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Owoeye

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(54) **THERMAL MANAGEMENT OF A FUEL CELL ASSEMBLY**

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(51) **Int. Cl.**

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H01M 8/0267	(2016.01)
H01M 8/04014	(2016.01)
H01M 8/04111	(2016.01)
H01M 8/2483	(2016.01)

(52) **U.S. Cl.**
CPC ***H01M 8/0258*** (2013.01); ***H01M 8/0247*** (2013.01); ***H01M 8/0267*** (2013.01); ***H01M 8/04022*** (2013.01); ***H01M 8/04111*** (2013.01); ***H01M 8/2483*** (2016.02)

(58) **Field of Classification Search**
CPC . H01M 8/0247; H01M 8/0258; H01M 8/0267
See application file for complete search history.

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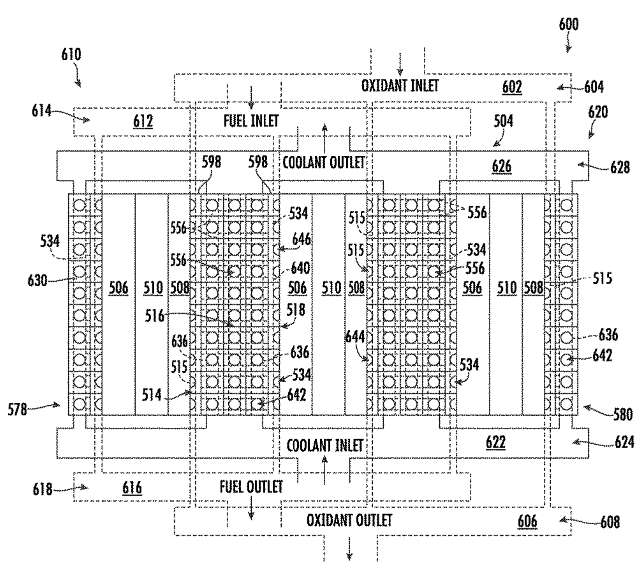
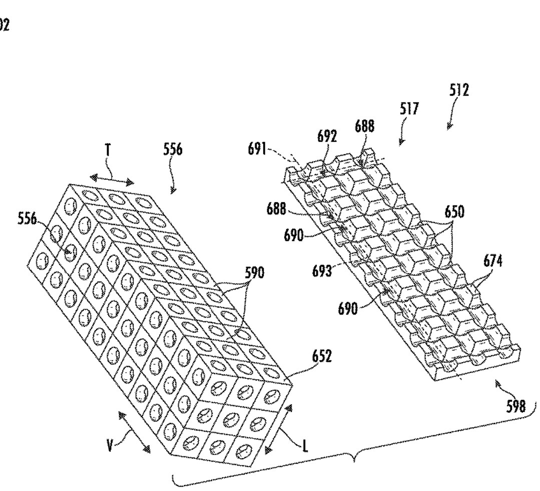
(57) **ABSTRACT**

A fuel cell assembly includes a plurality of fuel cells. The fuel cell includes a bipolar separator plate disposed between each fuel cell of the plurality of fuel cells. The bipolar separator plate includes one or more fuel cell sub-units each comprising a plurality of unit-cells. Each unit-cell in the plurality of unit-cells has an outer surface and defines an internal volume that extends in multiple directions between a plurality of openings defined on the outer surface. Each unit-cell in the plurality of unit-cells is disposed adjacent to a neighboring unit-cell in the plurality of unit-cells such that the plurality of unit-cells collectively define one or more channels.

12 Claims, 12 Drawing Sheets





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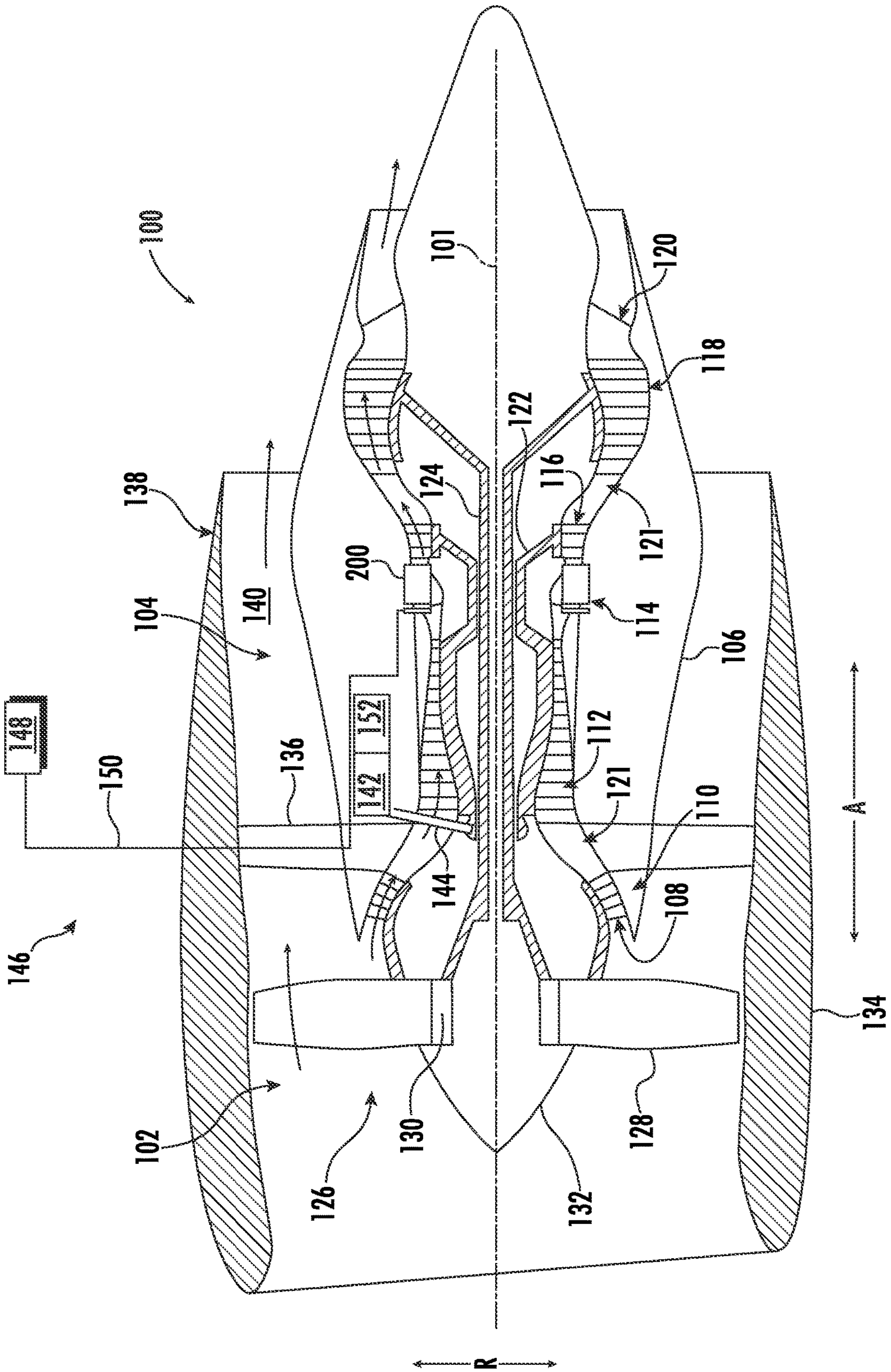
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FIG. 1

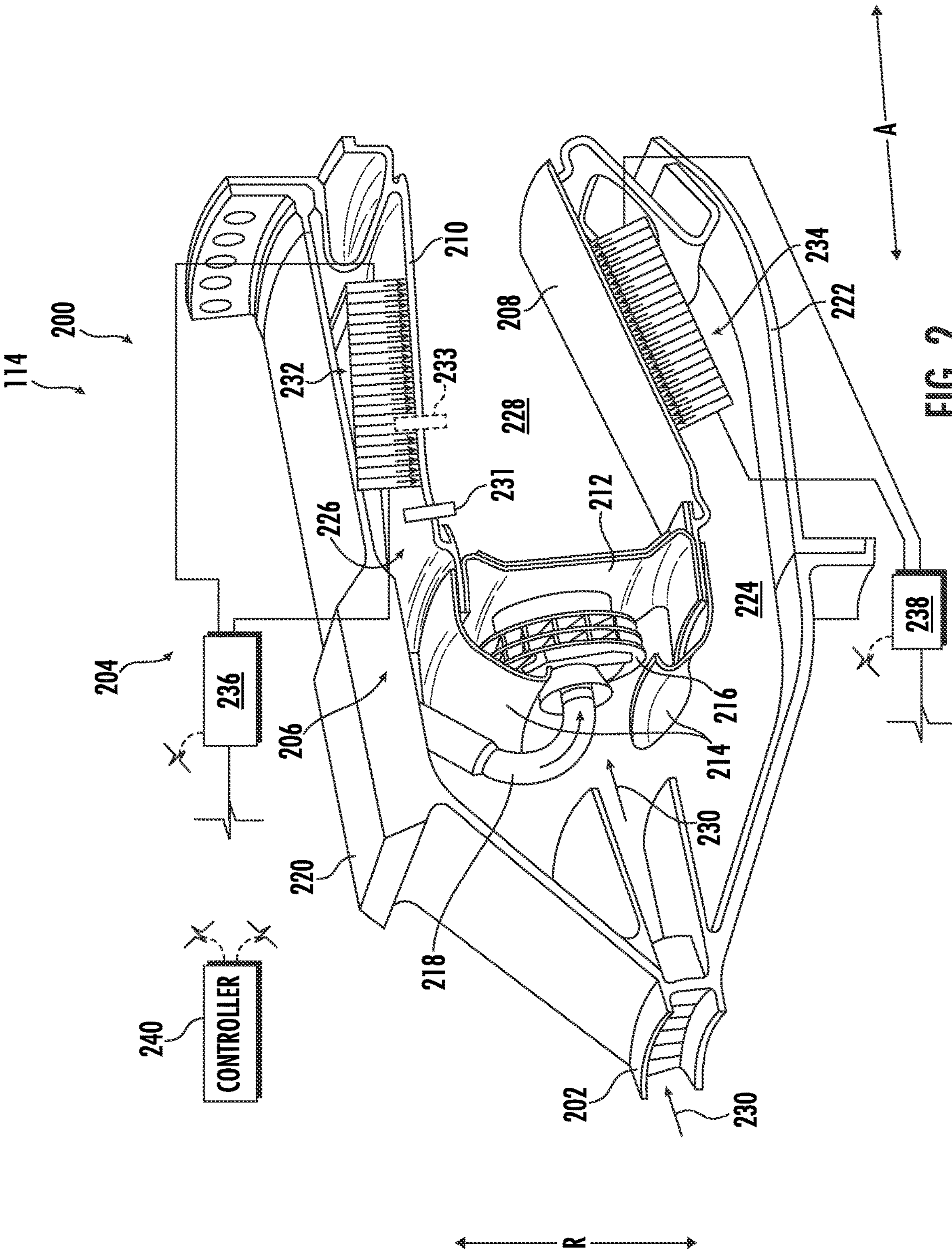
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FIG. 2

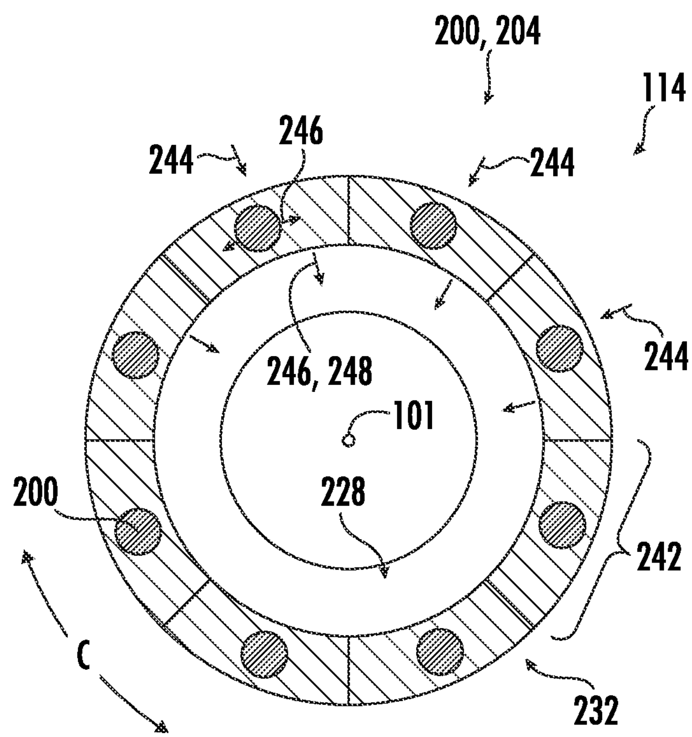
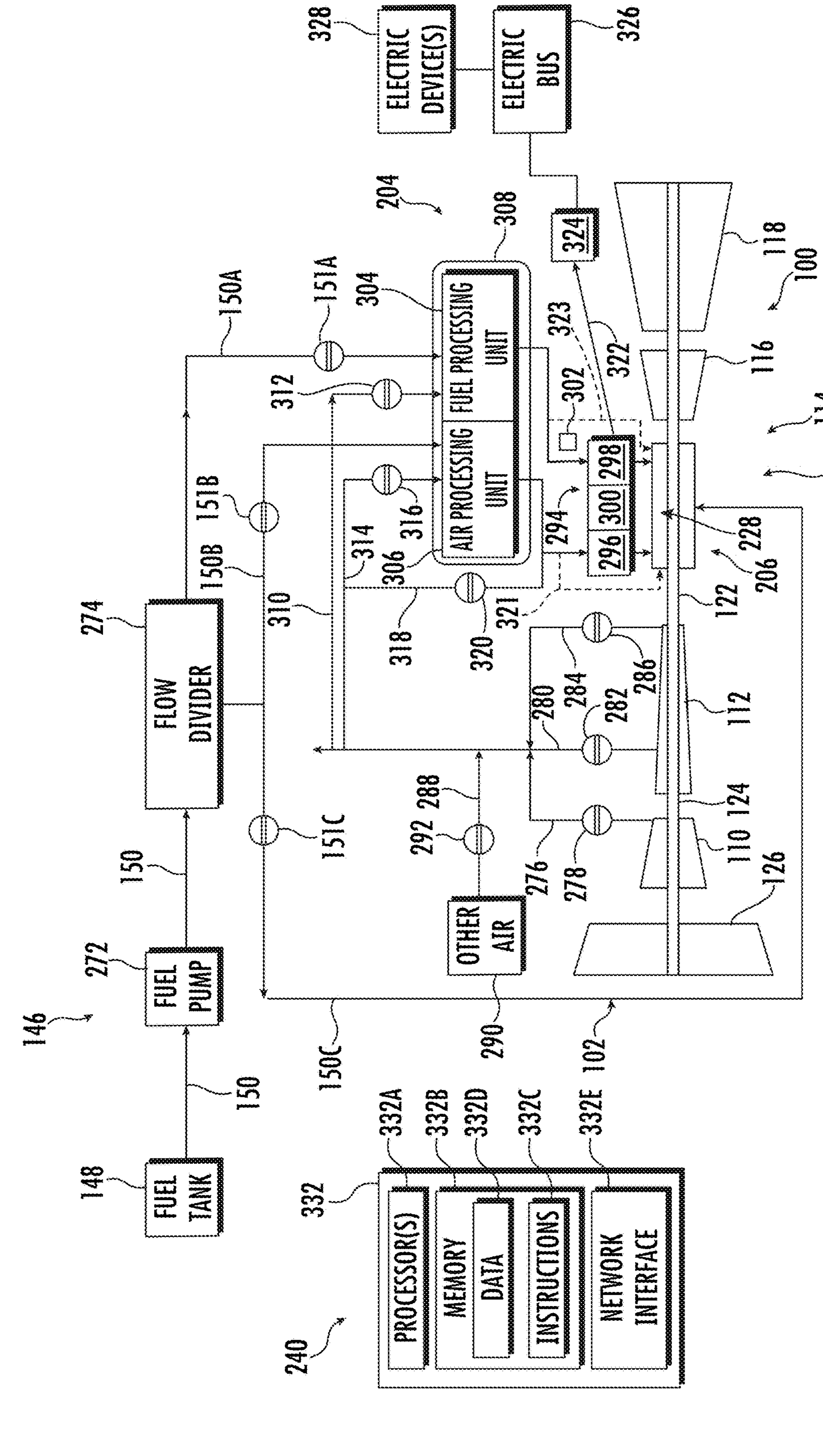


