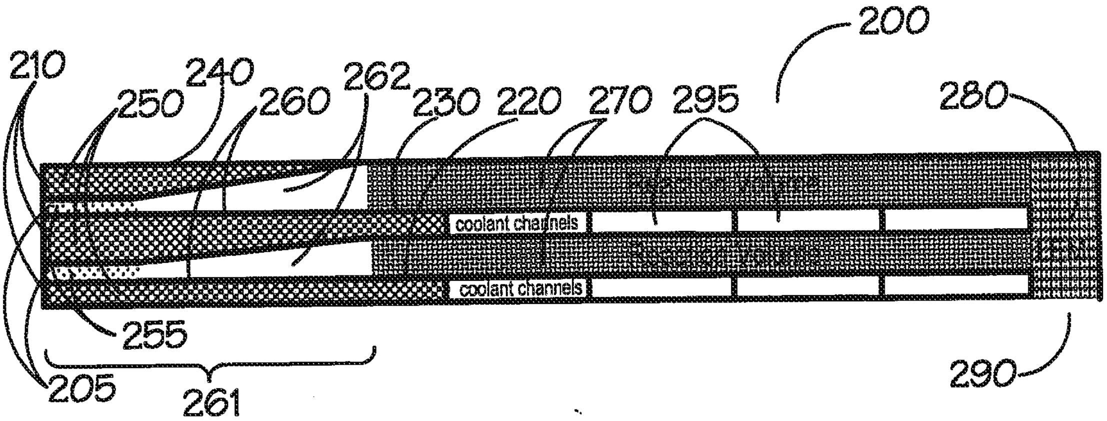

200
210
250
240
260
262
230
220
270
295
280
coolant channels
coolant channels
255
205
261
290

Fig.3.

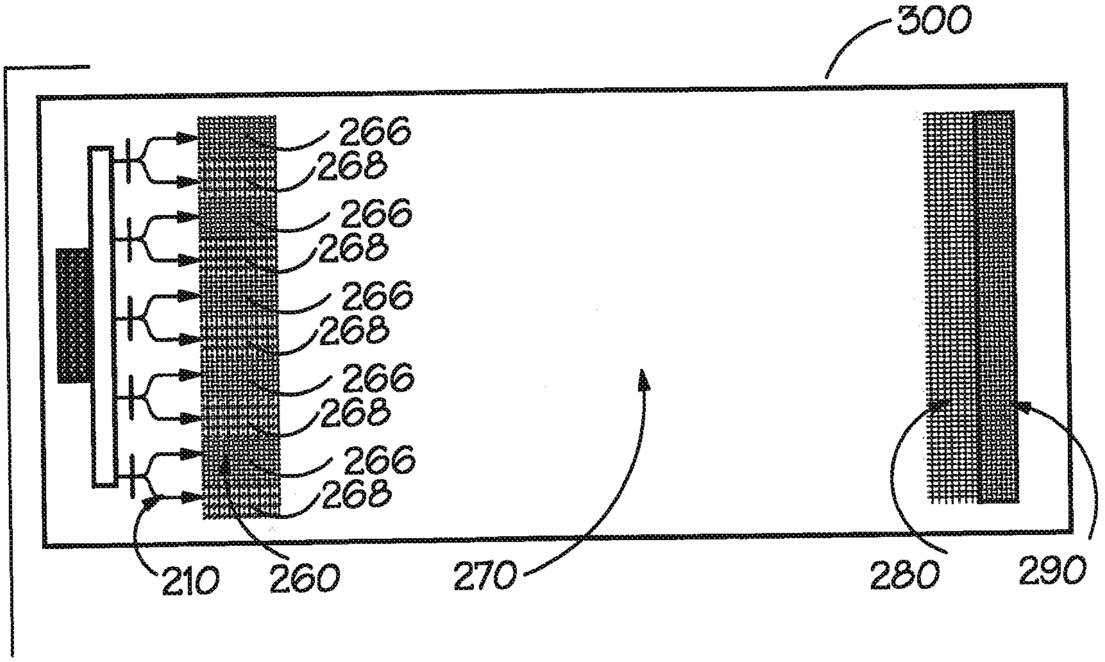
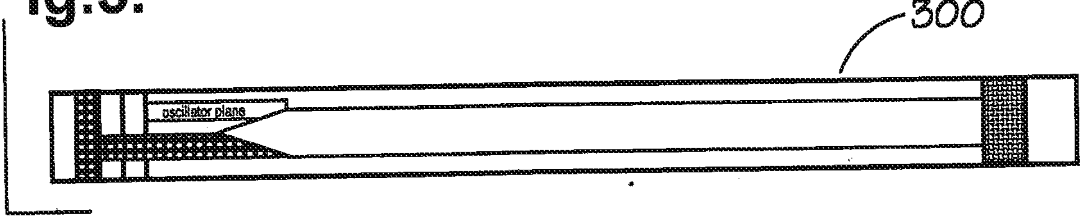

300
266
268
266
268
266
268
266
268
266
268
210
260
270
280
290

Fig.5.


