Chapter

Clean and Sustainable Hydrogen-Electric Propulsion

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Abstract

For future hypersonic and supersonic flight, clean, sustainable and energy-efficient propulsion should be addressed in the general background of the sensational clean electric transition of aircraft. This chapter is to draw the attention of the research communities on the possible feasibilities and challenges of hydrogen-electric propulsion in hypersonic and supersonic flight. This chapter is structured with the following aspects, (1) general design and hybridisation concepts of hydrogen-electric propulsion for general aircraft and their hypersonic and supersonic considerations; (2) merits of hydrogen-electric propulsion on thermofluids process integrations; (3) potential merits of hydrogen-electric propulsion projected through thermofluids structural engineering and re-engineering; (4) storage options and their challenges in design and operation; and (5) reliability considerations.

Keywords: hydrogen, cryogenic, electric propulsion, fuel cells, system design, operation

1. Introduction

Hydrogen has been considered a very promising clean, sustainable energy source for a long time. In recent decades, it has come back into the limelight [1]. Due to the current world situation, accompanied by changes in the climate and the increase in the price of traditional fossil energy sources, aircraft urgently needs a new propulsion technology to reduce polluting emissions and lower fossil fuel consumption [2]. Hydrogen propulsion is, therefore, widely seen as a solution to the current situation because of its renewable nature and the effective reduction of carbon dioxide emissions [3]. There are currently four mainstream hydrogen propulsion: (1) all-electric fuel cell propulsion, (2) fuel cell propulsion and complementary direct-drive hydrogen turbines, (3) hydrogen-fuelled turbofan electric propulsion and (4) pure combustion propulsion [4]. The mission range of the aircraft still determines the efficiency of these concepts. In the medium to long range, fuel cells will be more advantageous [5]. However, fuel cells still face more challenges in being used as an aviation application. Because of its lower power-to-weight ratio, the system's complexity [6] and the inconvenience of hydrogen storage and waste heat management [7] are all issues that need to be addressed. However, current trends suggest that aircraft capable of full hydrogen fuel cell propulsion remains the ultimate goal of long-term research. The challenges related to the application of hydrogen fuel cells in aviation are described in detail in Section 3, along with current research and future perspectives.

2. Fuel cell principles

A fuel cell is an energy conversion device that converts chemical energy stored in fuels and oxidisers into electrical energy through a redox reaction based on electrochemical principles. The fuel cell itself does not store energy; it is, like the internal combustion engine, a device that converts chemical energy into other forms of energy using 'fuel'. An internal combustion engine produces heat by burning fuel, and thermodynamic energy is converted into kinetic energy. On the other hand, a fuel cell has electrical power through an electrochemical reaction, and the electrical energy produced can be converted into other energy as required, such as mechanical energy through an electric motor. In this respect, it is more like a battery with a fuel tank. However, unlike conventional batteries, it does not require charging time, only refuelling, and it could have a higher energy density than traditional batteries especially on the system level. And the device itself produces no noise or vibrations in the workshop, and this electrochemical reaction does not produce pollutants that are harmful to the climate [8].

2.1 Working principle

The fuel cell consists of four main components: the anode, the cathode, the electrolyte, and the external circuit. Fuel gas and oxidation gas are fed through the anode and cathode of the fuel cell separately. The fuel gas emits electrons at the anode, which are transferred to the cathode via an external circuit and combined with the oxidation gas to form ions. The ions migrate through the electrolyte to the anode under the influence of an electric field and react with the fuel gas, forming a circuit and generating an electric current. At the same time, the fuel cell generates some heat due to its electrochemical reaction and the cell's internal resistance. In addition to conducting electrons, the cathode and anode of the cell act as catalysts for redox reactions (**Figure 1**).

2.2 Fuel cell types

There are numerous classifications of fuel cells, commonly based on the type of electrolyte, including proton exchange membrane fuel cells (PEMFCs), alkaline fuel cells (AFCs), phosphoric acid fuel cells (PAFCs), molten carbonate fuel cells (MCFCs), and solid oxide fuel cells (SOFCs) [9]. In addition, different variants of these types have been developed, such as the direct methanol fuel cell (DMFC), which is based on LT-PEMFC but uses methanol and the high-temperature (HT-)PEMFC, in which the phosphoric acid is stabilised in a polymer membrane. Proton ceramic fuel cells (PCFCs) have many similarities to SOFC but use proton-conducting electrolyte materials [10].