FIG. 3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ELECTRIC BUS
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AIR PROCESSING UNIT
FLOW DIVIDER
FUEL TANK
FUEL PUMP
OTHER AIR
PROCESSOR(S)
MEMORY
DATA
INSTRUCTIONS
NETWORK INTERFACE
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110
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292
151C
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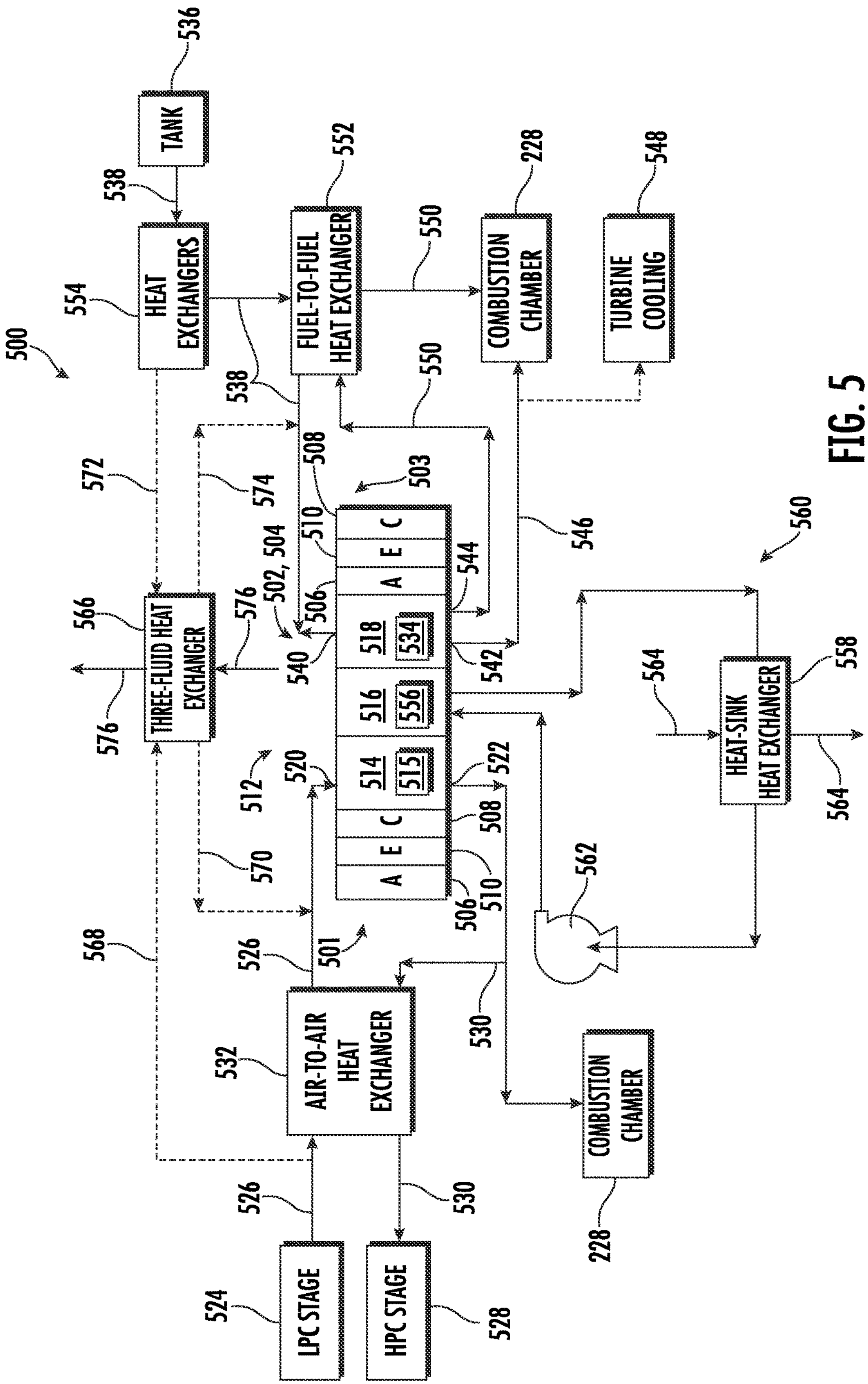
FIG. 4



TANK
HEAT EXCHANGERS
FUEL-TO-FUEL HEAT EXCHANGER
COMBUSTION CHAMBER
TURBINE COOLING
THREE-FLUID HEAT EXCHANGER
HEAT-SINK HEAT EXCHANGER
AIR-TO-AIR HEAT EXCHANGER
COMBUSTION CHAMBER
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FIG. 5

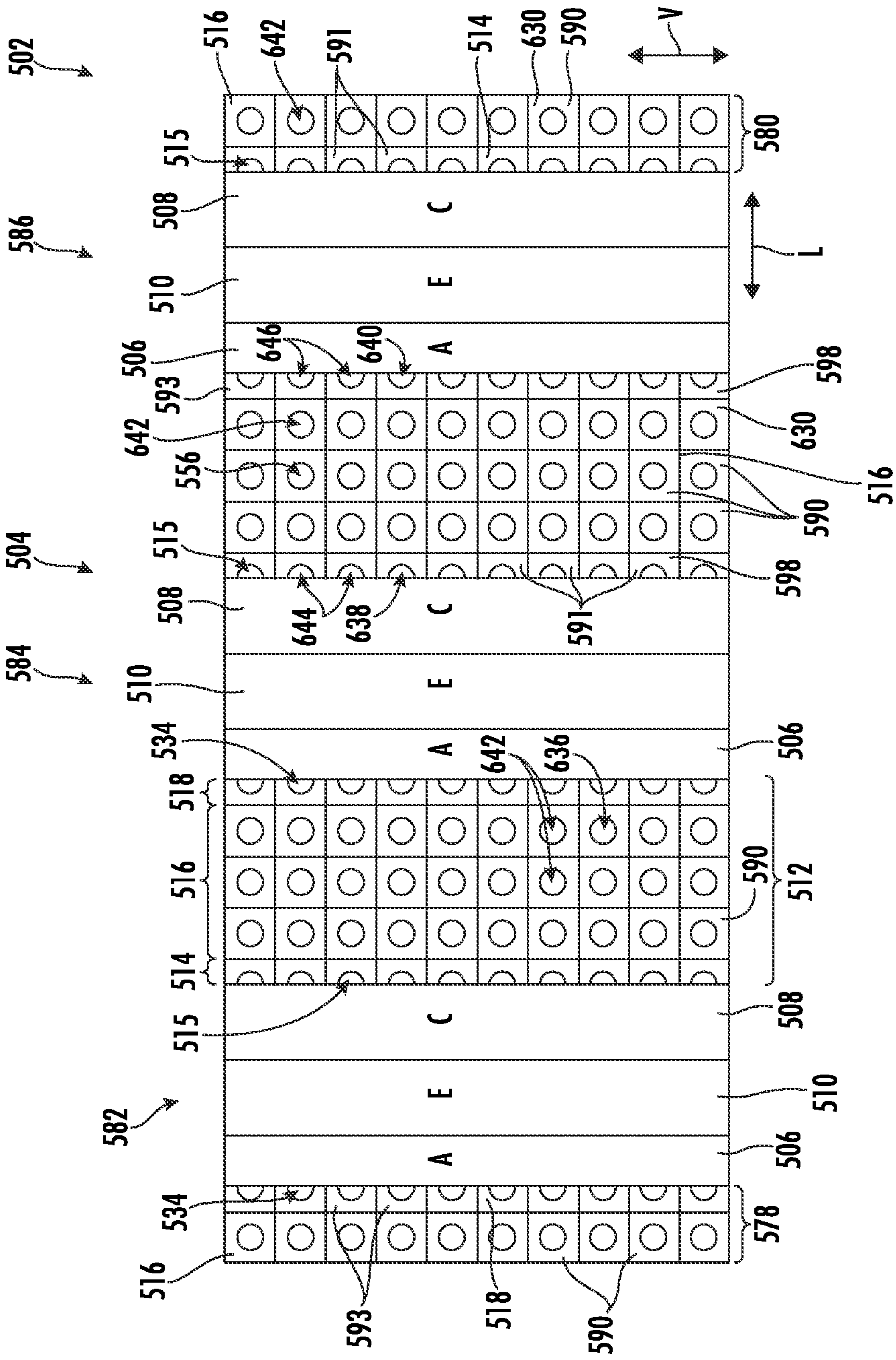
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FIG. 6

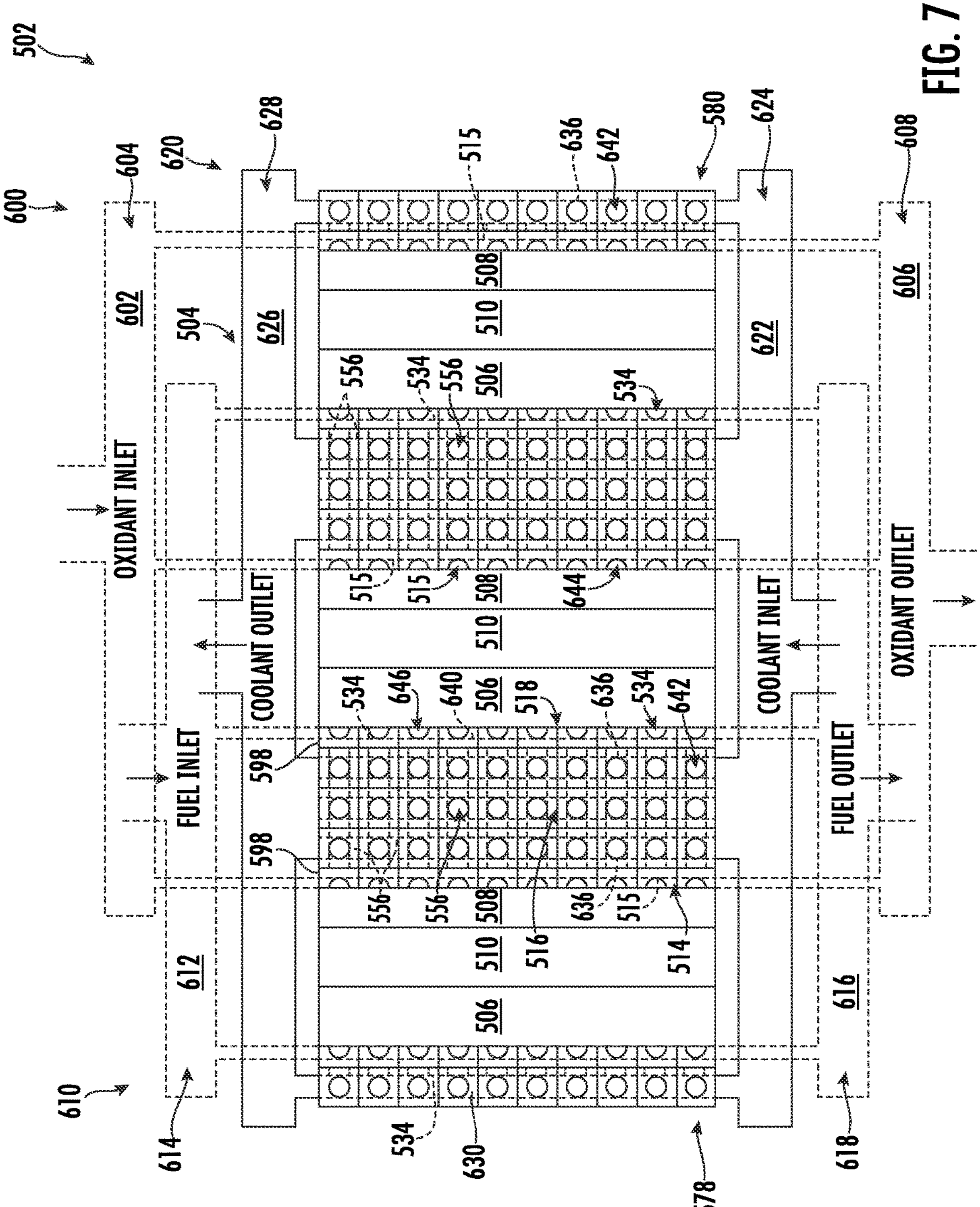
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FIG. 7

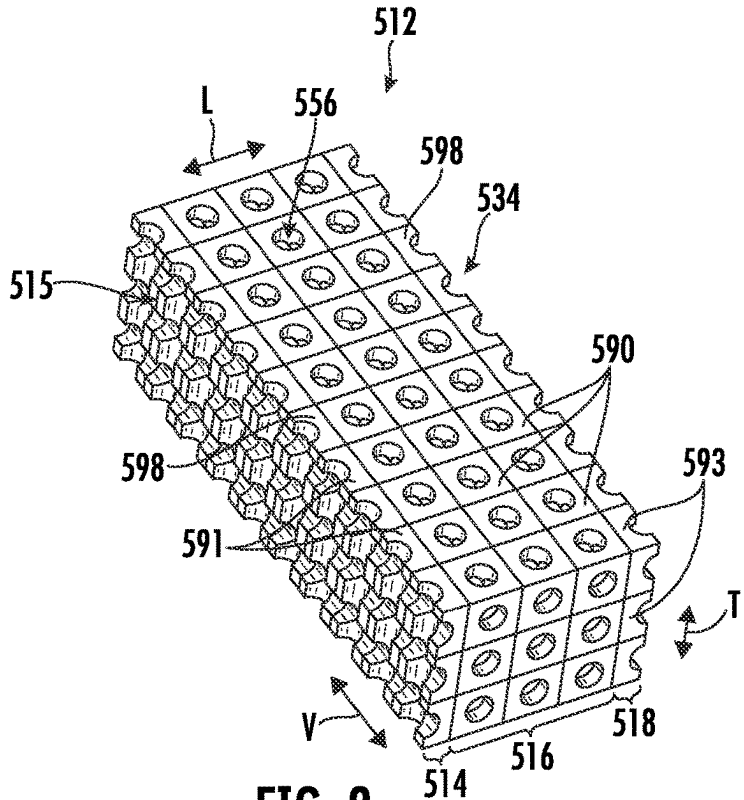
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FIG. 8

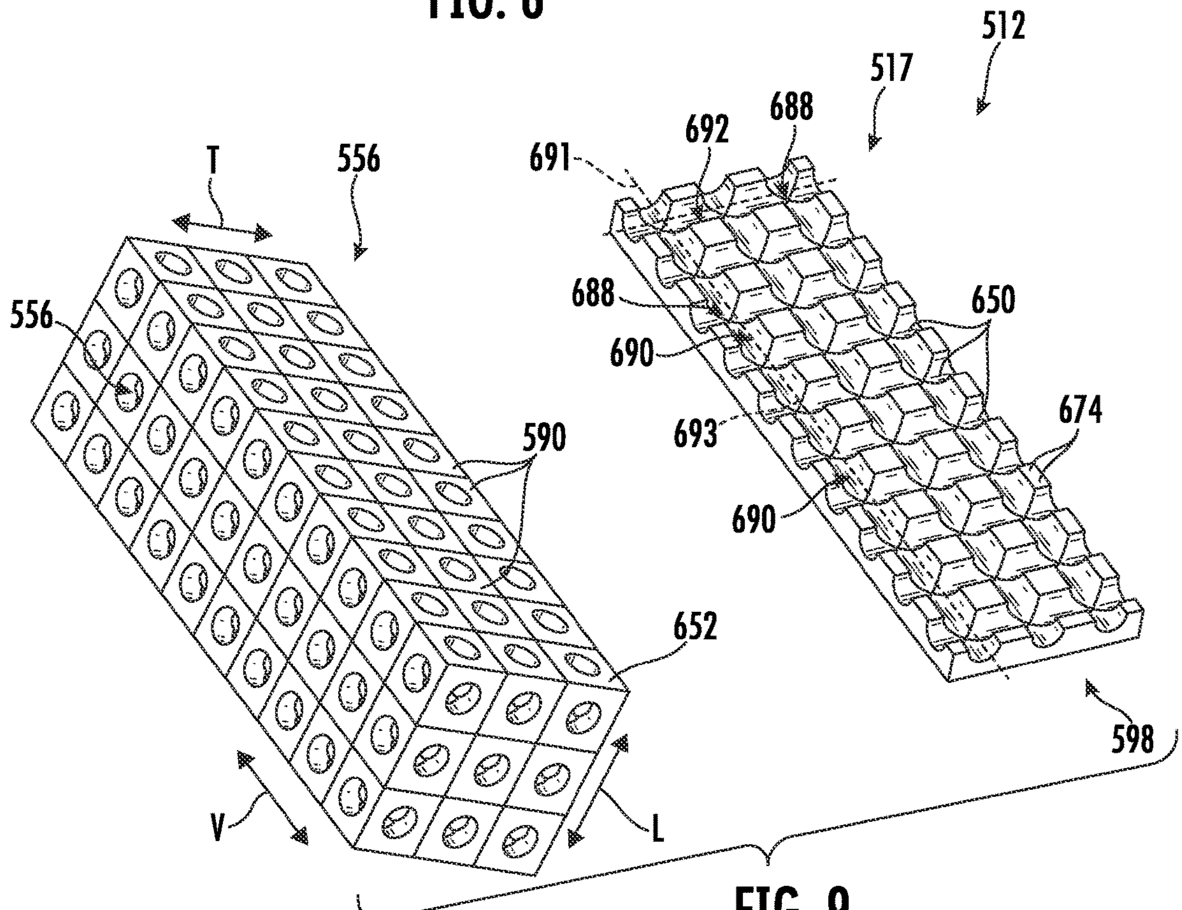
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FIG. 9