300
oscillator plans

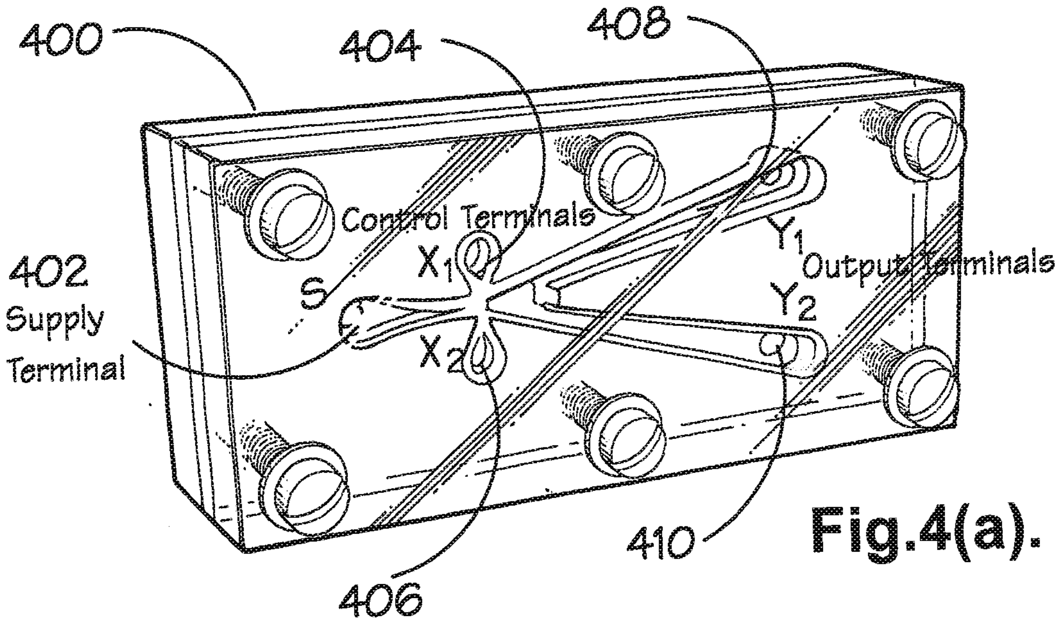
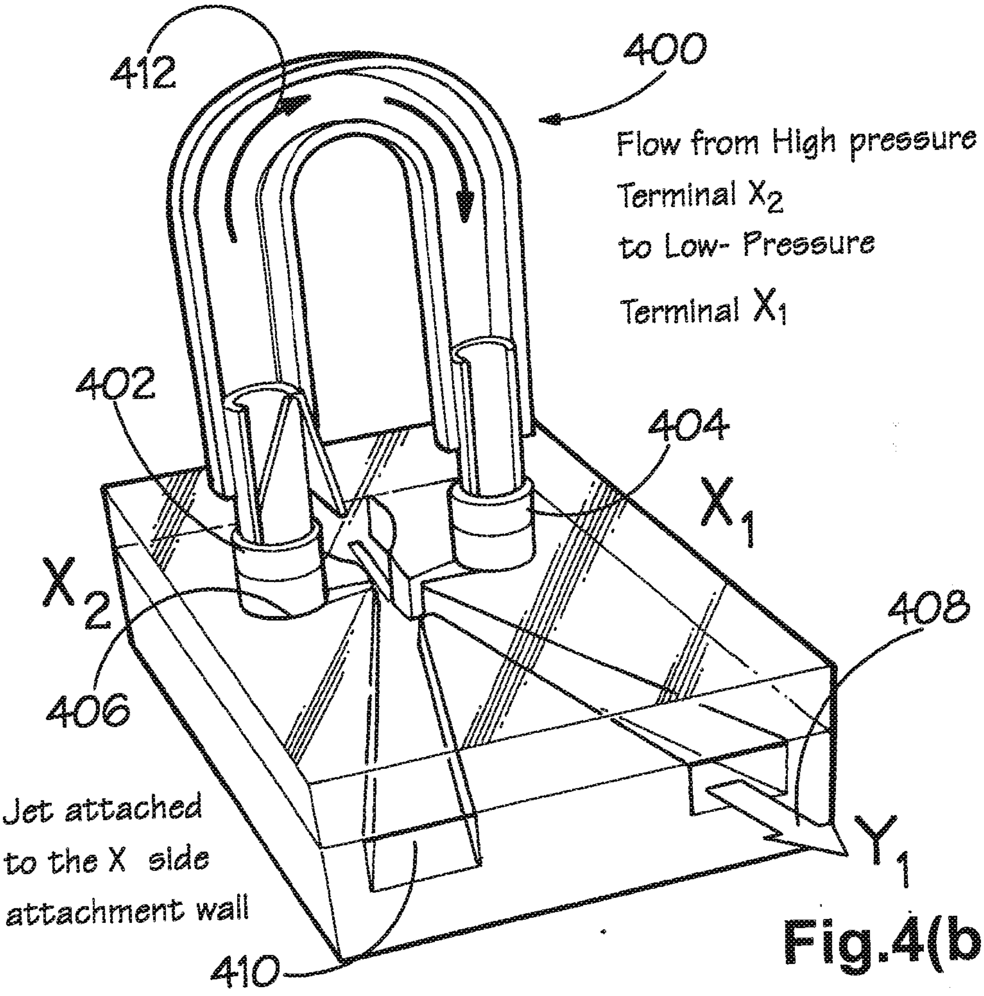


Fig.4(a).



Flow from High pressure Terminal X_2 to Low- Pressure Terminal X_1

Jet attached to the X side attachment wall

Fig.4(b).

24 06 13

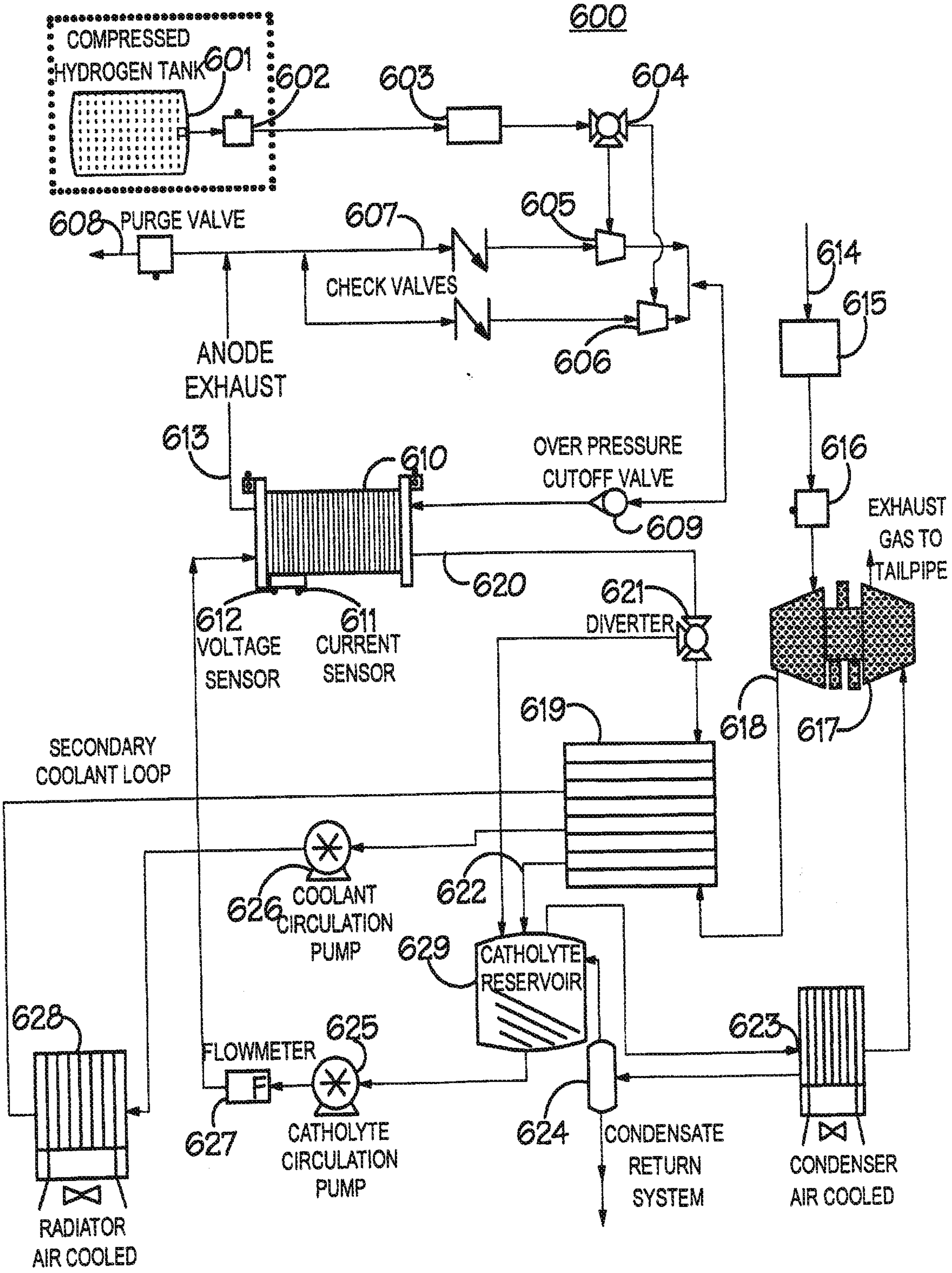

600
COMPRESSED HYDROGEN TANK
601
602
603
604
608
PURGE VALVE
607
605
CHECK VALVES
606
614
615
ANODE EXHAUST
613
610
OVER PRESSURE CUTOFF VALVE
609
616
EXHAUST GAS TO TAILPIPE
620
612
VOLTAGE SENSOR
611
CURRENT SENSOR
621
DIVERTER
619
618
617
SECONDARY COOLANT LOOP
622
626
COOLANT CIRCULATION PUMP
629
CATHOLYTE RESERVOIR
628
625
FLOWMETER
F
627
CATHOLYTE CIRCULATION PUMP
623
624
CONDENSATE RETURN SYSTEM
CONDENSER AIR COOLED
RADIATOR AIR COOLED

Fig.6.