The Proton Exchange Membrane Fuel Cell (PEMFC), also known as the Polymer Electrolyte Membrane Fuel Cell, was invented by General Electric in the late 1950s and used in NASA space missions [11]. The electrolyte is a very thin polymer membrane in this type of cell. This polymer membrane conducts protons but not electrons, thus ensuring ion exchange between the electrodes. Generally, proton exchange membrane fuel cells use platinum on carbon (Pt/C) as the catalyst for the cathode reaction (**Figure 2**).

The different membrane materials determine the specific conditions of use. LT-PEMFCs operate between 65°C and 85°C, which offers the possibility of using water

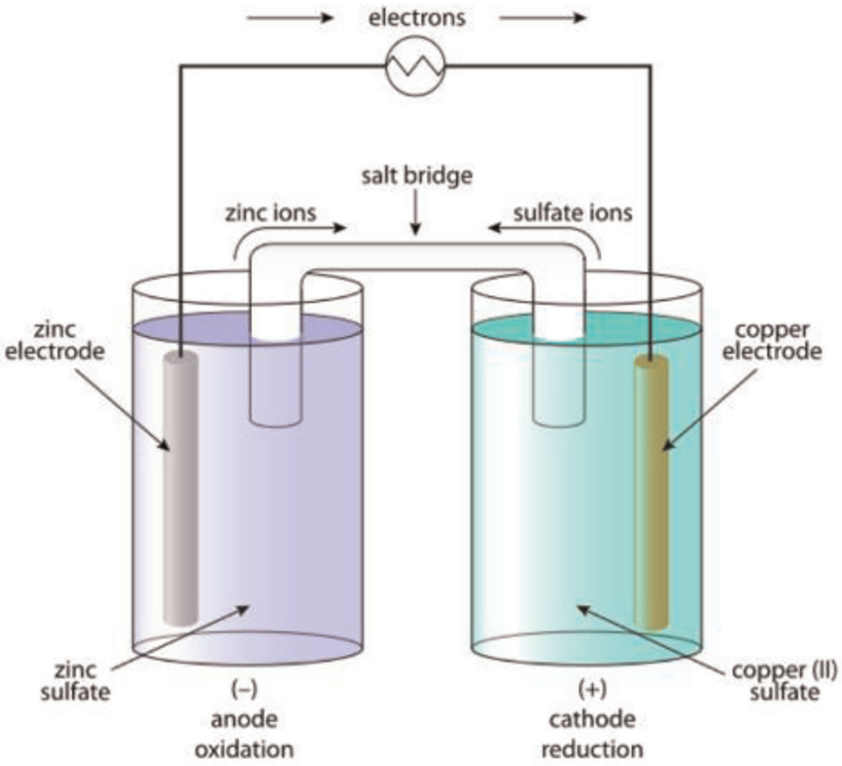


Figure 1.
Simplified schematic of the working principle of a fuel cell.