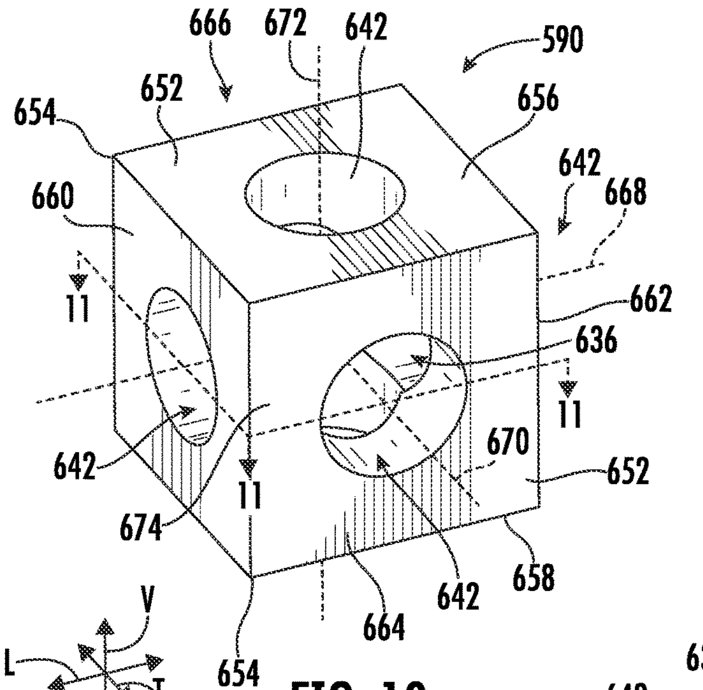

FIG. 10

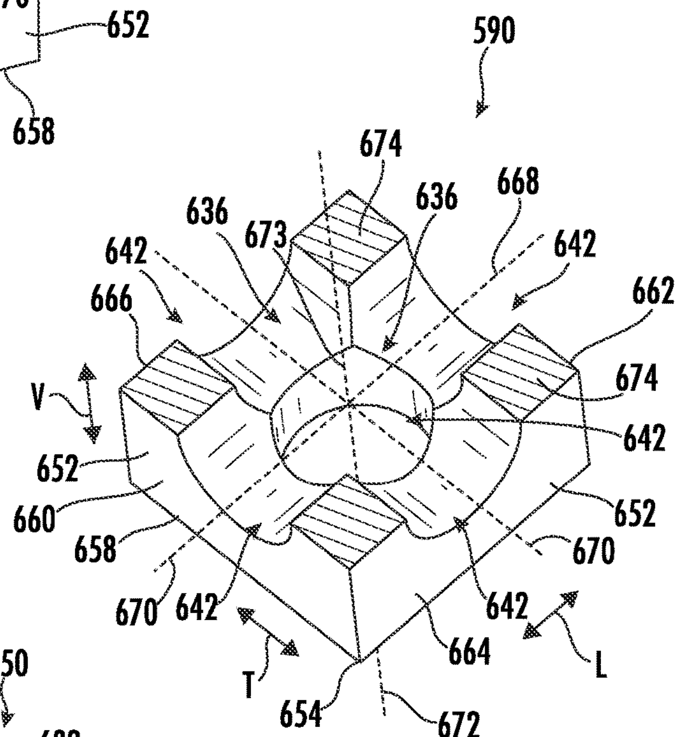

FIG. 11

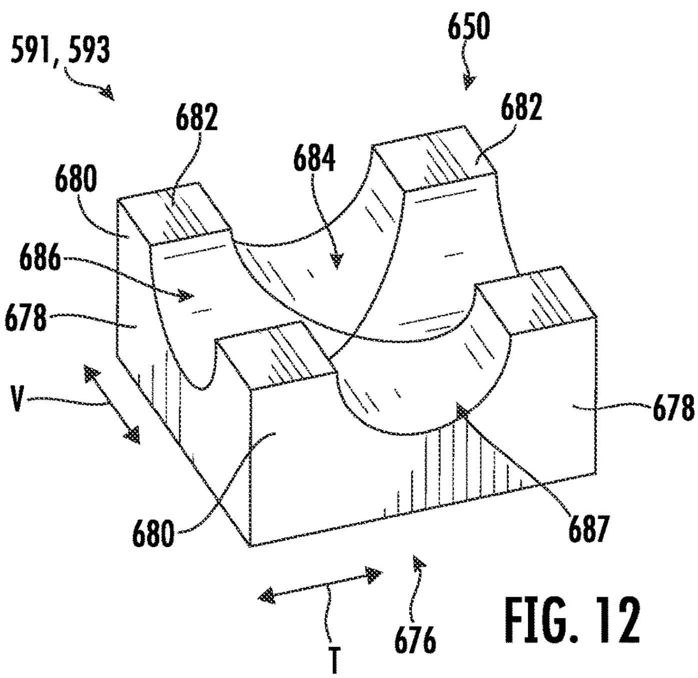

FIG. 12

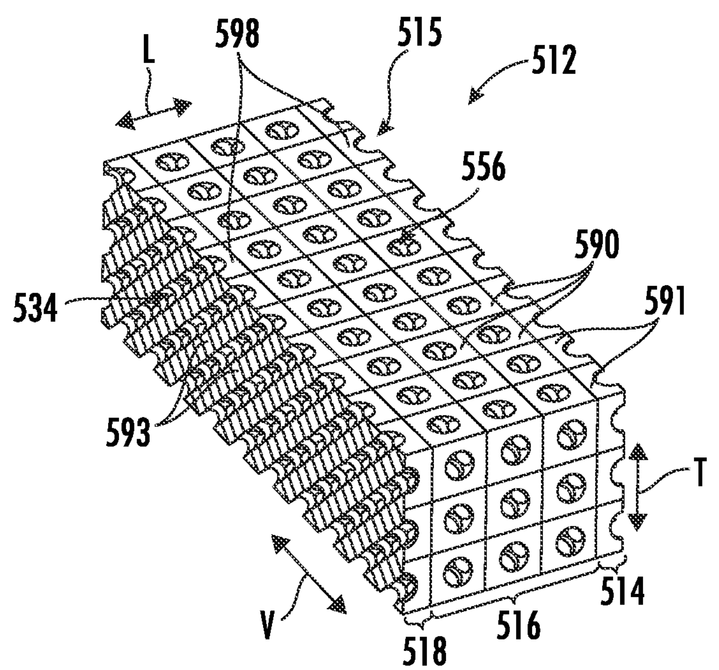
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FIG. 13

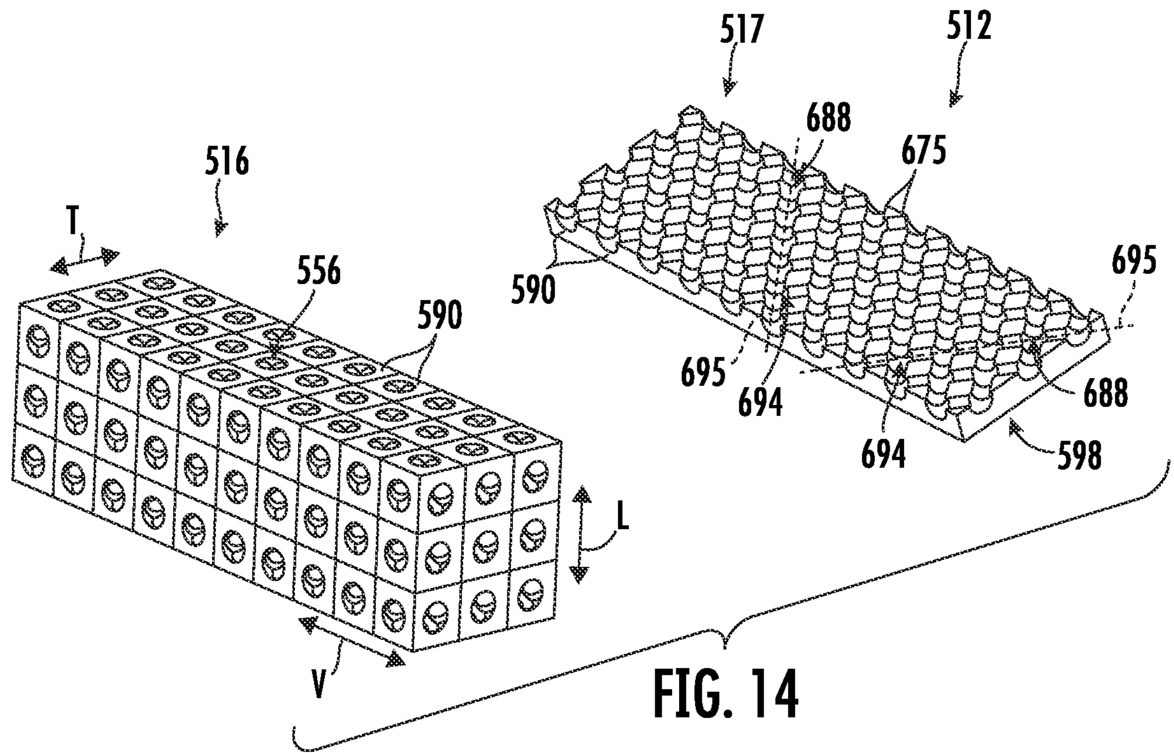
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FIG. 14

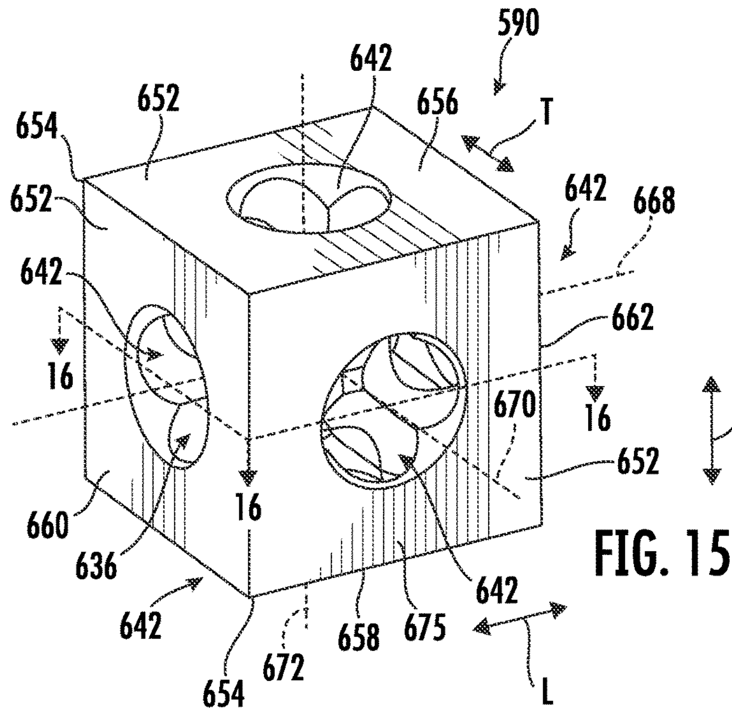

FIG. 15

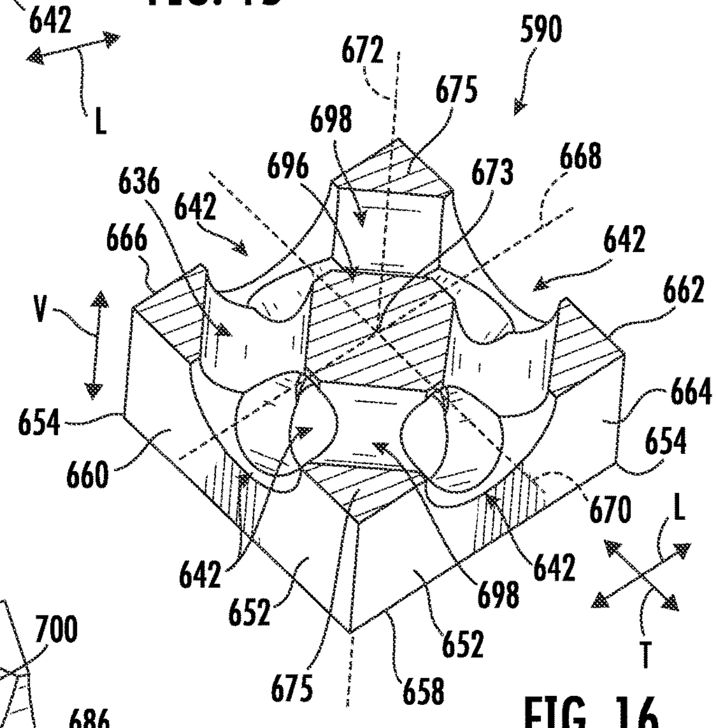

FIG. 16

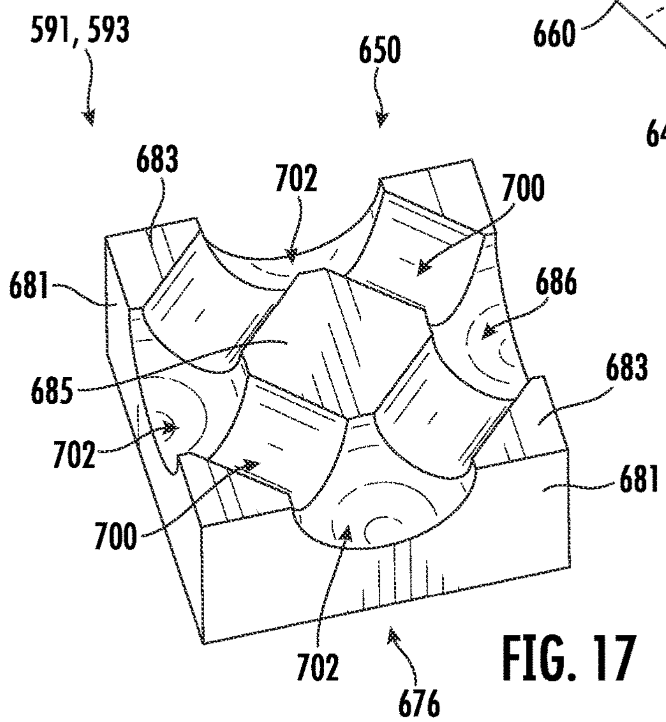

FIG. 17

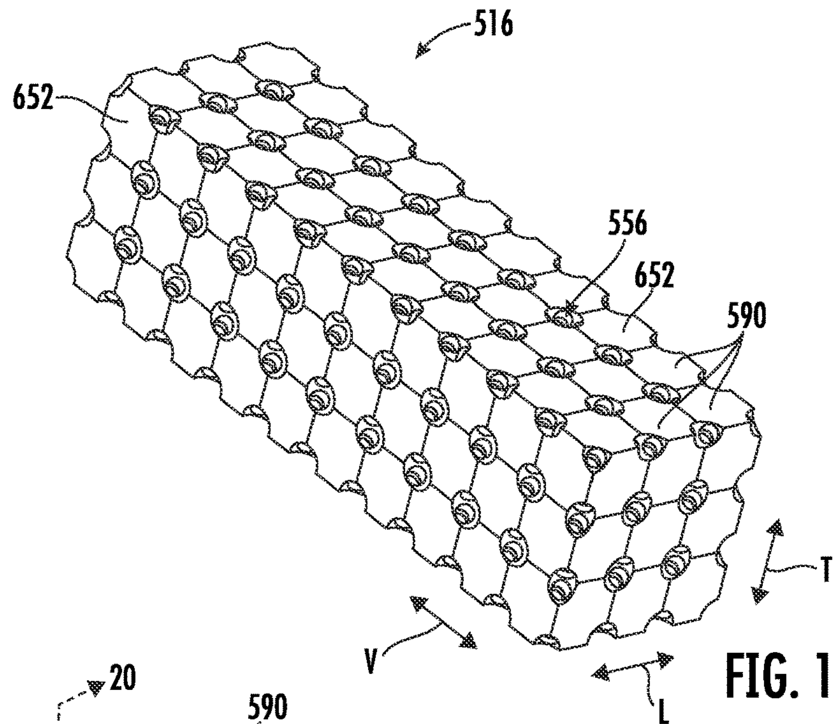

FIG. 18

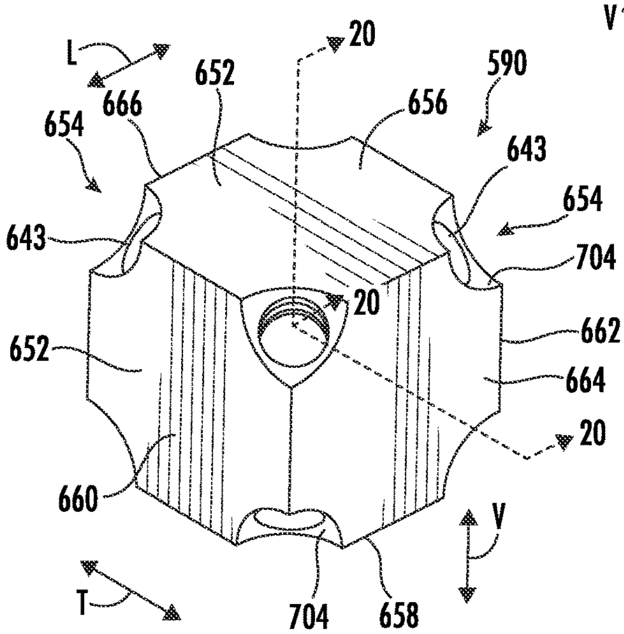

FIG. 19

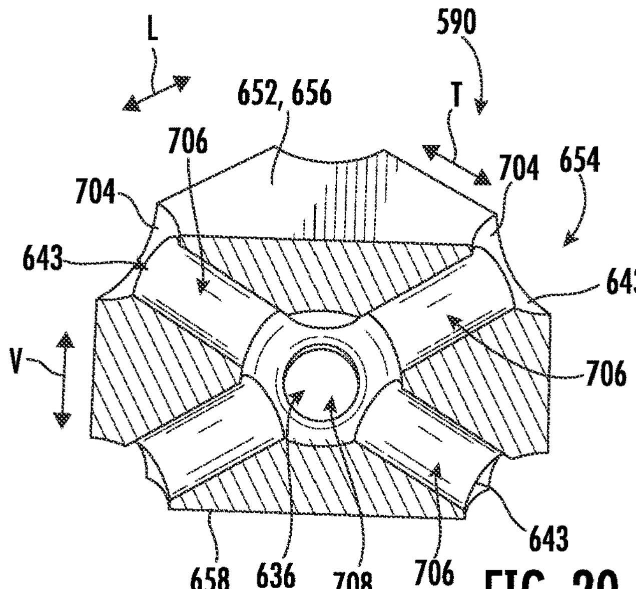

FIG. 20

THERMAL MANAGEMENT OF A FUEL CELL ASSEMBLY

FIELD

The present disclosure relates to the thermal management of a fuel cell assembly.

BACKGROUND

A gas turbine engine generally includes a turbomachine and a rotor assembly. Gas turbine engines, such as turbofan engines, may be used for aircraft propulsion. In the case of a turbofan engine, the turbomachine includes a compressor section, a combustion section, and a turbine section in serial flow order, and the rotor assembly is configured as a fan assembly.

During operation, air is compressed in the compressor and mixed with fuel and ignited in the combustion section for generating combustion gases which flow downstream through the turbine section. The turbine section extracts energy therefrom for rotating the compressor section and fan assembly to power the gas turbine engine and propel an aircraft incorporating such a gas turbine engine in flight.