Application No. GB1307611.2 RTM Date :29 October 2013

The following term is a registered trade mark and should be read as such wherever it occurs in this document:

ACAL

APPARATUS FOR COOLING A FUEL CELL

The invention relates to an apparatus for cooling a fuel cell, to a fuel cell, to a stack comprising a plurality of such fuel cells, to use of such a fuel cell or such a stack, and to an electronic, automotive or combined heat and power equipment comprising such a fuel cell.

Published international patent applications WO2010/128333, WO2011/107794 and WO2011/107795 disclose redox fuel cells in which a regeneration zone is provided for the oxidative regeneration of a redox active species which has been reduced at the cathode in operation of the cell. These fuel cells may use hydrogen as a fuel with air or oxygen as oxidant. The operation of indirect redox fuel cells of these types is such that the oxidant is not supplied directly to the electrode but instead reacts with the reduced form of a redox couple in the catholyte to oxidise the redox couple, and this oxidised species is fed to the cathode of the fuel cell. In the regenerator, the catholyte comes into contact with an oxidant such as air or oxygen and is regeneratively oxidised before flowing back to the fuel cell. The oxidant may be a mixture of gases including oxygen, such as air, and the term “air” will be used when describing embodiments of the invention for convenience and brevity however a person of ordinary skill in the art will recognise that embodiments are not limited to the use of air as an oxidant.

FIG. 1 is a simple flow diagram illustrating the redox reactions occurring in these types of fuel cell.

WO2011/107794 is to some extent concerned with the oxidative regeneration of the redox active species in a regeneration zone and describes the basic principles of liquid flow past a porous element through which gas is injected into the liquid thus creating high interfacial area between the gas and liquid phases by generating many small bubbles each having a gas-liquid interfacial membrane.

There are a number of constraints on this step of oxidising the redox couple. Oxidation of the redox couple should occur as rapidly as possible as a reduction in flow rate of the catholyte through the cathode will reduce the rate of energy production. The rate of energy production will also be reduced if oxidation of the redox couple is not as complete as possible, i.e. if a significant proportion of the redox couple remains unoxidised. The provision of apparatus which rapidly and completely oxidises redox couples present in catholyte solutions is made challenging by the need to ensure that the energy consumed when the oxidation step is taken is relatively low, otherwise the overall power generation performance of the fuel cell will be reduced. Additionally, the apparatus used to oxidise the redox couple should be as compact as possible, especially when the fuel cell is intended for use in portable or automotive applications. A very large interfacial surface area between the liquid catholyte and the oxidative gas promotes a higher oxidation rate.

The liquid catholyte does not require a dedicated liquid cooling system as the liquid catholyte transfers heat away from the fuel cell to the regeneration zone.

Aspects and embodiments in accordance with the present invention were devised with the foregoing in mind.

Viewed from a first aspect, there is provided apparatus for cooling a liquid electrolyte fuel cell, comprising:

a liquid electrolyte transport arrangement for bringing liquid electrolyte from a fuel cell into thermal communication with a thermal energy transfer medium and for communicating liquid electrolyte from thermal communication with the thermal energy transfer medium back to the fuel cell; and

a thermal energy transfer medium transport arrangement for communicating the thermal energy transfer medium to thermal communication with the liquid electrolyte from a heat sink and for communicating the thermal energy transfer medium from thermal communication with the liquid electrolyte to a heat sink.

Viewed from a second aspect, there is provided a method for cooling a liquid electrolyte fuel cell, comprising:

bringing liquid electrolyte from a fuel cell into thermal communication with a thermal energy transfer medium;

bringing liquid electrolyte from thermal communication with the thermal energy transfer medium back to the fuel cell;

bringing the thermal energy transfer medium from a heat sink into thermal communication with the liquid electrolyte; and

bringing the thermal energy transfer medium from thermal communication with the liquid electrolyte to a heat sink.

An embodiment in accordance with the first and second aspect may enhance cooling of the fuel cell by drawing heat away from the fuel cell via liquid electrolyte to the thermal energy transfer medium. The cooled liquid electrolyte then returns to the fuel cell. The thermal energy transfer medium in turn transfers the heat energy to a heat sink where it is cooled and returns cooled thermal energy transfer medium back to thermal communication with heated liquid electrolyte from the fuel cell. Since the electrolyte is electrically conducting, a circuit may be formed between the relatively high voltage on the fuel cell and the arrangement communicating the thermal energy transfer medium to the heat sink. In particular, since suitable electrolytes also are electrically conductive and so potential for the creation of an electrically conducting circuit is likely in an embodiment.

Electrically insulating the liquid electrolyte from the heat sink may be achieved, for example, by using an electrically insulating thermal energy transfer medium (coolant). The thermal energy transfer medium transport arrangement may optionally or additionally be electrically insulated from the liquid electrolyte.

Typically, the apparatus comprises a heat exchanger, the liquid electrolyte transport arrangement configured to bring liquid electrolyte to the heat exchanger and the thermal energy transfer medium transport arrangement configured to communicate the thermal energy transfer medium to the heat exchanger such that thermal communication between the liquid electrolyte and thermal energy transfer medium takes place through operation of the heat exchanger.

Suitably, the heat exchanger comprises a reaction chamber for the liquid electrolyte. Utilising the heat exchanger as a reaction chamber, or vice versa, synergistically combines the reaction chamber function with the heat transfer function of the heat exchanger in one unit. Consequently, the apparatus may comprise fewer parts than would otherwise be the case. In a particular arrangement, the reaction chamber is configured to regenerate the liquid electrolyte.

In one or more embodiments, the reaction chamber is configured to admit gas comprising oxygen for regenerating the liquid electrolyte. For such embodiments, typically the liquid electrolyte comprises a liquid catholyte. Suitably, the reaction chamber is configured for oxidation of reduced redox couples of the catholyte.

In one or more embodiments, the fuel cell is configured as a polymer exchange membrane indirect redox fuel cell.