At least certain gas turbine engines include a fuel cell assembly operable therewith.

BRIEF DESCRIPTION OF THE DRAWINGS

A full and enabling disclosure of the present disclosure, including the best mode thereof, directed to one of ordinary skill in the art, is set forth in the specification, which makes reference to the appended figures, in which:

FIG. **1** is a cross-sectional view of a gas turbine engine in accordance with an exemplary aspect of the present disclosure.

FIG. **2** is a perspective view of an integrated fuel cell and combustor assembly in accordance with the present disclosure.

FIG. **3** is a schematic, axial view of the exemplary integrated fuel cell and combustor assembly of FIG. **2**.

FIG. **4** is a schematic view of a fuel cell assembly in accordance with an exemplary aspect of the present disclosure as may be incorporated into the exemplary integrated fuel cell and combustor assembly of FIG. **2**.

FIG. **5** is a schematic view of a thermal management system in accordance with exemplary aspects of the present disclosure.

FIG. **6** is plan view of a fuel cell assembly in accordance with embodiments of the present disclosure.

FIG. **7** is a schematic view of a fuel cell assembly having one or more fluid connections in accordance with embodiments of the present disclosure.

FIG. **8** illustrates a perspective view of a bipolar separator plate in accordance with an exemplary aspect of the present disclosure.

FIG. **9** illustrates a perspective partially exploded view of a bipolar separator plate in accordance with an exemplary aspect of the present disclosure.

FIG. **10** illustrates a perspective view of a unit-cell of the plurality of unit-cells that collectively make up the coolant cell sub-unit of the bipolar separator plate shown in FIGS. **8** and **9** in accordance with an exemplary aspect of the present disclosure.

FIG. **11** illustrates a cross-sectional perspective view of the unit-cell shown in FIG. **10** from along the line **11-11** in accordance with an exemplary aspect of the present disclosure.

FIG. **12** illustrates a unit-cell of the plurality of unit-cells that collectively make up an electrode cell sub-unit shown in FIG. **9** in accordance with an exemplary aspect of the present disclosure.

FIG. **13** illustrates a perspective view of a bipolar separator plate in accordance with an exemplary aspect of the present disclosure.

FIG. **14** illustrates a perspective partially exploded view of a bipolar separator plate in accordance with an exemplary aspect of the present disclosure.

FIG. **15** illustrates a perspective view of a unit-cell of the plurality of unit-cells that collectively make up the coolant cell sub-unit of the bipolar separator plate shown in FIGS. **13** and **14** in accordance with an exemplary aspect of the present disclosure.

FIG. **16** illustrates a cross-sectional perspective view of the unit-cell shown in FIG. **15** from along the line **16-16** in accordance with an exemplary aspect of the present disclosure.

FIG. **17** illustrates a unit-cell of the plurality of unit-cells that collectively make up an electrode cell sub-unit shown in FIG. **14** in accordance with an exemplary aspect of the present disclosure.

FIG. **18** illustrates a perspective view of a coolant cell sub-unit of a bipolar separator plate in accordance with an exemplary aspect of the present disclosure.

FIG. **19** illustrates a perspective view of a unit-cell of the plurality of unit-cells that collectively make up the coolant cell sub-unit of the bipolar separator plate shown in FIG. **18**.

FIG. **20** illustrates a cross-sectional perspective view of the unit-cell from FIG. **19** from along the diagonal section line **20-20** shown in FIG. **19**.

DETAILED DESCRIPTION

Reference will now be made in detail to present embodiments of the disclosure, one or more examples of which are illustrated in the accompanying drawings. The detailed description uses numerical and letter designations to refer to features in the drawings. Like or similar designations in the drawings and description have been used to refer to like or similar parts of the disclosure.

The word “exemplary” is used herein to mean “serving as an example, instance, or illustration.” Any implementation described herein as “exemplary” is not necessarily to be construed as preferred or advantageous over other implementations. Additionally, unless specifically identified otherwise, all embodiments described herein should be considered exemplary.

For purposes of the description hereinafter, the terms “upper”, “lower”, “vertical”, “horizontal”, “top”, “bottom”, “lateral”, “longitudinal”, and derivatives thereof shall relate to the embodiments as they are oriented in the drawing figures. However, it is to be understood that the embodiments may assume various alternative variations, except where expressly specified to the contrary. It is also to be understood that the specific devices illustrated in the attached drawings, and described in the following specification, are simply exemplary embodiments of the disclosure. Hence, specific dimensions and other physical characteristics related to the embodiments disclosed herein are not to be considered as limiting.

As used herein, the terms “first”, “second”, and “third” may be used interchangeably to distinguish one component from another and are not intended to signify location or importance of the individual components.

As used herein, the term "line" may include a hose, pipe, or other fluid conduit that carries a fluid.

The terms "upstream" and "downstream" refer to the relative direction with respect to fluid flow in a fluid pathway. For example, "upstream" refers to the direction from which the fluid flows, and "downstream" refers to the direction to which the fluid flows.

The terms "coupled," "fixed," "attached to," and the like refer to both direct coupling, fixing, or attaching, as well as indirect coupling, fixing, or attaching through one or more intermediate components or features, unless otherwise specified herein.

The singular forms "a", "an", and "the" include plural references unless the context clearly dictates otherwise.

The term "at least one of" in the context of, e.g., "at least one of A, B, and C" or "at least one of A, B, or C" refers to only A, only B, only C, or any combination of A, B, and C.

Here and throughout the specification and claims, range limitations are combined and interchanged, such ranges are identified and include all the sub-ranges contained therein unless context or language indicates otherwise. For example, all ranges disclosed herein are inclusive of the endpoints, and the endpoints are independently combinable with each other.

As used herein "unit-cell" is a singular cell, which may be positioned adjacent to other unit-cells to collectively define a cell sub-unit. For example, a "cell sub-unit" may be a collection of unit-cells in contact, and in fluid communication, with one another.

A fuel cell assembly and a propulsion system are provided. The fuel cell assembly includes a plurality of fuel cells each having an anode, a cathode, and a solid electrolyte disposed between the anode and the cathode. The fuel cell assembly includes a bipolar separator plate that is disposed between each fuel cell of the plurality of fuel cells. The bipolar separator plate includes one or more fuel cell sub-units that each comprise a plurality of unit-cells. The plurality of unit-cells each define an interior volume and are be disposed adjacent to one another, such that the interior volume of the plurality of unit-cells collectively define one or more channels. The one or more channels may each receive a fluid for use in, or for the thermal management of, the fuel cell. For example, the one or more channels may include an oxidant channel for the cathode, a fuel channel for the anode, and a coolant channel disposed between the oxidant channel and the fuel channel for collection of heat from the fuel cell.

The fuel cell assembly of the present disclosure advantageously includes single-fluid (i.e., fluidly isolated) fuel cell sub-units that define the fuel, coolant, and oxygen channels in the bipolar separator plate and end plate. Each of the fuel cell sub-units include a plurality of single-fluid unit-cells that enable multidirectional flow at each channel to achieve better thermal distribution. To control the temperature of the fuel cell assembly, the coolant channel may be disposed in fluid communication on a dedicated coolant loop, which may use a coolant (e.g. supercritical CO_2, water, and air) as the working fluid. The bipolar separator plate may be integrally formed, e.g., manufactured as a single-material component to further reduces thermal stress across the fuel cell assembly.

Referring now to the drawings, wherein identical numerals indicate the same elements throughout the figures, FIG. **1** provides a schematic, cross-sectional view of an engine in accordance with an exemplary embodiment of the present disclosure. The engine may be incorporated into a vehicle. For example, the engine may be an aeronautical engine incorporated into an aircraft. Alternatively, however, the engine may be any other suitable type of engine for any other suitable vehicle.

For the embodiment depicted, the engine is configured as a high bypass gas turbine engine **100**. As shown in FIG. **1**, the gas turbine engine **100** defines an axial direction A (extending parallel to a centerline axis **101** provided for reference), a radial direction R, and a circumferential direction (extending about the axial direction A; not depicted in FIG. **1**). In general, the gas turbine engine **100** includes a fan section **102** and a turbomachine **104** disposed downstream from the fan section **102**.

The exemplary turbomachine **104** depicted generally includes a substantially tubular outer casing **106** that defines an annular inlet **108**. The outer casing **106** encases, in serial flow relationship, a compressor section including a booster or low pressure (LP) compressor **110** and a high pressure (HP) compressor **112**; a combustion section **114**; a turbine section including a high pressure (HP) turbine **116** and a low pressure (LP) turbine **118**; and a jet exhaust nozzle section **120**. The compressor section, combustion section **114**, and turbine section together define at least in part a core air flowpath **121** extending from the annular inlet **108** to the jet nozzle exhaust section **120**. The turbofan engine further includes one or more drive shafts. More specifically, the turbofan engine includes a high pressure (HP) shaft or spool **122** drivingly connecting the HP turbine **116** to the HP compressor **112**, and a low pressure (LP) shaft or spool **124** drivingly connecting the LP turbine **118** to the LP compressor **110**.

For the embodiment depicted, the fan section **102** includes a fan **126** having a plurality of fan blades **128** coupled to a disk **130** in a spaced apart manner. The fan blades **128** and disk **130** are together rotatable about the centerline axis **101** by the LP shaft **124**. The disk **130** is covered by a rotatable front hub **132** aerodynamically contoured to promote an airflow through the plurality of fan blades **128**. Further, an annular fan casing or outer nacelle **134** is provided, circumferentially surrounding the fan **126** and/or at least a portion of the turbomachine **104**. The nacelle **134** is supported relative to the turbomachine **104** by a plurality of circumferentially-spaced outlet guide vanes **136**. A downstream section **138** of the nacelle **134** extends over an outer portion of the turbomachine **104** so as to define a bypass airflow passage **140** therebetween.

In such a manner, it will be appreciated that gas turbine engine **100** generally includes a first stream (e.g., core air flowpath **121**) and a second stream (e.g., bypass airflow passage **140**) extending parallel to the first stream. In certain exemplary embodiments, the gas turbine engine **100** may further define a third stream extending, e.g., from the LP compressor **110** to the bypass airflow passage **140** or to ambient. With such a configuration, the LP compressor **110** may generally include a first compressor stage configured as a ducted mid-fan and downstream compressor stages. An inlet to the third stream may be positioned between the first compressor stage and the downstream compressor stages.

Referring still to FIG. **1**, the gas turbine engine **100** additionally includes an accessory gearbox **142** and a fuel delivery system **146**. For the embodiment shown, the accessory gearbox **142** is located within the cowling/outer casing **106** of the turbomachine **104**. Additionally, it will be appreciated that for the embodiment depicted schematically in FIG. **1**, the accessory gearbox **142** is mechanically coupled to, and rotatable with, one or more shafts or spools of the turbomachine **104**. For example, in the exemplary embodiment depicted, the accessory gearbox **142** is mechanically coupled to, and rotatable with, the HP shaft **122** through a suitable geartrain **144**. The accessory gearbox **142** may provide power to one or more suitable accessory systems of the gas turbine engine **100** during at least certain operations, and may further provide power back to the gas turbine engine **100** during other operations. For example, the accessory gearbox **142** is, for the embodiment depicted, coupled to a starter motor/generator **152**. The starter motor/generator may be configured to extract power from the accessory gearbox **142** and gas turbine engine **100** during certain operation to generate electrical power, and may provide power back to the accessory gearbox **142** and gas turbine engine **100** (e.g., to the HP shaft **122**) during other operations to add mechanical work back to the gas turbine engine **100** (e.g., for starting the gas turbine engine **100**).

Moreover, the fuel delivery system **146** generally includes a fuel source **148**, such as a fuel tank, and one or more fuel delivery lines **150**. The one or more fuel delivery lines **150** provide a fuel flow through the fuel delivery system **146** to the combustion section **114** of the turbomachine **104** of the gas turbine engine **100**. As will be discussed in more detail below, the combustion section **114** includes an integrated fuel cell and combustor assembly **200**. The one or more fuel delivery lines **150**, for the embodiment depicted, provide a flow of fuel to the integrated fuel cell and combustor assembly **200**.

It will be appreciated, however, that the exemplary gas turbine engine **100** depicted in FIG. **1** is provided by way of example only. In other exemplary embodiments, any other suitable gas turbine engine may be utilized with aspects of the present disclosure. For example, in other embodiments, the turbofan engine may be any other suitable gas turbine engine, such as a turboshaft engine, turboprop engine, turbojet engine, etc. In such a manner, it will further be appreciated that in other embodiments the gas turbine engine may have any other suitable configuration, such as any other suitable number or arrangement of shafts, compressors, turbines, fans, etc. Further, although the exemplary gas turbine engine depicted in FIG. **1** is shown schematically as a direct drive, fixed-pitch turbofan engine, in other embodiments, a gas turbine engine of the present disclosure may be a geared gas turbine engine (i.e., including a gearbox between the fan **126** and a shaft driving the fan, such as the LP shaft **124**), may be a variable pitch gas turbine engine (i.e., including a fan **126** having a plurality of fan blades **128** rotatable about their respective pitch axes), etc. Moreover, although the exemplary gas turbine engine **100** includes a ducted fan **126**, in other exemplary aspects, the gas turbine engine **100** may include an unducted fan **126** (or open rotor fan), without the nacelle **134**. Further, although not depicted herein, in other embodiments the gas turbine engine may be any other suitable type of gas turbine engine, such as a nautical gas turbine engine.

Referring now to FIG. **2**, illustrated schematically is a portion of the combustion section **114** including a portion of the integrated fuel cell and combustor assembly **200** used in the gas turbine engine **100** of FIG. **1**, according to an embodiment of the present disclosure.

As will be appreciated, the combustion section **114** includes a compressor diffuser nozzle **202** and extends between an upstream end and a downstream end generally along the axial direction A. The combustion section **114** is fluidly coupled to the compressor section at the upstream end via the compressor diffuser nozzle **202** and to the turbine section at the downstream end.

The integrated fuel cell and combustor assembly **200** generally includes a fuel cell assembly **204** (only partially depicted in FIG. **2**; see also FIGS. **3** through **5**) and a combustor **206**. The combustor **206** includes an inner liner **208**, an outer liner **210**, a dome assembly **212**, a cowl assembly **214**, a swirler assembly **216**, and a fuel flowline **218**. The combustion section **114** generally includes an outer casing **220** outward of the combustor **206** along the radial direction R to enclose the combustor **206** and an inner casing **222** inward of the combustor **206** along the radial direction R. The inner casing **222** and inner liner **208** define an inner passageway **224** therebetween, and the outer casing **220** and outer liner **210** define an outer passageway **226** therebetween. The inner casing **222**, the outer casing **220**, and the dome assembly **212** together define at least in part a combustion chamber **228** of the combustor **206**.

The dome assembly **212** is disposed proximate the upstream end of the combustion section **114** (i.e., closer to the upstream end than the downstream end) and includes an opening (not labeled) for receiving and holding the swirler assembly **216**. The swirler assembly **216** also includes an opening for receiving and holding the fuel flowline **218**. The fuel flowline **218** is further coupled to the fuel source **148** (see FIG. **1**) disposed outside the outer casing **220** along the radial direction R and configured to receive the fuel from the fuel source **148**. In such a manner, the fuel flowline **218** may be fluidly coupled to the one or more fuel delivery lines **150** described above with reference to FIG. **1**.

The swirler assembly **216** can include a plurality of swirlers (not shown) configured to swirl the compressed fluid before injecting it into the combustion chamber **228** to generate combustion gas. The cowl assembly **214**, in the embodiment depicted, is configured to hold the inner liner **208**, the outer liner **210**, the swirler assembly **216**, and the dome assembly **212** together.

During operation, the compressor diffuser nozzle **202** is configured to direct a compressed fluid **230** from the compressor section to the combustor **206**, where the compressed fluid **230** is configured to be mixed with fuel within the swirler assembly **216** and combusted within the combustion chamber **228** to generate combustion gasses. The combustion gasses are provided to the turbine section to drive one or more turbines of the turbine section (e.g., the high pressure turbine **116** and low pressure turbine **118**).

During operation of the gas turbine engine **100** including the integrated fuel cell and combustor assembly **200**, a flame within the combustion chamber **228** is maintained by a continuous flow of fuel and air. In order to provide for an ignition of the fuel and air, e.g., during a startup of the gas turbine engine **100**, the integrated fuel cell and combustor assembly **200** further includes an ignitor **231**. The ignitor **231** may provide a spark or initial flame to ignite a fuel and air mixture within the combustion chamber **228**. In certain exemplary embodiments, the integrated fuel cell and combustor assembly **200** may additionally include a dedicated fuel cell ignitor **233** (depicted in phantom). In particular, for the embodiment of FIG. **2**, the dedicated fuel cell ignitor **233** is positioned downstream of at least a portion of a fuel cell, and in particular of a fuel cell stack (described below). In such a manner, the dedicated fuel cell ignitor **233** may more effectively combust output products of the fuel cell.

As mentioned above and depicted schematically in FIG. **2**, the integrated fuel cell and combustor assembly **200** further includes the fuel cell assembly **204**. The exemplary fuel cell assembly **204** depicted includes a first fuel cell stack **232** and a second fuel cell stack **234**. More specifically, the first fuel cell stack **232** is configured with the outer liner **210** and the second fuel cell stack **234** is configured with the inner liner **208**. More specifically, still, the first fuel cell stack **232** is integrated with the outer liner **210** and the second fuel cell stack **234** is integrated with the inner liner **208**. Operation of the fuel cell assembly **204**, and more specifically of a fuel cell stack (e.g., first fuel cell stack **232** or second fuel cell stack **234**) of the fuel cell assembly **204** will be described in more detail below.