In a particular arrangement, the reaction chamber is substantially planar and the thermal energy transfer medium transport arrangement comprises one or more thermal energy transfer medium conduits disposed in thermal communication with a wall forming a major surface of the reaction chamber. Such thermal energy transfer medium conduits may be pipes formed separately from and/or integrally with the reaction chamber. The walls of the pipes, at least so far as they contact the wall of the reaction chamber, should be thermally conductive and preferably highly thermally conductive in order to promote effective transfer of heat from the liquid electrolyte to the thermal energy transfer medium.

Such an arrangement may allow for the integration of an indirect heat exchanger and coolant system within a part of a fuel cell energy system, for example a part of the applicant's ACAL Energy system. System complexity may be reduced by integrating an indirect heat exchanger between the liquid catholyte and thermal energy transfer medium.

Typically, the liquid electrolyte transport arrangement comprises a liquid electrolyte conduit in fluid communication with the reaction chamber. The liquid electrolyte conduit may be configured to effectively and efficiently communicate the liquid electrolyte to the reaction chamber.

The liquid electrolyte transport arrangement may comprise a porous member including first and second surfaces and the apparatus may be arranged to supply a gas to a first surface of the porous member and the liquid electrolyte to the second surface of the porous member and wherein the porous member is configured to communicate gas incident at the first surface through the porous member to the second surface of the porous member for producing bubbles in the liquid electrolyte proximal to the second surface. The amount of bubbles produced maybe such that the porous member defines a foam generation region for a foam generator comprised in the apparatus; the foam generator further comprising a gas supply modulator arranged to modulate a supply of the gas to the first surface.

Suitably, the foam generator is arranged to receive the gas from a gas supply common to at least one other foam generator. Such an arrangement is efficient in that a single gas supply may be used for supply gas to many foam generators rather than using multiple gas supplies e.g. canisters or gas bottles, which will take up a greater volume than would otherwise be necessary.

The one or more thermal energy transfer medium conduits may be configured to direct flow of the thermal energy transfer medium in a direction transverse to a flow of the liquid electrolyte in the reaction chamber. Such an arrangement would provide for an output manifold from the thermal energy transfer medium conduits to be placed along a side of the apparatus different from the outlet, and inlet, for the liquid electrolyte/catholyte.

One arrangement comprises a construction containing alternating gas/liquid contacting planes and thermal energy transfer medium planes. In one possible configuration, the thermal energy transfer medium can flow across (e.g. transversely to) the flow of catholyte/gas mixture, allowing a simple physical design with catholyte and thermal energy transfer medium manifolds aligned on transverse respective sides of the active region of the fuel cell (the region in which chemical reaction and heat exchange take place in the cell). According to such a configuration, the coolant channels may run at least partly transversely to the catholyte channels.

Suitably, the gas comprises an oxidant such as air or oxygen.

In one embodiment, there may be a stack of apparatus such as referred to above wherein respective reaction chambers are in fluid communication with a liquid catholyte output manifold; and respective liquid catholyte transport arrangements are in liquid communication with a liquid catholyte input manifold. Providing output and input manifolds is a suitably convenient way of distributing liquid catholyte from and to a stack of apparatus.

Likewise, whether in a stack or not, the apparatus may be arranged to supply gas to the first surface of the porous member from a gas supply manifold.

A particularly suitable embodiment is a fuel cell comprising apparatus as referred to above. Such a fuel cell may comprise a stack of apparatus. A stack may comprise a plurality of fuel cells such as referred to previously.

Fuel cells, whether in a stack or not may be used in electronic and/or automotive equipment and/or for generating combined heat and power. Electronic, automotive and/or combined heat and power equipment may comprise a fuel cell or a stack as referred to above.

The thermal energy transfer medium, which may be referred to as a coolant, may be a fluid having a low freezing temperature (lower than the freezing temperature of water). This has an advantage that the coolant does not have to be protected from freezing in a cold environment. Furthermore, the coolant may be at a lower temperature than water and so provide better cooling of a fuel cell.

A water and ethylene glycol mixture may be used as coolant. This has a freezing temperature lower than water, is relatively low-cost and readily available. Furthermore, a water and ethylene glycol mixture is an electrically insulating thermal energy transfer medium/coolant as it is not electrically conductive.

In order to reduce system complexity, it is desirable to integrate the indirect heat exchanger between catholyte and coolant within an existing element of the ACAL Energy system.

The above and further aspects and advantages of embodiments in accordance with the invention will become clearer from the following detailed description, given by way of example only and with reference to the appended drawings. It should be understood that the scope of protection sought by the applicant is defined by the appended claims and should not be considered as limited to any one of the described embodiments. In the drawings:

FIG. 1 is a flow diagram illustrating the redox reactions occurring in one type of redox fuel cell;

FIG. 2 is a schematic diagram of a redox fuel cell system;

FIG. 3 is a side sectional view of bubble-generating apparatus according to an embodiment;

FIG. 4(a) is an illustration of an example of a fluidic oscillator showing the main components;

FIG. 4(b) is a schematic illustration illustrating the function of a fluidic oscillator;

FIG. 5 shows both plan and side, transparent sectional views of a bubble-generating apparatus according to an embodiment of the invention; and

FIG. 6 schematically illustrates a fuel cell system incorporating an indirect heat exchanger in the gas liquid contactor secondary coolant loop in accordance with an embodiment of the invention.

FIG. 2 is a schematic diagram of a liquid electrolyte-based fuel cell system 101. The system 101 comprises two major components: fuel cell stack 201 and regenerator section 301. Fuel stack 201 as illustrated comprises four half-membrane electrode assemblies 401. Each membrane electrode assembly and cathode 401 is separated from its neighbouring membrane electrode assembly and cathode by a bipolar plate which will comprise flow channels for allowing hydrogen fuel (in the case of the anode side) to diffuse across the electrode surface in operation of the cell and a well to site the cathode electrode and catholyte (in the case of the cathode side), in a manner which is well known in the art. At each end of the fuel cell stack unipolar separating plates are provided (meaning that diffusion channels are provided on only one side thereof for the anode; the side facing the electrode, and a cathode well for the cathode). Figure 2 does not attempt to show these plates, since their configuration, assembly and function are well known in the art.

Catholyte channels 601 are also schematically shown in Figure 2 and the arrows indicate the direction of fuel flow around the cell.

Catholyte is supplied to the fuel stack in line 501 through recycle pump 701 and is recovered, the redox mediator couple component of the catholyte having been at least partially reduced at the cathode in operation of the cell. The catholyte containing at least partially reduced redox mediator couple is recovered and supplied to regeneration chamber 801 through first inlet port 901. Regeneration chamber 801 is further supplied in second inlet port 1001 with a flow of oxidant; in this case air.

The oxidant passes through a porous member 1201 into the interior of an adjacent channel (not shown) and contacts the at least partially reduced catholyte passing therethrough. The redox couple flowing in solution in the regeneration chamber in operation of the cell is used as a catalyst for the reduction of oxygen.

Catholyte solution containing regenerated oxidised redox couples is recovered from regeneration chamber 801 through first outlet port 1101 and may be supplied directly into line 501 through recycle pump 701. Some or all of the water vapour may be condensed in condenser and returned to the catholyte solution, via a demister (not shown) in order to assist in maintaining the humidity balance in the cell.

In operation of the cell, electrons generated at the anode by the oxidation of fuel gas flow in an electrical circuit (not shown) are returned to the cathode, in a manner well known in the art.

In the embodiment illustrated in Fig. 2, pipes 108 for conveying coolant are wrapped around the regeneration chamber 801 thereby providing conduits for a thermal energy transfer medium. The pipes 108 are configured to be in a thermal communication with the regeneration chamber 801. The coolant is input, 105, from a heat sink 107 and after passing through the pipes 108 is output, 106, to the heat sink 107. The combination of the regeneration chamber 801 and coolant pipes 108 form a heat exchanger mechanism in which thermal energy of the liquid catholyte in the regeneration chamber 801 may be transferred to the coolant by the thermal communication between the regeneration chamber 801 and the pipes 108.

Although illustrated schematically, the heat sink 107 may be a conventional heat sink such as a radiator which is particularly suitable for an embodiment utilised in a motor vehicle, but may be utilised in other configurations such as a static power supply.

Using conventional porous 'sparge' with a pore size of 2-microns such as supplied by Mott Corporation, the smallest size of bubble that can be created is around 150-microns or micrometres (μm).

Investigations have been carried out into the use of engineered surfaces with a controlled array of small holes typically produced by laser drilling a thin metal foil. European Patent Application Publication EP2542332 discloses the use of such engineered surfaces for fine bubble generation, and in particular the use of tapered holes to restrict the naturally rapid rate of growth of small bubbles.

An alternative approach towards restricting the size of bubbles is the use of oscillatory air flow to limit bubble growth. This has been described in "*On the Design and Simulation of an Airlift Loop Bioreactor with Microbubble Generation by Fluidic Oscillation*", by W Zimmerman, B Hewakandamby, V Tesar, H Bandulasena and O Omotowa (Zimmerman et al). The approach involves use of an oscillating air flow comprising high pressure pulses. The volume of air in each high pressure pulse restricts the size of bubble formed.

The applicant has experimented with applying fluidic oscillation to the production of fine bubbles, specifically in a catholyte regeneration system of a fuel cell. Experiments have concentrated on air pulses produced at relatively low frequencies for generation of the bubbles. There are of the order of 1,000 holes, typically less than 1,000 holes. At higher frequencies needed for the higher gas flow rates there are shorter wavelengths so coupling and avoidance of standing waves becomes an issue.

The inventors have found that it is desirable to generate a total air flow in excess of 1,000 litres per minute (16.66 litres per second). In order to achieve high enough rates of mass transfer it is desirable to create bubbles having diameters of between around 50 and 100 microns. It has been found to be desirable to generate bubbles having sizes of around 50 microns.This translates to generating of the order of 2 E 11 (2×10^{11}) bubbles per second. In order to limit the number of holes in the porous plate to a realistic number, say less than 100,000 present at any one time, and produce small bubbles at gas high flow rates the inventors have found that it is desirable to oscillate, or pulse, the air at a frequency or rate of 2 kHz or more, and further desirable to oscillate the air at a rate in excess of 3 kHz.

To achieve the required very small bubbles, high gas flow velocities in each gas-liquid contacting element are used, typically 1 to 20 litres per minute, that is around 17 to 330 cm^3 per second.

When implementing a fluid oscillator in a fuel cell, the inventors have found that it is beneficial to divide the oscillatory air flow between many individual gas-liquid contacting elements. If only a single element were used, it would be exceedingly large. Therefore, it is beneficial to restrict the size of such a gas-liquid contacting element by arranging the gas-liquid contacting element as a planar element and stacking multiple such planar elements in parallel. However, it has been found that doing this causes standing waves in the air flow. This becomes a particular problem when oscillation frequencies are increased into the kilohertz range suitable to generate the high air flow rates (and therefore high air flow velocities), and the very small bubbles, to achieve efficient mass transfer as explained above.

High frequencies of between 1 to 5 kHz, suitable to achieve the very small bubbles at such high gas flow velocities, result in standing waves whose dimensions are of the order of a few centimetres (cm). Due to these standing waves, matching of oscillating air flow to multiple gas-liquid contacting elements is complex and uses significant physical space. For example, at a frequency of 3 kHz, standing waves in any connecting fluid channel or pipework will have a physical length of around 5 cm. In this example, a length of fluid channel or piping may therefore be increased by up to 5cm so as to avoid or remove such a standing wave.

In a practical implementation, as suggested above, it will be beneficial to have multiple gas-liquid contacting elements or modules, typically stacked in parallel and operating in parallel, each having a porous region and a chamber where mass transfer is allowed to complete via gas-liquid contacting.

This arrangement of multiple (e.g. stacked) modules may present problems in a physical implementation in which large numbers of porous plates must be provided with oscillating air. This is because the length of each pipe connecting the oscillator to each of the individual elements (operating in parallel) should be selected, adjusted or tuned to take account of standing waves, resulting in a very complex design. For example, as many as 100 elements may be stacked in a complete system. In addition, such a design will only be effective at a single frequency.

Thus, the inventors have devised apparatus and method for generating a foam comprising very small bubbles at very high gas flow rates. One or more embodiments aim to achieve this while avoiding generation of standing waves within the foam.

Turning to FIG. 3, an apparatus for generating foam is shown, in which air is fed through a common inlet manifold 210 of a stack 200 of plural gas-liquid contacting elements 220, 230, 240, the manifold 210 distributing the air to each of the plural elements in the stack (one such element 230 being shown completely and two elements 220, 240 being shown partly in FIG. 2). The plural elements together form a multi element gas-liquid contacting device.

Each element has a gas supply input, or gas feed 250, and a liquid supply input 255, each shown to the left of the figure and feeding into a foam generator 261. Gas passes via the gas feed 250 through a porous member 260 into a foam generation region 262 and then onwards in the form of a foam into a liquid-containing region 270 (which can be termed a reaction volume) of the element. Liquid is supplied into the foam generation region 262 and onto the liquid-containing region 270 from a liquid inlet manifold 505. The gas at the gas output region of the porous element (upper side of the porous element, as shown) forms bubbles in the liquid proximal to the surface of the porous member 260 in foam generation region 262. The bubbles begin to grow in volume due to the continued injection of gas through the porous element 260.

The liquid is injected through the liquid inlet manifold 505 at a rate sufficient to cause the injected liquid to flow rapidly onto, across and/or along the (upper) surface of the porous member 260 in the foam generation region 262. This flow of liquid acts to separate or dislodge some of the recently formed bubbles from the surface. The bubbles collect to form foam and the foam passes (from left to right in FIG. 3) into the liquid-containing region 270. The liquid-containing region 270 can also be termed a reaction chamber 270 since, in this region, gas-liquid contacting occurs and oxygen from the gas reacts with the reduced catholyte to oxidise it.

To the right of FIG. 3, the foam passes into a mesh 280 comprising low-surface energy material. The mesh 280 acts to break or burst the bubbles of the foam, resulting in separation of the gas and liquid phases of the foam. The broken-down, or destroyed, foam, passes into an outlet manifold 290. The use of the low-surface energy material assists in breaking or bursting the bubbles. . An example of such an arrangement is disclosed in the Applicant's co-pending international patent application number PCT/GB2013/050174 incorporated herein by reference.