For the embodiment depicted, the fuel cell assembly **204** is configured as a solid oxide fuel cell ("SOFC") assembly, with the first fuel cell stack **232** configured as a first SOFC fuel cell stack and the second fuel cell stack **234** configured as a second SOFC fuel cell stack (each having a plurality of SOFC's). As will be appreciated, a SOFC is generally an electrochemical conversion device that produces electricity directly from oxidizing a fuel. In generally, fuel cell assemblies, and in particular fuel cells, are characterized by an electrolyte material utilized. The SOFC's of the present disclosure may generally include a solid oxide or ceramic electrolyte. This class of fuel cells generally exhibit high combined heat and power efficiency, long-term stability, fuel flexibility, and low emissions.

Moreover, the exemplary fuel cell assembly **204** further includes a first power converter **236** and a second power converter **238**. The first fuel cell stack **232** is in electrical communication with the first power converter **236** by a first plurality of power supply cables (not labeled), and the second fuel cell stack **234** is in electrical communication with the second power converter **238** by a second plurality of power supply cables (not labeled).

The first power converter **236** controls the electrical current drawn from the corresponding first fuel cell stack **232** and may convert the electrical power from a direct current ("DC") power to either DC power at another voltage level or alternating current ("AC") power. Similarly, the second power converter **238** controls the electrical current drawn from the second fuel cell stack **234** and may convert the electrical power from a DC power to either DC power at another voltage level or AC power. The first power converter **236**, the second power converter **238**, or both may be electrically coupled to an electric bus (such as the electric bus **326** described below).

The integrated fuel cell and combustor assembly **200** further includes a fuel cell controller **240** that is in operable communication with both of the first power converter **236** and second power converter **238** to, e.g., send and receive communications and signals therebetween. For example, the fuel cell controller **240** may send current or power setpoint signals to the first power converter **236** and second power converter **238**, and may receive, e.g., a voltage or current feedback signal from the first power converter **236** and second power converter **238**. The fuel cell controller **240** may be configured in the same manner as the controller **240** described below with reference to FIG. **4**.

It will be appreciated that in at least certain exemplary embodiments the first fuel cell stack **232**, the second fuel cell stack **234**, or both may extend substantially 360 degrees in a circumferential direction C of the gas turbine engine (i.e., a direction extending about the centerline axis **101** of the gas turbine engine **100**). For example, referring now to FIG. **3**, a simplified cross-sectional view of the integrated fuel cell and combustor assembly **200** is depicted according to an exemplary embodiment of the present disclosure. Although only the first fuel cell stack **232** is depicted in FIG. **3** for simplicity, the second fuel cell stack **234** may be configured in a similar manner.

As shown, the first fuel cell stack **232** extends around the combustion chamber **228** in the circumferential direction C, completely encircling the combustion chamber **228** around the centerline axis **101** in the embodiment shown. More specifically, the first fuel cell stack **232** includes a plurality of fuel cells **242** arranged along the circumferential direction C. The fuel cells **242** that are visible in FIG. **3** can be a single ring of fuel cells **242**, with fuel cells **242** stacked together along the axial direction A (see FIG. **2**) to form the first fuel cell stack **232**. In another instance, a plurality of additional rings of fuel cells **242** can be placed on top of each other to form the first fuel cell stack **232** that is elongated along the centerline axis **101**.

As will be explained in more detail, below, with reference to FIG. **4**, the fuel cells **242** in the first fuel cell stack **232** are positioned to receive discharged air **244** from, e.g., the compressor section and fuel **246** from the fuel delivery system **146**. The fuel cells **242** generate electrical current using this air **244** and at least some of this fuel **246**, and radially direct partially oxidized fuel **246** and unused portion of air **248** into the combustion chamber **228** toward the centerline axis **101**. The integrated fuel cell and combustor assembly **200** combusts the partially oxidized fuel **246** and air **248** in the combustion chamber **228** into combustion gasses that are directed downstream into the turbine section to drive or assist with driving the one or more turbines therein.

Referring now to FIG. **4**, operation of an integrated fuel cell and combustor assembly **200** in accordance with an exemplary embodiment of the present disclosure will be described. More specifically, FIG. **4** provides a schematic illustration of a gas turbine engine **100** and an integrated fuel cell and combustor assembly **200** according to an embodiment of the present disclosure. The gas turbine engine **100** and integrated fuel cell and combustor assembly **200** may, in certain exemplary embodiments, be configured in a similar manner as one or more of the exemplary embodiments of FIGS. **1** through **4**.

Accordingly, it will be appreciated that the gas turbine engine **100** generally includes a fan section **102** having a fan **126**, an LP compressor **110**, an HP compressor **112**, a combustion section **114**, an HP turbine **116**, and an LP turbine **118**. The combustion section **114** generally includes the integrated fuel cell and combustor assembly **200** having a combustor **206** and a fuel cell assembly **204**.

A propulsion system including the gas turbine engine **100** further includes a fuel delivery system **146**. The fuel delivery system **146** generally includes a fuel source **148** and one or more fuel delivery lines **150**. The fuel source **148** may include a supply of fuel (e.g., a hydrocarbon fuel, including, e.g., a carbon-neutral fuel or synthetic hydrocarbons) for the gas turbine engine **100**. In addition, it will be appreciated that the fuel delivery system **146** also includes a fuel pump **272** and a flow divider **274**, and the one or more fuel delivery lines **150** include a first fuel delivery line **150**A, a second fuel delivery line **150**B, and a third fuel delivery line **150**C. The flow divider **274** divides the fuel flow from the fuel source **148** and fuel pump **272** into a first fuel flow through the first fuel delivery line **150**A to the fuel cell assembly **204**, a second fuel flow through the second fuel delivery line **150**B also to the fuel cell assembly **204** (and in particular to an air processing unit, described below), and a third fuel flow through a third fuel delivery line **150**C to the combustor **206**. The flow divider **274** may include a series of valves (not shown) to facilitate such dividing of the fuel flow from the fuel source **148**, or alternatively may be of a fixed geometry. Additionally, for the embodiment shown, the fuel delivery system **146** includes a first fuel valve **151**A associated with the first fuel delivery line **150**A (e.g., for controlling the first fuel flow), a second fuel valve **151**B associated with the second fuel delivery line **150**B (e.g., for controlling the second fuel flow), and a third fuel valve **151**C associated with the third fuel delivery line **150**C (e.g., for controlling the third fuel flow).

The gas turbine engine **100** further includes a compressor bleed system and an airflow delivery system. More specifically, the compressor bleed system includes an LP bleed air duct **276** and an associated LP bleed air valve **278**, an HP bleed air duct **280** and an associated HP bleed air valve **282**, an HP exit air duct **284** and an associated HP exit air valve **286**.

The gas turbine engine **100** further includes an air stream supply duct **288** (in airflow communication with an airflow supply **290**) and an associated air valve **292**, which is also in airflow communication with the airflow delivery system for providing compressed airflow to the fuel cell assembly **204** of the integrated fuel cell and combustor assembly **200**. The airflow supply may be, e.g., a second gas turbine engine configured to provide a cross-bleed air, an auxiliary power unit (APU) configured to provide a bleed air, a ram air turbine (RAT), etc. The airflow supply may be complimentary to the compressor bleed system if the compressor air source is inadequate or unavailable.

The compressor bleed system (and air stream supply duct **288**) is in airflow communication with airflow delivery system for providing compressed airflow to the fuel cell assembly **204**, as will be explained in more detail below.

Referring still to FIG. **4**, the fuel cell assembly **204** of the integrated fuel cell and combustor assembly **200** includes a fuel cell stack **294**. The fuel cell stack **294** is depicted schematically as a single fuel cell having a cathode side **296**, an anode side **298**, and an electrolyte **300** positioned therebetween. As will generally be appreciated, the electrolyte **300** may, during operation, conduct negative oxygen ions from the cathode side **296** to the anode side **298** to generate an electric current and electric power.

Briefly, it will be appreciated that the fuel cell assembly **204** further includes a fuel cell sensor **302** configured to sense data indicative of a fuel cell assembly operating parameter, such as a temperature of the fuel cell stack **294** (e.g., of the cathode side **296** or anode side **298** of the fuel cell), a pressure within the fuel cell stack **294** (e.g., of within the cathode side **296** or anode side **298** of the fuel cell).

The fuel cell stack **294** is disposed downstream of the LP compressor **110**, the HP compressor **112**, or both. Further, as will be appreciated from the description above with respect to FIG. **2**, the fuel cell stack **294** may be coupled to or otherwise integrated with a liner of the combustor **206** (e.g., an inner liner **208** or an outer liner **210**). In such a manner, the fuel cell stack **294** may also be arranged upstream of a combustion chamber **228** of the integrated fuel cell and combustor assembly **200**, and further upstream of the HP turbine **116** and LP turbine **118**.

As shown in FIG. **4**, the fuel cell assembly **204** also includes a fuel processing unit **304** and an air processing unit **306**. The fuel processing unit **304** may be any suitable structure for generating a hydrogen rich fuel stream. For example, the fuel processing unit **304** may include a fuel reformer or a catalytic partial oxidation convertor (CPOx) for developing the hydrogen rich fuel stream for the fuel cell stack **294**. The air processing unit **306** may be any suitable structure for raising the temperature of air that is provided thereto to a temperature high enough to enable fuel cell temperature control (e.g., about 600° C. to about 800° C.). For example, in the embodiment depicted, the air processing unit includes a preburner system, operating based on a fuel flow through the second fuel delivery line **150**B, configured for raising the temperature of the air through combustion, e.g., during transient conditions such as startup, shutdown and abnormal situations.

In the exemplary embodiment depicted, the fuel processing unit **304** and air processing unit **306** are within a housing **308** to provide conditioned air and fuel to the fuel cell stack **294**.

It should be appreciated, however, that the fuel processing unit **304** may additionally or alternatively include any suitable type of fuel reformer, such as an autothermal reformer and steam reformer that may need an additional stream of steam inlet with higher hydrogen composition at the reformer outlet stream. Additionally, or alternatively, still, the fuel processing unit **304** may include a reformer integrated with the fuel cell stack **294**. Similarly, it should be appreciated that the air processing unit **306** of FIG. **4** could alternatively be a heat exchanger or another device for raising the temperature of the air provided thereto to a temperature high enough to enable fuel cell temperature control (e.g., about 600° C. to about 800° C.).

As mentioned above, the compressor bleed system (and air stream supply duct **288**) is in airflow communication with airflow delivery system for providing compressed airflow to the fuel cell assembly **204**. The airflow delivery system includes an anode airflow duct **310** and an associated anode airflow valve **312** for providing an airflow to the fuel processing unit **304**, a cathode airflow duct **314** and associated cathode airflow valve **316** for providing an airflow to the air processing unit **306**, and a cathode bypass air duct **318** and an associated cathode bypass air valve **320** for providing an airflow directly to the fuel cell stack **294** (or rather to the cathode side **296** of the fuel cell(s)). The fuel delivery system **146** is configured to provide the first flow of fuel through the first fuel delivery line **150**A to the fuel processing unit **304**, and the second flow of fuel through the second fuel delivery line **150**B to the air processing unit **306** (e.g., as fuel for a preburner system, if provided).

The fuel cell stack **294** outputs the power produced as a fuel cell power output **322**. Further, the fuel cell stack **294** directs a cathode air discharge and an anode fuel discharge (neither labeled for clarity purposes) into the combustion chamber **228** of the combustor **206**.

In operation, the air processing unit **306** is configured to heat/cool a portion of the compressed air, incoming through the cathode airflow duct **314**, to generate a processed air to be directed into the fuel cell stack **294** to facilitate the functioning of the fuel cell stack **294**. The air processing unit **306** receives the second flow of fuel from the second fuel delivery line **150**B and may, e.g., combust such second flow of fuel to heat the air received to a desired temperature (e.g., about 600° C. to about 800° C.) to facilitate the functioning of the fuel cell stack **294**. The air processed by the air processing unit **306** is directed into the fuel cell stack **294**. In an embodiment of the disclosure, as is depicted, the cathode bypass air duct **318** and the air processed by the air processing unit **306** may combine into a combined air stream to be fed into a cathode of the fuel cell stack **294**.

Further, as shown in the embodiment of FIG. **4**, the first flow of fuel through the first fuel delivery line **150**A is directed to the fuel processing unit **304** for developing a hydrogen rich fuel stream (e.g., optimizing a hydrogen content of a fuel stream), to also be fed into the fuel cell stack **294**. As will be appreciated, and as discussed below, the flow of air (processed air and bypass air) to the fuel cell stack **294** (e.g., the cathode side **296**) and fuel from the fuel processing unit **304** to the fuel cell stack **294** (e.g., the anode side **298**) may facilitate electrical power generation.

Because the inlet air for the fuel cell stack **294** may come solely from the upstream compressor section without any other separately controlled air source, it will be appreciated that the inlet air for the fuel cell stack **294** discharged from the compressor section is subject to the air temperature changes that occur at different flight stages. By way of illustrative example only, the air within a particular location in the compressor section of the gas turbine engine **100** may work at 200° C. during idle, 600° C. during take-off, 268° C. during cruise, etc. This type of temperature change to the inlet air directed to the fuel cell stack **294** may lead to significant thermal transient issues (or even thermal shock) to the ceramic materials of the fuel cell stack **294**, which could range from cracking to failure.

Thus, by fluidly connecting the air processing unit **306** between the compressor section and the fuel cell stack **294**, the air processing unit **306** may serve as a control device or system to maintain the air processed by the air processing unit **306** and directed into the fuel cell stack **294** within a desired operating temperature range (e.g., plus or minus 100° C., or preferably plus or minus 50° C., or plus or minus 20° C.). In operation, the temperature of the air that is provided to the fuel cell stack **294** can be controlled (relative to a temperature of the air discharged from the compressor section) by controlling the flow of fuel to the air processing unit **306**. By increasing a fuel flow to the air processing unit **306**, a temperature of the airflow to the fuel cell stack **294** may be increased. By decreasing the fuel flow to the air processing unit **306**, a temperature of the airflow to the fuel cell stack **294** may be decreased. Optionally, no fuel can be delivered to the air processing unit **306** to prevent the air processing unit **306** from increasing and/or decreasing the temperature of the air that is discharged from the compressor section and directed into the air processing unit **306**.

Moreover, as is depicted in phantom, the fuel cell assembly **204** further includes an airflow bypass duct **321** extending around the fuel cell stack **294** to allow a portion or all of an airflow conditioned by the air processing unit **306** (and combined with any bypass air through duct **318**) to bypass the cathode side **296** of the fuel cell stack **294** and go directly to the combustion chamber **228**. The bypass duct **321** may be in thermal communication with the fuel cell stack **294**. The fuel cell assembly further includes a fuel bypass duct **323** extending around the fuel cell stack **294** to allow a portion or all of a reformed fuel from the fuel processing unit **304** to bypass the anode side **298** of the fuel cell stack **294** and go directly to the combustion chamber **228**.

As briefly mentioned above, the fuel cell stack **294** converts the anode fuel stream from the fuel processing unit **304** and air processed by the air processing unit **306** sent into the fuel cell stack **294** into electrical energy, the fuel cell power output **322**, in the form of DC current. This fuel cell power output **322** is directed to a power convertor **324** in order to change the DC current into DC current or AC current that can be effectively utilized by one or more subsystems. In particular, for the embodiment depicted, the electrical power is provided from the power converter to an electric bus **326**. The electric bus **326** may be an electric bus dedicated to the gas turbine engine **100**, an electric bus of an aircraft incorporating the gas turbine engine **100**, or a combination thereof. The electric bus **326** is in electric communication with one or more additional electrical devices **328**, which may be a power source, a power sink, or both. For example, the additional electrical devices **328** may be a power storage device (such as one or more batteries), an electric machine (an electric generator, an electric motor, or both), an electric propulsion device, etc. For example, the one or more additional electrical devices **328** may include the starter motor/generator of the gas turbine engine **100**.

Moreover, as is further depicted schematically in FIG. **4**, the propulsion system, an aircraft including the propulsion system, or both, includes a controller **240**. For example, the controller **240** may be a standalone controller, a gas turbine engine controller (e.g., a full authority digital engine control, or FADEC), an aircraft controller, supervisory controller for a propulsion system, a combination thereof, etc.

The controller **240** is operably connected to various the sensors, valves, etc. within at least one of the gas turbine engine **100** and the fuel delivery system **146**. More specifically, for the exemplary aspect depicted, the controller **240** is operably connected to the valves of the compressor bleed system (valves **278**, **282**, **286**), the airflow delivery system (valves **312**, **316**, **320**), and the fuel delivery system **146** (flow divider **274**, valves **151**A, **151**B, **151**C) of the gas turbine engine **100** and the fuel cell sensor **302**. As will be appreciated from the description below, the controller **240** may be in wired or wireless communication with these components. In this manner, the controller **240** may receive data from a variety of inputs (including the fuel cell sensor **302**), may make control decisions, and may provide data (e.g., instructions) to a variety of output (including the valves of the compressor bleed system to control an airflow bleed from the compressor section, the airflow delivery system to direct the airflow bled from the compressor section, and the fuel delivery system **146** to direct the fuel flow within the gas turbine engine **100**).

Referring particularly to the operation of the controller **240**, in at least certain embodiments, the controller **240** can include one or more computing device(s) **332**. The computing device(s) **332** can include one or more processor(s) **332**A and one or more memory device(s) **332**B. The one or more processor(s) **332**A can include any suitable processing device, such as a microprocessor, microcontroller, integrated circuit, logic device, and/or other suitable processing device. The one or more memory device(s) **332**B can include one or more computer-readable media, including, but not limited to, non-transitory computer-readable media, RAM, ROM, hard drives, flash drives, and/or other memory devices.