The supply of gas via the gas supply input 250 of each element is modulated by means of a gas supply modulator (not shown in FIG. 3), which is located either proximal to, or within the gas supply input 250. The modulator is arranged to urge input gas towards the porous element with a varying pressure, typically cyclically varying. It should be understood that the variation may have constant or non-constant period.

When the pressure differential, i.e. the difference between the pressure of the gas at the gas input side of the porous member 260 and the pressure of the liquid on the other side of the porous member 260, is above a threshold value, gas passes into the liquid and causes a bubble to form or grow. When the pressure differential is below the threshold value, bubbles at the porous member 260 substantially do not form or grow. The period during which the pressure differential is below the threshold is known as the "dwell time". During the dwell time bubbles are substantially static and if not already separated from the porous member are removed (swept away) from the porous member by liquid flowing past the porous member. Bubbles formed this way are likely to be very small since their growth has been inhibited by the reduction of the gas pressure under the influence of the modulator.

In this case, because each element has its own modulator or oscillator associated with it (either proximal to the element or within the element) the matching of the oscillation of gas to the porous element may be achieved for each individual element 220, 230 and 240. Each element may extend in transverse directions to provide a large reaction volume 270 which would likely result in a large area of porous material.

The embodiment illustrated in FIG. 3 also includes coolant channels, 295, which extend between the reaction volumes 270 (regenerators) in a direction transverse to the flow of liquid catholyte/foam in the reaction volumes 270. As with the embodiment illustrated in FIG. 2, the coolant channels 295 are in thermal communication with respective reaction volumes 270 such that heat energy in the liquid catholyte is transferred to a coolant flowing in the coolant channels 295. In the described embodiment, the coolant is a water and ethylene glycol mix which is non-conducting and therefore even if the walls of the reaction volumes 270 and coolant channels 295 are electrically conductive the coolant does not act as a conductor.

A coolant outlet manifold, not shown, is coupled to respective coolant channels 295 to a side of the apparatus 200 different from the sides coupled to the respective liquid catholyte, gas and foam output manifold's. The coolant output manifold is coupled to the apparatus 200 by way of an electrically insulating coupling arrangement such as a rubber gasket. Thus, any downstream equipment may be electrically insulated from the apparatus 200 by virtue of the electrically incinerating coupling arrangement and the non-electrically conducting water/ethylene glycol coolant mix.

Fluidic oscillators of the type described by Zimmerman et al have a substantially planar configuration and may be particularly suitable as modulators for one or more embodiments in accordance with the present invention in which relatively low profile foam generation apparatus is utilised. Such fluidic oscillators are not limited to use with low profile foam generation apparatus. An example of such a fluidic oscillator is illustrated in FIG 4.

Fig. 4(a) illustrates a model of a so-called fluidic jet-deflection amplifier, details of which are disclosed in Tesa˘r, V., Hung, C.-H. and Zimmerman, W.B., 2006, *No moving part hybrid synthetic jet mixer* Sensors and Actuators A,125(2): 159–169, which forms the basic component of a fluidic oscillator. A steady supply of air is input to a supply terminal 402 of the fluidic amplifier 400. The supply of air to one of the two output terminals 408 and 410 is under control of the control signals (air flow) sent to control terminals 404 and 406. The control signals applied to control terminals 404 and 406 deflects the jet of air issuing from the main nozzle into one or other of output terminals 408 and 410.

The arrangement illustrated in Fig. 4(a) is known as an amplifier because powerful output flow through output terminals 408 and 410 is controlled by much weaker control flows input into control terminals 404 and 406.

Operation of a fluidic oscillator is illustrated with reference to FIG. 4(b) in which a fluidic amplifier 400 is schematically illustrated having a feedback loop 412 coupled between control terminals 404 and 406. Air supplied at terminal 402 attaches to a wall of either one of the output channels leading to respective output terminals 408 and 410 due to the so-called Coanda effect. The deflection of air into one or other of the output channels causes a pressure gradient across the airflow.

For the situation illustrated in FIG. 4(b), a decrease in pressure at control port 404 is caused which then draws air through the feedback loop 412 from the opposite control terminal 406 where pressure is higher. Once airflow in the feedback loop 212 has gained momentum the control flow in control terminal 404 switches the main airflow from the channel leading to terminal 408 and diverts it to the channel leading to terminal 410. Due to the device being substantially symmetrical, following a delay for the feedback airflow to gain sufficient momentum in an opposite direction, the main airflow is diverted back to the channel leading to terminal 408 thus leading to an oscillation of airflow between respective output terminals 408 and 410.

The length of feedback loop 412 will determine the periodicity of the oscillation. Additionally, although the schematic illustration of FIG.4(b) shows a feedback loop extending a considerable distance prowled of the substantially planar configuration of the fluidic amplifier 400, the feedback loop may be made with a lower profile by appropriately configuring the feedback loop conduit.

Typical feedback loop length would be equivalent to about or equal to half the wavelength at the frequency of oscillation

In order to gain effective coupling of the air from the oscillator to a large area of porous material, two or more individual oscillators may be incorporated in each element 220, 230, and 240 of the stack 200.

FIG. 5 shows such an arrangement or apparatus in which plural oscillators 310 are incorporated in an element 300. The element 300 illustrated in FIG. 5 has five modulators or oscillators 310 within it, distributed along a width of the element and each fed by a port of gas inlet manifold 320.

As should be apparent from the above, and from FIG. 5, the alternating air/gas outputs or supplies are fed to individual isolated areas of the porous member 260, preventing internal cancellation due to standing wave(s). Optionally, respective oscillators or groups of oscillators may be modulated at different rates.

The apparatus shown in FIG. 5 (upper portion of the figure) has plural oscillators, as suggested above, integrated into a single planar (low profile) gas-liquid contactor element 300. The height of the element (direction out of the page in the upper portion of FIG. 5 and upward in the lower portion of FIG. 5) is small relative to the width of the element (up-down in the upper portion of FIG. 5, into/out of the page in the lower portion of FIG. 5). Thus, each such element can form one element of a multi-element stack.

Referring now to FIG. 6 a fuel cell system is schematically illustrated incorporating an indirect coolant arrangement in accordance with an embodiment of the present invention. A compressed hydrogen tank 601 comprises a source of fuel for the fuel cells in a fuel cell stack 610. The hydrogen gas is output to a pneumatic control valve 602 to an in-line filter 603 for filtering out impurities in the hydrogen gas. The filtered hydrogen is input to a divert valve 604 which directs high flow hydrogen to ejector 605 and low flow hydrogen to ejector 606. Check valves 607 control anode exhaust 613 permitting its flow to the high or low flow hydrogen ejectors 605 and 606 or to hydrogen purge valve 608. A purpose of the ejector/s is to provide uniform humidity across the anode.

Hydrogen gas from the ejector 605 and 606 are input to the feel stack 610 file overpressure cut-off valve 609. The fuel cell stack 610 comprises individual fuel cells and may be configured such as illustrated as reference 201 in FIG. 2. The feel stack 610 also includes a current centre 611 and voltage sensor 612 for monitoring the electrical output of the stack.

Liquid catholyte is input to the fuel cell stack 610 from flowmeter 267 which receives liquid catholyte from the catholyte reservoir 621 via circulation pump 625. The liquid catholyte is circulated via the fuel cells of the fuel cell stack 610 and output 620 to diverter 621 from which the liquid catholyte is input to a unit 619 indicated in the embodiment illustrated in FIG. 6 as a planar contactor heat exchanger. Diverter 621 also may direct liquid catholyte to a catholyte reservoir 629.

Liquid catholyte from the heat exchanger 619, for example from an output manifold 290 of apparatus labelled 200 in Fig. 3 of the drawings and containing a low energy material 280, is also input 622 to catholyte reservoir 629.
Air from the regenerator contains water vapour and desirable if not necessary to condense the water when more would be evaporated than is generated by the reaction between Hydrogen and Oxygen. This may happen when operating the system at high temperatures. Thus, a condenser 623 is included in the exhaust air stream from the catholyte reservoir 629 and may be used to reduce excess water loss from the system. Water condensed in condenser 623 is collected and returned to the catholyte reservoir 629 to maintain a constant volume of electrolyte solution.

In the illustrated embodiment, the oxidant, oxygen, is derived from reactant air 614 which is input to an air filter 615 and then to an air mass flow sensor 616 before being input to compressor 618. Compressed air is input to the heat exchanger 619 in order to generate bubbles in the liquid catholyte as described previously with reference to FIG.s 2, 3, 4 and 5 of the drawings.

A coolant, in the described embodiment a water and ethylene glycol mix, is pumped round a secondary coolant loop by pump 626. The coolant is drawn from the heat exchanger 619 through the pump 626 to radiator 628 which acts as a heat sink. In the illustrated embodiment, radiator 628 is a cooled but other cooling mechanisms may be utilised. Cooled coolant is then taken from the radiator 628 and inputs backed to the heat exchanger 619.

As used herein any reference to “one embodiment” or “an embodiment” means that a particular element, feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment. The appearances of the phrase “in one embodiment” or the phrase “in an embodiment” in various places in the specification are not necessarily all referring to the same embodiment.
As used herein, the terms “comprises,” “comprising,” “includes,” “including,” “has,” “having” or any other variation thereof, are intended to cover a non-exclusive inclusion. For example, a process, method, article, or apparatus that comprises a list of elements is not necessarily limited to only those elements but may include other elements not expressly listed or inherent to such process, method, article, or apparatus. Further, unless expressly stated to the contrary, “or” refers to an inclusive or and not to an exclusive or. For example, a condition A or B is satisfied by any one

of the following: A is true (or present) and B is false (or not present), A is false (or not present) and B is true (or present), and both A and B are true (or present).
In addition, use of the "a" or "an" are employed to describe elements and components of the invention. This is done merely for convenience and to give a general sense of the invention. This description should be read to include one or at least one and the singular also includes the plural unless it is obvious that it is meant otherwise.

In view of the foregoing description it will be evident to a person skilled in the art that various modifications may be made within the scope of the invention. For example, although embodiments in accordance with the invention has been described with reference to a liquid catholyte, the principles disclosed herein may be applicable to liquid electrolytes in general to facilitate reaction with other components and particularly where a large mass transfer is desirable. Furthermore, embodiments in accordance with the present invention are not limited to fuel cell technologies or the particular fuel cell configurations described herein.

Although embodiments have been described utilising air, another gas mixture comprising oxygen or oxygen alone may be suitable. For other applications, other gas mixtures comprising different gases may be utilised.

Although a fluidic oscillator of the jet-diverter type has been described other fluidic oscillators may be utilised in one or more embodiments in accordance with the present invention. Furthermore, other mechanisms for modulating airflow may be utilised such as a swiftly switched valve or intermittent pump arrangement .However, such devices which can operate at the required frequencies are likely to require external drive force and hence connections and additional energy requirements which mitigates against their use in a fuel cell.

Although a water and ethylene glycol coolant mix has been described as a thermal energy transfer medium other transfer medium is may be used. Additionally, although the water and ethylene glycol coolant is insulating, thermal energy transfer medium is may not necessarily be in slating provided that there is electrical insulation between the liquid electrolyte and the coolant. For example, the walls of the reaction volume and/or coolant channel may comprise an electrically insulating material.

The scope of the present disclosure includes any novel feature or combination of features disclosed therein either explicitly or implicitly or any generalisation thereof irrespective of whether or not it relates to the claimed invention or mitigate against any or all of the problems addressed by the present invention. The applicant hereby gives notice that new claims may be formulated to such features during prosecution of this application or of any such further application derived therefrom. In particular, with reference to the appended claims, features from dependent claims may be combined with those of the independent claims and features from respective independent claims may be combined in any appropriate manner and not merely in specific combinations enumerated in the claims.

CLAIMS:

1. Apparatus for cooling a liquid electrolyte fuel cell, comprising:

a liquid electrolyte transport arrangement for bringing liquid electrolyte from a fuel cell into thermal communication with a thermal energy transfer medium and for communicating liquid electrolyte from thermal communication with the energy transfer medium back to the fuel cell; and

a thermal energy transfer medium transport arrangement for communicating the thermal energy transfer medium to thermal communication with the liquid electrolyte from a heat sink and for communicating the thermal energy transfer medium from thermal communication with the liquid electrolyte to a heat sink.

2. Apparatus according to claim 1, further comprising a heat exchanger, the liquid electrolyte transport arrangement configured to bring liquid electrolyte to the heat exchanger and the thermal energy transfer medium transport arrangement configured to communicate the thermal energy transfer medium to the heat exchanger such that thermal communication between the liquid electrolyte and thermal energy transfer medium takes place through operation of the heat exchanger.

3. Apparatus according to claim 2, wherein the heat exchanger comprises a reaction chamber for the liquid electrolyte.

4. Apparatus according to claim 3, wherein the reaction chamber is configured to regenerate the liquid electrolyte.

5. Apparatus according to claim 4, wherein the reaction chamber is configured to admit gas comprising oxygen for regenerating the liquid electrolyte.

6. Apparatus according to claim 5, wherein the liquid electrolyte comprises a catholyte.

7. Apparatus according to claim 6, wherein the reaction chamber is configured for oxidation of reduced redox couples of the catholyte.

8. Apparatus according to claim 7, wherein the fuel cell is configured as a polymer exchange membrane indirect redox fuel cell.

9. Apparatus according to any of claims 3 to 8, wherein the reaction chamber is substantially planar and the thermal energy transfer medium transport arrangement comprises one or more thermal energy transfer medium conduits disposed in thermal communication with a wall forming a major surface of the reaction chamber.

10. Apparatus according to claim 9, wherein the liquid electrolyte transport arrangement comprises a liquid electrolyte conduit in fluid communication with the reaction chamber.

11. Apparatus according to claim 10, further comprising a porous member including first and second surfaces disposed in the liquid electrolyte conduit, the apparatus arranged to supply a gas to a first surface of the porous member and the

liquid electrolyte to the second surface of the porous member and wherein the porous member is configured to communicate gas incident at the first surface through the porous member to the second surface of the porous member for producing bubbles in the liquid electrolyte proximal to the second surface.