The one or more memory device(s) **332**B can store information accessible by the one or more processor(s) **332**A, including computer-readable instructions **332**C that can be executed by the one or more processor(s) **332**A. The instructions **332**C can be any set of instructions that when executed by the one or more processor(s) **332**A, cause the one or more processor(s) **332**A to perform operations. In some embodiments, the instructions **332**C can be executed by the one or more processor(s) **332**A to cause the one or more processor(s) **332**A to perform operations, such as any of the operations and functions for which the controller **240** and/or the computing device(s) **332** are configured, the operations for operating a propulsion system, as described herein, and/or any other operations or functions of the one or more computing device(s) **332**. The instructions **332**C can be software written in any suitable programming language or can be implemented in hardware. Additionally, and/or alternatively, the instructions **332**C can be executed in logically and/or virtually separate threads on processor(s) **332**A. The memory device(s) **332**B can further store data **332**D that can be accessed by the processor(s) **332**A. For example, the data **332**D can include data indicative of power flows, data indicative of gas turbine engine **100**/aircraft operating conditions, and/or any other data and/or information described herein.

The computing device(s) **332** also includes a network interface **332**E configured to communicate, for example, with the other components of the gas turbine engine **100** (such as the valves of the compressor bleed system (valves **278**, **282**, **286**), the airflow delivery system (valves **312**, **316**, **320**), and the fuel delivery system **146** (flow divider **274**, valves **151**A, **151**B, **151**C) of the gas turbine engine **100** and the fuel cell sensor **302**), the aircraft incorporating the gas turbine engine **100**, etc. The network interface **332**E can include any suitable components for interfacing with one or more network(s), including for example, transmitters, receivers, ports, controllers, antennas, and/or other suitable components. In such a manner, it will be appreciated that the network interface **332**E may utilize any suitable combination of wired and wireless communications network(s).

The technology discussed herein makes reference to computer-based systems and actions taken by and information sent to and from computer-based systems. It will be appreciated that the inherent flexibility of computer-based systems allows for a great variety of possible configurations, combinations, and divisions of tasks and functionality between and among components. For instance, processes discussed herein can be implemented using a single computing device or a plurality of computing devices working in combination. Databases, memory, instructions, and applications can be implemented on a single system or distributed across a plurality of systems. Distributed components can operate sequentially or in parallel.

It will be appreciated that the gas turbine engine **100**, the exemplary fuel delivery system **146**, the exemplary integrated fuel cell and combustor assembly **200**, and the exemplary fuel cell assembly **204** are provided by way of example only. In other embodiments, the integrated fuel cell and combustor assembly **200** and fuel cell assembly **204** may have any other suitable configuration. For example, in other exemplary embodiments, the fuel cell assembly **204** may include any other suitable fuel processing unit **304**. Additionally, or alternatively, the fuel cell assembly **204** may not require a fuel processing unit **304**, e.g., when the combustor of the gas turbine engine **100** is configured to burn hydrogen fuel and the fuel delivery system **146** is configured to provide hydrogen fuel to the integrated fuel cell and combustor assembly **200**, and in particular to the fuel cell assembly **204**.

Referring now to FIG. **5**, a schematic view of a thermal management system **500** is illustrated in accordance with exemplary aspects of the present disclosure. For example, the thermal management system **500** may be incorporated in the propulsion system described above with reference to FIGS. **1** through **4**. As shown, the thermal management system **500** may include a fuel cell assembly **502** (which may be the same as the fuel cell assembly **204** described above or a different fuel cell assembly). As shown in FIG. **5**, the fuel cell assembly **502** may include a plurality of fuel cells **504** each having an anode **506**, a cathode **508**, and a solid electrolyte **510** disposed between the anode **506** and the cathode **508**. For example, the fuel cell assembly **502** may include a first fuel cell **501** and a second fuel cell **503**. In many embodiments, the fuel cell assembly **502** may include a bipolar separator plate **512** disposed between the first fuel cell **501** and the second fuel cell **503** of the plurality of fuel cells **504**. Particularly, the bipolar separator plate **512** may include a cathode cell sub-unit **514**, a coolant cell sub-unit **516**, and an anode cell sub-unit **518**. The cathode cell sub-unit **514** may be disposed adjacent (i.e., in contact) to the cathode **508** of the first fuel cell **501**, and the anode cell sub-unit **518** may be disposed adjacent (i.e., in contact) to the anode **506** of the second fuel cell **503**. The coolant cell sub-unit **516** may be disposed between the anode cell sub-unit **518** and the cathode cell sub-unit **514**.

In various embodiments, the cathode cell sub-unit **514** may defines an oxidant channel **515** fluidly coupled to the compressor section. For example, the oxidant channel **515** may be in fluid communication with one or more stages of the compressor section, such that the oxidant channel **515** may receive a flow of air (e.g., bleed air) from a stage in the compressor section, utilize the flow of air for transferring heat from the plurality of fuel cells **504**, and return the flow of air to the compressor section (e.g., to another of the one or more stages in the compressor section). Particularly, the oxidant channel **515** may include an oxidant inlet **520** and an oxidant outlet **522**. The oxidant inlet **520** may be fluidly coupled to a low pressure compressor stage **524** of the compressor section via a bleed air line **526**. The oxidant outlet **522** may be fluidly coupled to a high pressure compressor stage **528** of the compressor section via a cathode exhaust line **530**. For example, the low pressure compressor stage **524** may be a stage in the LP compressor **110** described above with reference to FIG. **1**, such that the oxidant channel **515** may receive a flow of low pressure air from the LP compressor **110**. Similarly, the high pressure compressor stage **528** may be a stage in the HP compressor **112**, such that air from the oxidant channel **515** may be returned to the HP compressor **112**. Additionally, or alternatively, the oxidant outlet **522** may be fluidly coupled to the combustion chamber **228** such that the exhaust air from the oxidant channel **515** is directly sent to the combustion chamber **228**.

In some embodiments, an air-to-air heat exchanger **532** (e.g., a first recuperator heat exchanger) may thermally couple the bleed air line **526** and the cathode exhaust line **530**. For example, the air-to-air heat exchanger **532** may exchange heat between the air in the bleed air line **526** and the air in the cathode exhaust line **530**. The air-to-air heat exchanger **532** may be disposed in fluid communication on the bleed air line **526** upstream of the oxidant channel **515** with respect to a flow of air through the bleed air line **526**. Further, the air-to-air heat exchanger **532** may be disposed in fluid communication on the cathode exhaust line **530** downstream of the oxidant channel **515** with respect to a flow of air through the cathode exhaust line **530**.

In exemplary embodiment, the anode cell sub-unit **518** may define a fuel channel **534** that is fluidly coupled to the combustion section. For example, the fuel channel **534** may receive a flow of fuel (e.g., liquid hydrogen or other suitable fuel) from a fuel tank **536** via a fuel supply line **538**. In particular, the fuel channel **534** may include a fuel inlet **540** and one or more outlets (e.g., a first outlet **542** and a second outlet **544**). In many embodiments, the fuel inlet **540** may be fluidly coupled to the fuel supply line **538**. The one or more outlets **542**, **544** may be fluidly coupled to the combustion chamber **228**. Particularly, the first outlet **542** of the fuel channel **534** may exhaust water **546** from the anode **506** (e.g., anode water). The water **546** may be provided to one or both of the combustion chamber **228** to reduce nitrogen oxide (NOx) emission and/or the turbine section for turbine cooling **548**. The water **546** may be provided to one or more stages in the turbine section. For example, turbine cooling **548** may include cooling of one or more turbine section components (e.g., one or more turbine rotor blades, stator vanes, or other components in the turbine section). The second outlet **544** of the fuel channel **534** may exhaust excess fuel not utilized by the anode **506** in the fuel channel **534** via an excess fuel line **550**.

In many embodiments, a fuel-to-fuel heat exchanger **552** (e.g., second recuperator heat exchanger) may thermally couple the fuel supply line **538** and the excess fuel line **550** from the fuel outlet **544**. Particularly, the fuel-to-fuel heat exchanger **552** may be disposed in fluid communication on the fuel supply line **538** upstream of the fuel channel **534** with respect to the flow of fuel through the fuel supply line **538**. Additionally, the fuel-to-fuel heat exchanger **552** may be disposed in fluid communication on the excess fuel line **550** downstream of the fuel channel **534** with respect to the flow of fuel through the excess fuel line **550**.

In various embodiments, the thermal management system **500** may further include a series of heat exchangers **554** fluidly and thermally coupled to the fuel supply line **538** upstream of the fuel-to-fuel heat exchanger **552**. The series of heat exchangers **554** may include an hydrogen-to-oil heat exchanger, a hydrogen-to-air heat exchanger, and/or a hydrogen-to-coolant (e.g., coolant from the fuel cell assembly dedicated coolant loop). The series of heat exchangers **554** may receive liquid hydrogen (H_2) from the fuel tank **536** and transfer heat to (or away from) the liquid hydrogen, such that the hydrogen provided to the fuel cell assembly **502** and/or the combustion chamber **228** has a desired temperature. Particularly, the hydrogen may leave the fuel tank **536** in a liquid state, and the hydrogen may be provided to the fuel cell assembly **502** and/or the combustion chamber **228** in a gaseous state.

In exemplary embodiments, the bipolar separator plate **512** may further include a coolant cell sub-unit **516** that defines a coolant channel **556**. The coolant channel **556** may function to remove heat from the fuel cell assembly **502** as part of a thermal transport bus where the coolant acts as the working fluid being recirculated between the heat source (the fuel cell assembly **502**, and more particularly the coolant channel **556**) and the heat-sink heat exchanger **558** in a closed cycle loop.

For example, in many embodiments, the coolant channel **556** may be in fluid communication with a heat-sink heat exchanger **558**, which may remove heat from the coolant. Particularly, the coolant channel may be disposed in fluid communication on a dedicated coolant loop or closed cycle loop **560**. The dedicated coolant loop **560** may circulate coolant fluid (e.g., with a pump **562**) through the coolant channel **556** and the heat-sink heat exchanger **558**. The coolant fluid may be supercritical CO_2, air, water, or other suitable coolant fluid. The heat-sink heat exchanger **558** may thermally couple the coolant fluid within the dedicated coolant loop **560** with a sink fluid **564**, such that the sink fluid **564** may remove heat from the coolant fluid via the heat-sink heat exchanger **558**. The sink fluid **564** may be liquid hydrogen (e.g., from the fuel supply line **538**), air, or other suitable fluids.

In many embodiments, each of the channels **515**, **534**, **556** defined in the bipolar separator plate **512** may be fluidly isolated from one another. For example, the oxidant channel **515** defined in the cathode cell sub-unit **514** of the bipolar separator plate **512**, the fuel channel **534** defined in the anode cell sub-unit **518** of the bipolar separator plate **512**, and the coolant channel **556** defined in the coolant cell sub-unit **516** may each be fluidly isolated from one another. Additionally, the oxidant channel **515** may be at least partially defined by the cathode **508** of the first fuel cell **501** in the plurality of fuel cells **504**, such that the oxidant channel **515** is defined collectively by the cathode **508** and the cathode cell sub-unit **514**. Similarly, the fuel channel **534** may be at least partially defined by the anode **506** of the second fuel cell **503** in the plurality of fuel cells **504**, such that the fuel channel **534** is collectively defined by the anode **506** and the anode cell sub-unit **518**.

In various embodiments, the thermal management system **500** may further include a three-fluid heat exchanger **566** in fluid communication with the oxidant channel **515** and the fuel channel **534** to preheat the fuel and air (prior to being sent to the fuel cell assembly) during transient conditions such as startup. For example, the three-fluid heat exchanger **566** may be fluidly coupled to the bleed air line **526** via an air supply line **568**. The air supply line **568** may extend from the bleed air line **526**, upstream of the air-to-air heat exchanger **532**, to the three-fluid heat exchanger **566**. An air return line **570** may extend from the three-fluid heat exchanger **566** to the bleed air line **526** downstream of the air-to-air heat exchanger **532**. Additionally, the three-fluid heat exchanger **566** may be one of the series of heat exchangers **554**, or may be a separate heat exchanger in addition to the series of heat exchangers **554**. The three-fluid heat exchanger **566** may be fluidly coupled to the series of heat exchangers **554** (and/or the fuel supply line **538**) via a fuel input line **572**. A fuel output line **574** may extend from the three-fluid heat exchanger **566** to the fuel supply line **538** downstream of the fuel-to-fuel heat exchanger **552**. Furthermore, the three-fluid heat exchanger **566** may receive a flow of exhaust gases **576** (e.g. from one or more nozzles or elsewhere), and the three-fluid heat exchanger **566** may exhaust the exhaust gases **576** to the atmosphere. In this way, the three-fluid heat exchanger **566** may exchange heat between air (prior to the air being sent to the fuel cell assembly **502**), fuel (prior to the fuel being sent to the fuel cell assembly **502**), and exhaust gases **576**.

Referring now to FIG. **6**, a fuel cell assembly **502** is illustrated in accordance with embodiments of the present disclosure. As shown, the fuel cell assembly **502** may include a plurality of fuel cells **504** each having an anode **506**, a cathode **508**, and a solid electrolyte **510** disposed between the anode **506** and the cathode **508**. For example, the fuel cell assembly **502** may include a first fuel cell **582**, one or more intermediary fuel cells **584**, and a last fuel cell **586**. During operation of the fuel cell assembly **502**, electrical current may flow from the anode **506** of the first fuel cell **582** to the cathode **508** of the last fuel cell **586**.

In many embodiments, the fuel cell assembly **502** may include one or more bipolar separator plates **512** disposed between the plurality of fuel cells **504**. Particularly, the bipolar separator plate **512** may include one or more fuel cell sub-units **514**, **516**, **518** each comprising a plurality of unit-cells **590**, **591**, **593**. In exemplary embodiments, the one or more fuel cell sub-units **514**, **516**, **518** may include a cathode cell sub-unit **514**, a coolant cell sub-unit **516**, and an anode cell sub-unit **518**. The cathode cell sub-unit **514** may be disposed adjacent (i.e., in contact) to the cathode **508** of the first fuel cell **582** (or one of the intermediary fuel cells **584**), and the anode cell sub-unit **518** may be disposed adjacent (i.e., in contact) to the anode **506** of the last fuel cell **586** (or one of the intermediary fuel cells **584**). The coolant cell sub-unit **516** may be disposed between the anode cell sub-unit **518** and the cathode cell sub-unit **514**. Additionally, in many embodiments, the fuel cell assembly **502** may include end plates (e.g., a first end plate **578** and a second end plate **580**) disposed on opposite sides of the fuel cell assembly **502**. The first end plate **578** may be in contact with the anode **506** of the first fuel cell **582**, and the second end plate **580** may be in contact with the cathode **508** of the last fuel cell **586**.

In exemplary embodiments, the coolant cell sub-unit **516** may be collectively formed by the plurality of unit-cells **590**, the cathode cell sub-unit **514** may be collectively formed by the plurality of unit-cells **591**, and the anode cell sub-unit **518** may be collectively formed by the plurality of unit-cells **593**. In many embodiments, the anode cell sub-unit **518** and the cathode cell sub-unit **514** may be formed from the same type of unit-cell, such that the anode cell sub-unit **518** and the cathode cell sub-unit **514** are substantially the same component disposed on opposite sides of the coolant cell sub-unit **516**. In exemplary embodiments, each unit-cell in the plurality of unit-cells **590**, **591**, **593** may include an outer surface **630** (e.g., an exterior surface) and may define an internal volume **636**, **638**, **640** that extends in a plurality of directions (e.g., the vertical direction V, the longitudinal direction L, and the transverse direction T described below) between a plurality of openings **642**, **644**, **646** defined on the respective outer surface **630**. Additionally, each unit-cell in the plurality of unit-cells **590**, **591**, **593** may be disposed adjacent to (and in contact with) a neighboring unit-cell in the plurality of unit-cells **590**, **591**, **593** such that the plurality of unit-cells **590**, **591**, **593** collectively define the one or more channels **515**, **534**, **556**.

For example, each unit-cell **590** in the plurality of unit-cells **590** of the coolant cell sub-unit **516** may be disposed adjacent to (e.g., in contact with and fixedly coupled to) a neighboring unit-cell **590** in the plurality of unit-cells **590** of the coolant cell sub-unit **516**, such that the plurality of unit-cells **590** of the coolant cell sub-unit **516** collectively define the coolant channel **556**. Similarly, each unit-cell **591** in the plurality of unit-cells **591** of the cathode cell sub-unit **514** may be disposed adjacent to (e.g., in contact with and fixedly coupled to) a neighboring unit-cell **591** in the plurality of unit-cells **591** of the cathode cell sub-unit **514**, such that the plurality of unit-cells **591** of the cathode cell sub-unit **514** collectively define the oxidant channel **515**. Likewise, each unit-cell **593** in the plurality of unit-cells **593** of the anode cell sub-unit **518** may be disposed adjacent to (e.g., in contact with and fixedly coupled to) a neighboring unit-cell **593** in the plurality of unit-cells **593** of the anode cell sub-unit **518**, such that the plurality of unit-cells **593** of the anode cell sub-unit **518** collectively define the fuel channel **534**.