12. Apparatus according to claim 11, wherein the porous member defines a foam generation region for a foam generator comprised in the apparatus; the foam generator further comprising a gas supply modulator arranged to modulate a supply of the gas to the first surface.

13. Apparatus according to claim 12, wherein the foam generator is arranged to receive the gas from a gas supply common to at least one other foam generator.

14. Apparatus according to any of claims 9 to 13, wherein the one or more thermal energy transfer medium conduits are configured to direct flow of the thermal energy transfer medium in a direction transverse to a flow of the liquid electrolyte in the reaction chamber. Yes in that previous claims are not limted to transverse flows.

15. Apparatus according to any of claims 9 to 14, wherein the one or more thermal energy transfer medium conduits are coupled to a thermal energy transfer medium output manifold.

16. Apparatus according to claim 11 or any of claims 12 to 15 dependent on claim 11, wherein the gas comprises an oxidant, for example air or oxygen.

17. A stack of apparatus according to any of claims 9 to 16, wherein respective reaction chambers are in fluid communication with a liquid catholyte output manifold; and respective liquid catholyte transport arrangements are in liquid communication with a liquid catholyte input manifold.

18. A stack of apparatus according to claim 17, dependent on claim 11 or any of claims 12 to 16 dependent on claim 11, wherein the apparatus is arranged to supply gas to the first surface of the porous member from a gas supply manifold.

19. A fuel cell comprising apparatus as claimed in any of claims 1 to 16.

20. A fuel cell comprising a stack as claimed in claim 17 or claim 18.

21. A stack comprising a plurality of fuel cells, at least one of the plurality of fuel cells as claimed in claim 19, the plurality of fuel cells being stacked together.

22. Use of a fuel cell as claimed in claim 19 or 20 or a stack as claimed in Claim 21, for use in electronic and/or automotive equipment and/or for generating combined heat and power.

23. An electronic, automotive and/or combined heat and power equipment comprising a fuel cell as claimed in claim 19 or 20 or a stack as claimed in claim 21.

24. A method for cooling a liquid electrolyte fuel cell, comprising:

bringing liquid electrolyte from a fuel cell into thermal communication with a thermal energy transfer medium;

bringing liquid electrolyte from thermal communication with the thermal energy transfer medium back to the fuel cell;

bringing the thermal energy transfer medium from a heat sink into thermal communication with the liquid electrolyte; and

bringing the thermal energy transfer medium from thermal communication with the liquid electrolyte to a heat sink.

25. A method according to claim 24, further comprising bringing liquid electrolyte to a heat exchanger and communicating the thermal energy transfer medium to the heat exchanger such that thermal communication between the liquid electrolyte and thermal energy transfer medium takes place through operation of the heat exchanger.

26. A method according to claim 25, wherein the heat exchanger comprises a reaction chamber for the liquid electrolyte, the method further comprising regenerating the liquid electrolyte in the reaction chamber.

27. A method according to claim 26, further comprising regenerating the liquid electrolyte with a gas comprising oxygen.

28. A method according to claim 27, wherein the liquid electrolyte comprises catholyte.

29. A method according to claim 28, further comprising oxidising reduced redox couples of the catholyte during regeneration.

30. A method according to claim 29, wherein the fuel cell is configured as a polymer exchange membrane indirect redox fuel cell.

31. A method according to any of claims 25 to 30, wherein the reaction chamber is substantially planar and the method further comprises providing one or more thermal energy transfer medium conduits disposed in thermal communication with a wall forming a major surface of the reaction chamber.

32. A method according to claim 31, further comprising providing a liquid electrolyte conduit in fluid communication with the reaction chamber.

33. A method according to claim 32, further comprising:

disposing a porous member including first and second surfaces in the liquid electrolyte conduit;

supplying a gas to a first surface of the porous member and the liquid electrolyte to the second surface of the porous member; and

wherein the porous member is configured to communicate gas incident at the first surface through the porous member to the second surface of the porous member for producing bubbles in the liquid electrolyte proximal to the second surface.

34. A method according to claim 33, further comprising modulating a supply of the gas to the first surface.

35. A method according to claim 33 or 34, further comprising receiving the gas from a gas supply common to at least one other foam generator.

36. A method according to any of claims 31 to 35, further comprising configuring the one or more thermal energy transfer medium conduits to direct flow of the thermal energy transfer medium in a direction transverse to a flow of the liquid electrolyte in the reaction chamber.

37. A method according to any of claims 31 to 36, further comprising coupling the one or more thermal energy transfer medium conduits to a thermal energy transfer medium output manifold.

38. A method according to claim 33 or any of claims 34 to 27 dependent on claim 33, wherein the gas comprises an oxidant such as air or oxygen.

39. A method according to any of claims 33 to 38, further comprising:

stacking a plurality of fuel cells; and

configuring respective reaction chambers to be in fluid communication with a liquid catholyte output manifold and in liquid communication with a liquid catholyte input manifold.

40. A method according to claim 39, dependent on claim 33 or any of claims 34 to 39 dependent on claim 33, further comprising supplying gas to the first surface of the porous member from a gas supply manifold.

41. Apparatus substantially as hereinbefore described and with reference to figures 1, 2 and 6, and figures 1, 3, 4, 5 and 6 of the drawings.

42. A method substantially as hereinbefore described and with reference to figures 1, 2 and 6, and figures 1, 3, 4, 5 and 6 of the drawings.

Application No:	GB1307611.2	**Examiner:**	Dr Steven Chadwell
Claims searched:	1-42	**Date of search:**	29 October 2013

Patents Act 1977: Search Report under Section 17

Documents considered to be relevant:

Category	Relevant to claims	Identity of document and passage or figure of particular relevance
X	1, 2, 19, 21-25	EP 2535973 A1 (PRATT & WHITNEY) see whole document, especially the abstract, figure 1, and paragraphs [0008] and [0016]
X	1, 2, 19, 21-25	EP 0517217 A1 (AGENCY OF INDUSTRIAL SCIENCE AND TECHNOLOGY) see figure 1 and page 4 lines 19-26 in particular
X	1, 2, 19, 21-25	US 2010/0291429 A1 (FARMER) see figures 1 and 2, and paragraphs [0039], [0041], [0043], [0046] and [0051]
X	1, 2, 19, 21-25 at least	CN 102110830 A (SHANGHAI LINYANG ENERGY STORAGE) see whole document, especially figures 1 and 3, and also the EPODOC abstract and WPI Abstract Accession No. 2011-J84845

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X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
&	Member of the same patent family	E	Patent document published on or after, but with priority date earlier than, the filing date of this application.

Field of Search:

Search of GB, EP, WO & US patent documents classified in the following areas of the UKC^X :

Worldwide search of patent documents classified in the following areas of the IPC

H01M

The following online and other databases have been used in the preparation of this search report

WPI, EPODOC, INSPEC, XPRD

International Classification:

Subclass	Subgroup	Valid From
H01M	0008/04	01/01/2006
H01M	0002/40	01/01/2006
H01M	0008/18	01/01/2006
H01M	0008/20	01/01/2006