In exemplary embodiments, at least one opening of the plurality of openings **642**, **644**, **646** of each unit-cell in the plurality of unit-cells **590**, **591**, **593** may align with a neighboring opening of the plurality of openings **642**, **644**, **646** in the neighboring unit-cell of the plurality of unit-cells **590**, **591**, **593** such that the internal volume **636**, **638**, **640** of each unit-cell of the plurality of unit-cells **590**, **591**, **593** collectively define the one or more channels **515**, **534**, **556**. For example, at least one opening **642** of the plurality of openings **642** of each unit-cell **590** in the coolant cell sub-unit **516** may align with a neighboring opening **642** in a neighboring unit-cell **590** in the coolant cell sub-unit **516**, such that the internal volumes **636** of the plurality of unit-cells **590** in the coolant cell sub-unit **516** collectively define the coolant channel **556**. Similarly, at least one opening **644** of the plurality of openings **644** of each unit-cell **591** in the cathode cell sub-unit **514** may align with a neighboring opening **644** in a neighboring unit-cell **591** in the cathode cell sub-unit **514**, such that the internal volumes **638** of the plurality of unit-cells **591** in the cathode cell sub-unit **514** collectively define the oxidant channel **515**. Likewise, at least one opening **646** of the plurality of openings **646** of each unit-cell **593** in the anode cell sub-unit **518** may align with a neighboring opening **646** in a neighboring unit-cell **593** in the anode cell sub-unit **518**, such that the internal volumes **640** of the plurality of unit-cells **593** in the anode cell sub-unit **518** collectively define the fuel channel **534**.

The multidirectional internal volumes **636**, **638**, **640** of each unit-cell **590**, **591**, **593** advantageously increases the thermal distribution and heat transfer efficiency of the entire bipolar separator plate **512**, thereby extending the hardware life of the bipolar separator plate **512** and increasing the efficiency of the fuel cell assembly **502**.

In many embodiments, the bipolar separator plate **512** described herein may be integrally formed as a single component. That is, each of the subcomponents, e.g., the cathode cell sub-unit **514**, the coolant cell sub-unit **516**, and the anode cell sub-unit **518**, and any other subcomponent of the bipolar separator plate **512** (such as the plurality of unit-cells **590**, **591**, **593**), may be manufactured together as a single body or object. In exemplary implementations, this may be done by utilizing an additive manufacturing system and method, such as direct metal laser sintering (DMLS), direct metal laser melting (DMLM), or other suitable additive manufacturing techniques. In other embodiments, other manufacturing techniques, such as casting or other suitable techniques, may be used. In this regard, by utilizing additive manufacturing methods, the bipolar separator plate **512** may be integrally formed as a single piece of continuous metal and may thus include fewer sub-components and/or joints compared to prior designs. The integral formation of the bipolar separator plate **512** through additive manufacturing may advantageously improve the overall assembly process. For example, the integral formation reduces the number of separate parts that are assembled, thus reducing associated time and overall assembly costs. Additionally, existing issues with, for example, leakage, joint quality between separate parts, and overall performance may advantageously be reduced.

Referring now to FIG. **7**, a fuel cell assembly **502** having one or more fluid connections is illustrated in accordance with embodiments of the present disclosure. In exemplary embodiments, the one or more channels **515**, **534**, **556** may include an oxidant channel **515** defined in a cathode cell sub-unit **514** of the one or more fuel cell sub-units, a coolant channel **556** defined in a coolant cell sub-unit **516** of the one or more fuel cell sub-units, and a fuel channel **556** defined in an anode cell sub-unit **518** of the one or more fuel cell sub-units. In various embodiments, the oxidant channel **515**, the coolant channel **556**, and the fuel channel **534** are fluidly isolated from one another. For example, the cathode cell sub-unit **514** and the anode cell sub-unit **518** may each include a solid wall portion **598** that contacts the coolant cell sub-unit **516** to fluidly isolate the one or more channels **515**, **534**, **556**. Particularly, the coolant cell sub-unit **516** may be disposed between the solid wall portion **598** of the cathode cell sub-unit **514** and the solid wall portion **598** of the anode cell sub-unit **518**. The oxidant channel **515** may be at least partially defined by a cathode **508** in the plurality of fuel cells **504**, such that the oxidant channel **515** is defined collectively by the cathode **508** and the cathode cell sub-unit **514**. Similarly, the fuel channel **534** may be at least partially defined by an anode **506** in the plurality of fuel cells **504**, such that the fuel channel **534** is collectively defined by the anode **506** and the anode cell sub-unit **518**.

As shown in FIG. **7**, each oxidant channel **515** may be fluidly coupled to an oxidant circuit **600**. The oxidant circuit **600** may include an oxidant inlet **602** having an oxidant inlet manifold **604** that distributes an oxidant to a respective oxidant channel **515** in the fuel cell assembly **502**. Additionally, the oxidant circuit **600** may include an oxidant outlet **606** having an outlet manifold **608**. Similarly, the fuel channel **534** may be fluidly coupled to a fuel circuit **610**. The fuel circuit **610** may include a fuel inlet **612** having a fuel inlet manifold **614** that distributes a fuel to a respective fuel channel **534** in the fuel cell assembly **502**. Additionally, the fuel circuit **610** may include a fuel outlet **616** having an outlet manifold **618**. Furthermore, each coolant channel **556** may be fluidly coupled to a coolant circuit **620**. The coolant circuit **620** may include a coolant inlet **622** having a coolant inlet manifold **624** that distributes an oxidant to a respective coolant channel **556** in the fuel cell assembly **502**. Additionally, the coolant circuit **620** may include a coolant outlet **626** having an outlet manifold **628**. The fuel and air stream are in similar flow direction to ensure effective operation of the fuel cell. For example, the fuel and air stream may flow in a first flow direction. The coolant flow can either be in counterflow (opposite) direction, co-flow (same) direction, or in cross flow (perpendicular) direction with the fuel and air flow direction. In this way, the coolant flow may flow in a second flow direction that is either the same as the first flow direction or different than the first flow direction. When the coolant flow is in crossflow direction with the fuel and air flows (i.e. coolant flows into/out of the page in FIG. **7**), the coolant inlet and outlet manifolds would be perpendicular to the inlet and outlet manifold of the fuel and air stream (not illustrated). The different flow configurations may be used based on requirements for the fuel cell assembly cooling load, compactness, allowable coolant pressure-drop, etc.

As shown by the arrows in FIG. **7** (which indicate flow direction of the fluids in each circuit), oxidants (such as air or other oxidants) may flow through the oxidant channel **515** in a first flow direction. Fuel may flow through the fuel channel **534** in the first flow direction, such that the fuel in the fuel channel **534** and the oxidants in the oxidant channel **515** flow in the same direction (e.g., co-flow). In various embodiments, coolant may flow through the coolant channel **556** in a second flow direction. The second flow direction may be the same or different than the first flow direction. For example, the second flow direction may be one of a countercurrent flow direction (e.g., 180° different than the first flow direction), a co-flow direction (e.g., the same direction as the first flow direction), or cross-flow direction (e.g., 90° different than the first flow direction).

Referring now to FIGS. **8** and **9**, various aspects of a bipolar separator plate **512** are illustrated in accordance with an embodiment of the present disclosure. For example, FIG. **8** illustrates a perspective view of the bipolar separator plate **512**. FIG. **9** illustrates a perspective partially exploded view of the bipolar separator plate **512**, in which the coolant cell sub-unit **516** is separated from an electrode cell sub-unit **517**. The electrode cell sub-unit **517** may be representative of either (or both) of the anode or cathode cell sub-units **514** or **518** described above.

As shown in FIG. **8**, the bipolar separator plate **512** may define a cartesian coordinate system having a vertical direction V, a longitudinal direction L, and a transverse direction T mutually perpendicular to one another. The bipolar separator plate **512** may be stacked with unit-cells vertically, longitudinally, and transversely. For example, the coolant cell sub-unit **516** may include a plurality of rows of unit-cells stacked together along each of the vertical direction V, the longitudinal direction L, and the transverse direction T. In some embodiment, as shown, the cathode cell sub-unit **514** and the anode cell sub-unit **518** may each include a plurality of rows of unit-cells stacked together along each of the vertical direction V and the transverse direction T, but the cathode cell sub-unit **514** and the anode cell sub-unit **518** may each only include a singular row of unit-cells stacked along the longitudinal direction L. In many embodiments, the cathode cell sub-unit **514** and the anode cell sub-unit **518** may each include a solid wall portion **598** that contacts the coolant cell sub-unit **516** to fluidly isolate the one or more channels **515**, **534**, **556**. Particularly, the coolant cell sub-unit **516** may be disposed between the solid wall portion **598** of the cathode cell sub-unit **514** and the solid wall portion **598** of the anode cell sub-unit **518**.

As shown in FIG. **9**, the electrode cell sub-unit **517** may partially define a channel **688** (which may be either the oxidant channel **515** or the fuel channel **534** described above depending on the electrode that the electrode cell sub-unit **517** is placed in contact with). For example, if the electrode cell sub-unit **517** is positioned in contact with the anode **506**, then the anode **506** and the electrode cell sub-unit **517** may collectively define the fuel channel **534**. Likewise, if the electrode cell sub-unit **517** is positioned in contact with a cathode **508**, then the cathode **508** and the electrode cell sub-unit **517** may collectively define the oxidant channel **515**. As shown in FIG. **9**, the channel **688** may include vertically extending portions **690** and transversely extending portions **692**. For example, each of the vertically extending portions **690** of the channel **688** may extend along a vertical axis **691** without interruption (i.e., no blockages or other impediments) from a top of the electrode cell sub-unit **517** to a bottom of the electrode cell sub-unit **517**. Similarly, each of the transversely extending portions **692** may extend along a transverse axis **693** without interruption from a first end to a second end of the electrode cell sub-unit **517**.

FIG. **10** illustrates a perspective view of a unit-cell **590** (e.g., a single-fluid unit-cell) in the plurality of unit-cells **590** that collectively make up the coolant cell sub-unit **516** of the bipolar separator plate **512**. FIG. **11** illustrates a cross-sectional perspective view of the unit-cell **590** from along the line **11-11** shown in FIG. **10**. As shown in FIGS. **10** and **11**, the unit-cell **590** may be shaped as a polyhedron having a plurality of side surfaces **652** and a plurality of corners **654** (or vertices) defined at junctions between the plurality of side surfaces **652**. In exemplary embodiments, as shown, the unit-cell **590** may be shaped as a cuboid, rectangular prism, or a cube, such that the unit-cell **590** has six side surfaces **652** and eight corners **654**. Each side surface **652** may be perpendicular to four other side surfaces **652** and parallel to one other side surface **652**. The plurality of side surfaces **652** may include a top side surface **656** and a bottom side surface **658** spaced apart from one another in the vertical direction V. The plurality of side surfaces **652** may further include a first side surface **660** and a second side surface **662** spaced apart from one another in the longitudinal direction L. The plurality of side surfaces **652** may further include a third side surface **664** and a fourth side surface **666** spaced apart from one another in the transverse direction T.

In exemplary embodiments, the unit-cell **590** may define a plurality of openings **642** and an internal volume **636** extending along the longitudinal direction L, the vertical direction V, and the transverse direction T between each of the openings **642** on two opposite side surfaces **652**. For example, each opening **642** of the plurality of openings **642** may be defined on a respective side surface **652**. Each of the openings **642** may be shaped as a circle; however, in other embodiments, the openings **642** may be shaped as an oval, square, rectangle, or other shapes. Particularly, the openings **642** may each be defined on the center of a respective side surface **652** (e.g., the side surface **652** may be shaped as a square and the opening **642** may be centered on the square).

As shown in FIGS. **10** and **11**, each unit-cell **590** may defines a longitudinal centerline **668**, a transverse centerline **670**, and a vertical centerline **672** each extending through a centroid **673** (e.g., where all the centerlines intersect) of the unit-cell **590** and mutually orthogonal to one another. For example, the longitudinal centerline **668** may extend in the longitudinal direction L through the centroid **673** (i.e., geometric center) of the unit-cell **590**, the transverse centerline **670** may extend in the transverse direction T through the centroid **673** of the unit-cell **590**, and the vertical centerline **672** may extend in the vertical direction V through the centroid **673** of the unit-cell **590**. In exemplary embodiments, as shown, the internal volume **636** may extend along the longitudinal centerline **668**, the transverse centerline **670**, and the vertical centerline **672** between respective openings **642** of the plurality of openings **642**. Particularly, the internal volume **636** may include a cylindrically shaped portion extending along each of the centerlines **668**, **670**, **672**. For example, the internal volume **636** may include a first cylindrically shaped portion that extends along the longitudinal centerline **668** between two openings **642** on opposite side surfaces **652**. Further, the internal volume **636** may include a second cylindrically shaped portion that extends along the transverse centerline **670** between two openings **642** on opposite side surfaces **652**. Furthermore, the internal volume **636** may include a third cylindrically shaped portion that extends along the vertical centerline **672** between two openings **642** on opposite side surfaces **652**.

The unit-cell **590** may define three cylindrically shaped passages that each extend through the centroid **673** of the cell, extend mutually perpendicularly to one another, and collectively define the internal volume **636**. For example, as shown in FIGS. **10** and **11**, the internal volume **636** may extend along the longitudinal centerline **668** from a first opening defined on the first side surface **660**, through a centroid **673** of the unit-cell **590**, to a second opening defined on the second side surface **662**. Additionally, the internal volume **636** may extend along the transverse centerline **670** from a third opening defined on the third side surface **664**, through the centroid **673** of the unit-cell **590**, to a fourth opening defined on the fourth side surface **666**. Furthermore, the internal volume **636** may extend along the vertical centerline **672** from a fifth opening defined on a bottom side surface **656**, through the centroid **673** of the unit-cell, to a sixth opening defined on a top side surface **658**.

As shown in FIG. **11**, the unit-cell **590** may include a plurality of edge portions **674** each extending between two corners **654** of the plurality of corners **654**. As shown in FIG. **11**, the edge portions **674** may each have a generally rectangular shaped cross-sectional shape.

FIG. **12** illustrates a unit-cell **650** (e.g., a single-fluid unit cell) from the electrode cell sub-unit **517**. The unit-cell **650** may be representative of either or both of the unit-cell **591** or the unit-cell **593** described above, such that the unit-cell **650** may be included in the cathode cell sub-unit **514** and/or the anode cell sub-unit **518**. The unit-cell **650** may include a solid side **676** and a plurality of side surfaces **678** each extending perpendicularly from the solid side **676**. When implemented in a fuel cell sub-unit, such as the electrode cell sub-unit **517**, the solid sides **676** of the unit-cells **650** may collectively define the solid wall portion **598**. As used herein "solid side" may include a wall or surface that does not include any openings, voids, or cavities (i.e., the surface is impermeable). When assembled, the solid side **676** of the unit-cell **650** may contact one or more unit-cells **590** in the coolant cell sub-unit **516** to partially define the coolant channel **556**. The unit-cell **650** may include four edge portions **680** each extending from the solid side **676** to a free end **682**. The free end **682** may have a generally rectangular or square cross-sectional shape. When assembled, each of the free ends **682** may contact (directly contact) an electrode (e.g., the anode **506** or the cathode **508**), such that the electrode and the plurality of unit-cells **650** define a channel (i.e., either the fuel channel or the oxidant channel).

Generally, as shown in FIG. **12**, the unit-cell **650** may generally be shaped as a rectangular prism and may define an internal volume **684** that includes two semi-cylindrical portions **686**, **687**. The first semi-cylindrical portion **686** may extend generally vertically from a first semi-circular opening to a second semi-circular opening, and the second semi-cylindrical portion **687** may extend generally transversely from a third semi-circular opening to a fourth semi-circular opening.

Referring now to FIGS. **13** and **14**, various aspects of a bipolar separator plate **512** are illustrated in accordance with another embodiment of the present disclosure. For example, FIG. **13** illustrates a perspective view of the bipolar separator plate **512**. FIG. **14** illustrates a perspective partially exploded view of the bipolar separator plate **512**, in which the coolant cell sub-unit **516** is separated from an electrode cell sub-unit **517**. The electrode cell sub-unit **517** may be representative of either (or both) of the anode or cathode cell sub-units **514** or **518** described above.

As shown in FIG. **14**, the electrode cell sub-unit **517** may partially define a channel **688** (which may be either the oxidant channel **515** or the fuel channel **534** described above depending on the electrode that the electrode cell sub-unit **517** is placed in contact with). For example, if the electrode cell sub-unit **517** is positioned in contact with the anode **506**, then the anode **506** and the electrode cell sub-unit **517** may collectively define the fuel channel **534**. Likewise, if the electrode cell sub-unit **517** is positioned in contact with a cathode **508**, then the cathode **508** and the electrode cell sub-unit **517** may collectively define the oxidant channel **515**. As shown in FIG. **14**, the channel **688** may include a plurality of oblique extending portions **694**. Each of the oblique extending portions **694** may extend generally oblique to both the vertical direction V and the transverse direction T. For example, each of the oblique extending portions **694** of the channel **688** of the electrode cell sub-unit **517** may extend without interruption along an oblique axis **695**.

FIG. **15** illustrates a perspective view of a unit-cell **590** (e.g., a single-fluid unit-cell) in the plurality of unit-cells **590** that collectively make up the coolant cell sub-unit **516** of the bipolar separator plate **512**. FIG. **16** illustrates a cross-sectional perspective view of the unit-cell **590** from FIG. **15** along the line **16-16**. As shown in FIGS. **15** and **16**, the unit-cell **590** may be shaped as a polyhedron having a plurality of side surfaces **652** and a plurality of corners **654** (or vertices) defined at junctions between the plurality of side surfaces **652**. In exemplary embodiments, as shown, the unit-cell **590** may be shaped as a cuboid, rectangular prism, or a cube, such that the unit-cell **590** has six side surfaces **652** and eight corners **654**. Each side surface **652** may be perpendicular to four other side surfaces **652** and parallel to one other side surface **652**. The plurality of side surfaces **652** may include a top side surface **656** and a bottom side surface **658** spaced apart from one another in the vertical direction V. The plurality of side surfaces **652** may further include a first side surface **660** and a second side surface **662** spaced apart from one another in the longitudinal direction L. The plurality of side surfaces **652** may further include a third side surface **664** and a fourth side surface **666** spaced apart from one another in the transverse direction T.

In exemplary embodiments, the unit-cell **590** may define a plurality of openings **642** and an internal volume **636** extending in a plurality of directions between each of the openings **642** on two adjacent side surfaces **652**. For example, each opening **642** of the plurality of openings **642** may be defined on a respective side surface **652**. Each of the openings **642** may be shaped as a circle; however, in other embodiments, the openings **642** may be shaped as an oval, square, rectangle, or other shapes. Particularly, the openings **642** may each be defined on the center of a respective side surface **652** (e.g., the side surface **652** may be shaped as a square and the opening **642** may be centered on the square).

As shown in FIGS. **15** and **16**, each unit-cell **590** may defines a longitudinal centerline **668**, a transverse centerline **670**, and a vertical centerline **672** each extending through a centroid **673** (e.g., where all the centerlines intersect) of the unit-cell **590** and mutually orthogonal to one another. For example, the longitudinal centerline **668** may extend in the longitudinal direction L through the centroid **673** (i.e., geometric center) of the unit-cell **590**, the transverse centerline **670** may extend in the transverse direction T through the centroid **673** of the unit-cell **590**, and the vertical centerline **672** may extend in the vertical direction V through the centroid **673** of the unit-cell **590**. In exemplary embodiments, as shown, the internal volume **636** may extend at least partially along the longitudinal centerline **668**, the transverse centerline **670**, and the vertical centerline **672** between respective openings **642** of the plurality of openings **642** without extending through the centroid **673** of the unit-cell **590**.

As shown in FIG. **16**, the unit-cell **590** may include a plurality of edge portions **675** each extending between two corners **654** of the plurality of corners **654**. As shown in FIG. **16**, the edge portions **675** may each have a triangular shaped cross-sectional shape.

Additionally, as shown in FIG. **16** the centroid **673** of the unit-cell **590** may be solid and partially define the internal volume **636**. For example, the centroid **673** of the unit-cell **590** may be disposed on a solid center portion **696**. The solid center portion **696** may have a generally rectangular or square shaped cross-section. In many embodiments, as shown in FIG. **16**, the internal volume **636** may further include a plurality of cylindrically shaped portions **698**. Each of the cylindrically shaped portions **698** may extend generally oblique to each of the vertical direction V, the longitudinal direction L, and the transverse direction T of the unit-cell **590**. For example, each of the cylindrically shaped portions **698** may extend between the solid center portion **696** and the edge portion **675**. Particularly, as shown in FIG. **16**, each of the cylindrically shaped portions **698** may extend between a straight edge of the solid center portion **696** and a hypotenuse of the edge portion **675**.

FIG. **17** illustrates a unit-cell **650** (e.g., a single-fluid unit-cell) from the electrode cell sub-unit **517**. The unit-cell **650** may be representative of either or both of the unit-cell **591** or the unit-cell **593** described above, such that the unit-cell **650** may be included in the cathode cell sub-unit **514** and/or the anode cell sub-unit **518**. The unit-cell **650** may include a solid side **676** and a plurality of side surfaces **678** each extending perpendicularly from the solid side **676**. As used herein "solid side" may include a wall or surface that does not include any openings, voids, or cavities (i.e., the surface is impermeable). When assembled, the solid side **676** of the unit-cell **650** may contact one or more unit-cells **590** in the coolant cell sub-unit **516** to partially define the coolant channel **556**. The unit-cell **650** may include four edge portions **681** each extending from the solid side **676** to a free end **683**. The free end **683** may have a generally triangular cross-sectional shape. When assembled, each of the free ends **683** may contact (directly contact) an electrode (e.g., the anode **506** or the cathode **508**), such that the electrode and the plurality of unit-cells **650** define a channel (i.e., either the fuel channel or the oxidant channel).

As shown in FIG. **17**, the unit-cell **650** may generally be shaped as a rectangular prism and may define an internal volume **685** that includes four semi-cylindrical portions **700** each extending between opening portions **702**. The unit-cell may include a solid center portion **685** shaped as a rectangular prism (e.g., a square) having four sides and four corners. Each of the opening portions **702** may be defined between two edge portions **681** and a corner of the solid center portion **685**, and each of the semi-cylindrical portions **700** may extend between two opening portions **702** oblique to each of the vertical direction V and the longitudinal direction L. For example, each of the semi-cylindrical portions **700** may be defined by a side of the solid center portion **685** and a hypotenuse side of an edge portion **681**.

Referring now to FIGS. **18** through **20**, various aspects of a bipolar separator plate **512** is illustrated in accordance with another embodiment of the present disclosure. For example, FIG. **18** illustrates a perspective view of a coolant cell sub-unit **516** of a bipolar separator plate **512**. FIG. **19** illustrates a perspective view of a unit-cell **590** (e.g., a single-fluid unit-cell) in the plurality of unit-cells **590** that collectively make up the coolant cell sub-unit **516** of the bipolar separator plate **512**. FIG. **20** illustrates a cross-sectional perspective view of the unit-cell **590** from FIG. **19** from along the diagonal section line **20-20** shown in FIG. **19**.

As shown in FIGS. **18** through **20**, the unit-cell **590** may be shaped as a polyhedron having a plurality of side surfaces **652** and a plurality of corners **654** (or vertices) defined at junctions between the plurality of side surfaces **652**. In exemplary embodiments, as shown, the unit-cell **590** may be shaped as a cuboid, rectangular prism, or a cube, such that the unit-cell **590** has six side surfaces **652** and eight corners **654**. Each side surface **652** may be perpendicular to four other side surfaces **652** and parallel to one other side surface **652**. The plurality of side surfaces **652** may include a top side surface **656** and a bottom side surface **658** spaced apart from one another in the vertical direction V. The plurality of side surfaces **652** may further include a first side surface **660** and a second side surface **662** spaced apart from one another in the longitudinal direction L. The plurality of side surfaces **652** may further include a third side surface **664** and a fourth side surface **666** spaced apart from one another in the transverse direction T.

In exemplary embodiments, the unit-cell **590** may define a plurality of openings **643** and an internal volume **636** extending in a plurality of directions between each of the openings **643**. For example, each opening **643** of the plurality of openings **643** may be defined on a respective corner **654**. Each of the openings **643** may be shaped as a circle; however, in other embodiments, the openings **642** may be shaped as an oval, square, rectangle, or other shapes. In exemplary embodiments, as shown, the at least one corner **654** of the plurality of corners **654** may define a chamfered end **704** that forms part of a sphere. In such embodiments, as shown, each of the openings **643** may be disposed on a respective chamfered end **704** (e.g., centered on the chamfered end). The chamfered end may form $1/8^{th}$ of sphere, such that when eight unit-cells are disposed adjacent to one another, the eight chamfered ends may collectively define an entire sphere. Alternatively stated, when four unit-cells are disposed adjacent to one another (as shown in FIG. **18**), the four chamfered ends may collectively define a half sphere.

As shown in FIG. **20**, the internal volume **636** may include a plurality of cylindrically shaped portions **706** each extending between diagonally opposite corners **654** (e.g., diametrically opposed corners **654**). of the plurality of corners **654**. For example, each of the cylindrically shaped portions **706** may extend diagonally (or oblique) to the vertical direction V, the longitudinal direction L, and the transverse direction between a first corner and a second corner opposite the first corner. Each of the cylindrically shaped portions **706** may extend through the centroid of the unit-cell **590**. Particularly, the internal volume **636** may further include a spherical center **708**, and each of the cylindrically shaped portions **706** may extend from a respective corner **654** to the spherical center **708** of the internal volume **636**.

Further aspects are provided by the subject matter of the following clauses:

A fuel cell assembly comprising: a plurality of fuel cells; and a bipolar separator plate disposed between each fuel cell of the plurality of fuel cells, the bipolar separator plate comprising: one or more fuel cell sub-units each comprising a plurality of unit-cells, each unit-cell in the plurality of unit-cells having an outer surface and defining an internal volume that extends in multiple directions between a plurality of openings defined on the outer surface, and wherein each unit-cell in the plurality of unit-cells is disposed adjacent to a neighboring unit-cell in the plurality of unit-cells such that the plurality of unit-cells collectively define one or more channels.

The fuel cell assembly as in one or more of these clauses, wherein at least one opening of the plurality of openings of each unit-cell in the plurality of unit-cells aligns with a neighboring opening of the plurality of openings in the neighboring unit-cell of the plurality of unit-cells such that the internal volume of each unit-cell of the plurality of unit-cells collectively define the one or more channels.

The fuel cell assembly as in one or more of these clauses, wherein the one or more channels comprises an oxidant channel defined in a cathode cell sub-unit of the one or more fuel cell sub-units, a coolant channel defined in a coolant cell sub-unit of the one or more fuel cell sub-units, and a fuel channel defined in an anode cell sub-unit of the one or more fuel cell sub-units, and wherein the oxidant channel, the coolant channel, and the fuel channel are fluidly isolated from one another.

The fuel cell assembly as in one or more of these clauses, wherein each fuel cell of the plurality of fuel cells comprises an anode, a cathode, and a solid electrolyte disposed between the anode and the cathode, wherein the oxidant channel is at least partially defined by the cathode of a first fuel cell in the plurality of fuel cells, and wherein the fuel channel is at least partially defined by the anode of a second fuel cell in the plurality of fuel cells.

The fuel cell assembly as in one or more of these clauses, wherein each unit-cell of the plurality of unit-cells is shaped as a polyhedron having a plurality of side surfaces and a plurality of corners defined at junctions between the plurality of side surfaces.

The fuel cell assembly as in one or more of these clauses, wherein each opening of the plurality of openings is defined on a respective side surface.

The fuel cell assembly as in one or more of these clauses, wherein each unit-cell of the plurality of unit-cells defines a longitudinal centerline, a transverse centerline, and a vertical centerline each extending through a centroid of the unit-cell and mutually orthogonal to one another, and wherein the internal volume extends along the longitudinal centerline, the transverse centerline, and the vertical centerline between each of the openings on two opposite side surfaces.

The fuel cell assembly as in one or more of these clauses, wherein the internal volume extends between each of the openings on adjacent side surfaces.

The fuel cell assembly as in one or more of these clauses, wherein each opening of the plurality of openings is defined on a corner of the plurality of corners and wherein the internal volume includes a plurality of cylindrically shaped portions each extending between diagonally opposite corners of the plurality of corners and wherein at least one corner of the plurality of corners defines a chamfered end forming part of a sphere.

The fuel cell assembly as in one or more of these clauses, wherein the oxidant channel is fluidly coupled to an oxidant inlet manifold and an oxidant outlet manifold, the fuel channel is fluidly coupled to a fuel inlet manifold and a fuel outlet manifold, and the coolant channel is fluidly coupled to a coolant inlet manifold and a coolant outlet manifold.

The fuel cell assembly as in one or more of these clauses, wherein oxidants flow through the oxidant channel in a first flow direction, wherein fuel flows through the fuel channel in the first flow direction, and wherein coolant flows through the coolant channel in a second flow direction, and wherein the second flow direction is one of the same or different than the first flow direction.

The fuel cell assembly as in one or more of these clauses, wherein a centroid of each unit-cell of the plurality of unit-cells is solid and partially defines the internal volume and wherein the internal volume comprises a plurality of cylindrically shaped portions.

A propulsion system comprising: a turbomachine comprising a compressor section and a combustion section; and a fuel cell assembly comprising: a plurality of fuel cells; and a bipolar separator plate disposed between each fuel cell of the plurality of fuel cells, the bipolar separator plate including a cathode cell sub-unit that defines an oxidant channel fluidly coupled to the compressor section, a coolant cell sub-unit that defines a coolant channel, and an anode cell sub-unit that defines a fuel channel fluidly coupled to the combustion section, wherein the oxidant channel, the coolant channel, and the fuel channel are fluidly isolated from one another.

The propulsion system as in one or more of these clauses, wherein the oxidant channel is at least partially defined by the cathode of a first fuel cell in the plurality of fuel cells, and wherein the fuel channel is at least partially defined by the anode of a second fuel cell in the plurality of fuel cells.

The propulsion system as in one or more of these clauses, wherein the oxidant channel comprises an oxidant inlet and an oxidant outlet, wherein the oxidant inlet is fluidly coupled to a low pressure compressor stage of the compressor section via a bleed air line, and wherein the oxidant outlet is fluidly coupled to one of a high pressure compressor stage of the compressor section via a cathode exhaust line or the combustion section.

The propulsion system as in one or more of these clauses, wherein the fuel channel comprises a fuel inlet and one or more outlets, wherein the fuel inlet fluidly is fluidly coupled a fuel supply line, and wherein the one or more outlets of the fuel channel is fluidly coupled to one of the combustion section or one or more turbine stage in the turbine section.

The propulsion system as in one or more of these clauses, wherein an air-to-air heat exchanger thermally couples the bleed air line and the cathode exhaust line, and wherein a fuel-to-fuel heat exchanger thermally couples the fuel supply line and the one or more fuel channel outlets.

The propulsion system as in one or more of these clauses, wherein the coolant channel is in fluid communication with a heat-sink heat exchanger in a closed cycle loop.

The propulsion system as in one or more of these clauses, wherein each fuel cell of the plurality of fuel cells comprises an anode, a cathode, and a solid electrolyte disposed between the anode and the cathode, wherein the oxidant channel is at least partially defined by the cathode of a first fuel cell in the plurality of fuel cells, and wherein the fuel channel is at least partially defined by the anode of a second fuel cell in the plurality of fuel cells.

The propulsion system as in one or more of these clauses, wherein the bipolar separator plate further comprises a plurality of unit-cells each having an outer surface, each unit-cell of the plurality of unit-cells defining an internal volume that extends in multiple directions between a plurality of openings defined on the outer surface, wherein each unit-cell in the plurality of unit-cells is disposed adjacent to a neighboring unit-cell in the plurality of unit-cells such that the plurality of unit-cells collectively define one or more channels, and wherein the one or more channels comprises the oxidant channel, the coolant channel, and the fuel channel.

This written description uses examples to disclose the present disclosure, including the best mode, and also to enable any person skilled in the art to practice the disclosure, including making and using any devices or systems and performing any incorporated methods. The patentable scope of the disclosure is defined by the claims, and may include other examples that occur to those skilled in the art. Such other examples are intended to be within the scope of the claims if they include structural elements that do not differ from the literal language of the claims, or if they include equivalent structural elements with insubstantial differences from the literal languages of the claims.

I claim:

1. A fuel cell assembly comprising:

a plurality of fuel cells; and

a bipolar separator plate disposed between each fuel cell of the plurality of fuel cells, the bipolar separator plate comprising:

one or more fuel cell sub-units each comprising a plurality of unit-cells, each unit-cell in the plurality of unit-cells having an outer surface and defining an internal volume that extends in a plurality of directions between a plurality of openings defined on the outer surface, and wherein each unit-cell in the plurality of unit-cells is disposed adjacent to a neighboring unit-cell in the plurality of unit-cells such that the plurality of unit-cells collectively define one or more channels.

2. The fuel cell assembly as in claim **1**, wherein at least one opening of the plurality of openings of each unit-cell in the plurality of unit-cells aligns with a neighboring opening of the plurality of openings in the neighboring unit-cell of the plurality of unit-cells such that the internal volume of each unit-cell of the plurality of unit-cells collectively define the one or more channels.

3. The fuel cell assembly as in claim **1**, wherein the one or more channels comprises an oxidant channel defined in a cathode cell sub-unit of the one or more fuel cell sub-units, a coolant channel defined in a coolant cell sub-unit of the one or more fuel cell sub-units, and a fuel channel defined in an anode cell sub-unit of the one or more fuel cell sub-units, and wherein the oxidant channel, the coolant channel, and the fuel channel are fluidly isolated from one another.

4. The fuel cell assembly as in claim **3**, wherein each fuel cell of the plurality of fuel cells comprises an anode, a cathode, and a solid electrolyte disposed between the anode and the cathode, wherein the oxidant channel is at least partially defined by the cathode of a first fuel cell in the plurality of fuel cells, and wherein the fuel channel is at least partially defined by the anode of a second fuel cell in the plurality of fuel cells.

5. The fuel cell assembly as in claim **4**, wherein the oxidant channel is fluidly coupled to an oxidant inlet manifold and an oxidant outlet manifold, the fuel channel is fluidly coupled to a fuel inlet manifold and a fuel outlet manifold, and the coolant channel is fluidly coupled to a coolant inlet manifold and a coolant outlet manifold.

6. The fuel cell assembly as in claim **5**, wherein oxidants flow through the oxidant channel in a first flow direction, wherein fuel flows through the fuel channel in the first flow direction, and wherein coolant flows through the coolant channel in a second flow direction, and wherein the second flow direction is one of the same or different than the first flow direction.

7. The fuel cell assembly as in claim **1**, wherein each unit-cell of the plurality of unit-cells is shaped as a polyhedron having a plurality of side surfaces and a plurality of corners defined at junctions between the plurality of side surfaces.

8. The fuel cell assembly as in claim **7**, wherein each opening of the plurality of openings is defined on a respective side surface.

9. The fuel cell assembly as in claim **8**, wherein each unit-cell of the plurality of unit-cells defines a longitudinal centerline, a transverse centerline, and a vertical centerline each extending through a centroid of the unit-cell and mutually orthogonal to one another, and wherein the internal volume extends along the longitudinal centerline, the transverse centerline, and the vertical centerline between each of the plurality of openings on two opposite side surfaces.

10. The fuel cell assembly as in claim **8**, wherein the internal volume extends between each of the plurality of openings on adjacent side surfaces.

11. The fuel cell assembly as in claim **7**, wherein each opening of the plurality of openings is defined on a corner of the plurality of corners and wherein the internal volume includes a plurality of cylindrically shaped portions each extending between diagonally opposite corners of the plurality of corners and wherein at least one corner of the plurality of corners defines a chamfered end forming part of a sphere.

12. The fuel cell assembly as in claim **1**, wherein a centroid of each unit-cell of the plurality of unit-cells is solid and partially defines the internal volume and wherein the internal volume comprises a plurality of cylindrically shaped portions.

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