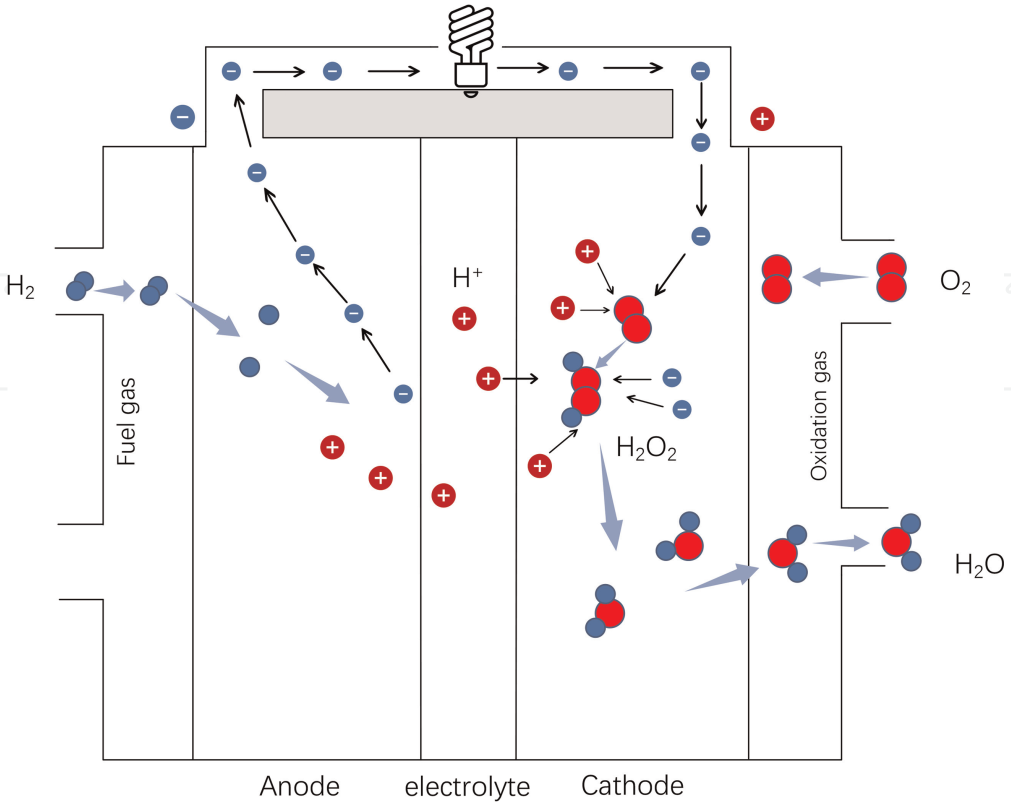


Figure 2.
Working principle of PEMFC.

cooling in the fuel cell cooling system. HT-PEMFCs operate between 140°C and 180°C, where the proton conductivity is high enough, and the polymer membrane remains chemically stable. Ceramic membranes used in SOFCs require temperatures of 500–1000°C to achieve sufficiently high ionic conductivity, depending on the electrolyte material and thickness. These operating temperatures determine the materials of the cell and system.

2.3 Fuel cell systems

As the chemical electromotive force of a fuel cell is well below 1 V, the clamping voltage and the electrical power generated can be increased by connecting several cells in series to make the fuel cell fit for everyday use. Each cell is separated by interconnected bipolar plates and sealed with gaskets, thus forming a fuel cell stack. By designing the bipolar plate structure, air and fuel can be evenly distributed within the cell, thus increasing the efficiency of the fuel cell. For low-temperature fuel cells where liquid cooling can be used, the passage of the coolant is also an essential part of the bipolar plate structure. (This is described in more detail in Section 3.2).

The fuel cell stack is the core part of the overall fuel cell system and is used to generate electricity. At the same time, to ensure the fuel cell stack's stability, other components must work together to supply the fuel, air, and coolant to the fuel cell stack in the correct operating environment. Depending on the operating environment, different parts are used, often referred to as BoP (Balance of Plant). These may include pumps, blowers, valves, heat exchangers, humidifiers, filters, chemical reactors, injectors, burners, gas purification, electric actuators, power converters, and everything else required for the operation of the fuel cell system.

2.4 Fuel cell characteristics

Different types of fuel cells have different physical characteristics, and it is crucial to select a suitable type of fuel cell for the best possible application in various fields. In 2009, the German Aerospace Centre (DLR) used a 16 kW high-temperature polymer electrolyte membrane fuel cell (HT-PEMFC) in an Antares motor glider for a test flight [12]. This system was upgraded with a 30 kW low-temperature polymer electrolyte exchange membrane fuel cell (LT-PEMFC). The experience from the appeal platform led to another successful human-crewed test flight in 2016 [13, 14]. Based on the application of fuel cells in aviation, the following section focuses on the characteristics of low-temperature polymer electrolyte membrane fuel cells (LT-PEMFC) and high-temperature polymer electrolyte membrane fuel cells (HT-PEMFC).

2.4.1 Lt-PEMFC

LT-PEMFC typically operates at temperatures between 65°C and 85°C. Its operating temperature is limited because it uses a solid polymer-acid membrane (usually PFSA) which conducts protons when wetted. The character of this hydrated membrane is such that the LT-PEMFC must be operated at a temperature below the boiling point of water. However, the operating temperature must be neither too low (below 65°C) to flood the polymer membrane with condensed water nor too high (above 85°C) to degrade the polymer membrane after dehydration [15]. In addition to the control of temperature, the management of water inside the fuel cell is also a crucial point. As the product of the hydrogen fuel cell reaction is water, if the water produced through the electrochemical reaction is not managed, too much water will soak into the electrodes, and the reactants will not be able to enter the reaction point. Dehydration of the polymer membrane will reduce ionic conductivity, so proper wetting of the polymer membrane is also required. The wetting of the membrane can be maintained by the water produced in the electrochemical reaction, and the excess water must be removed. To effectively control moisture in the fuel cell, individual gas diffusion layers can be designed into the cell structure to allow the gas reactants to participate more efficiently in the reaction and to direct the drainage of liquid water from the electrodes [16]. In addition, catalysts are required to increase the power density of the fuel cell to make it more efficient. In general, platinum is a perfect catalyst for electrochemical reactions, which can effectively improve the efficiency of fuel cells at low temperatures.

The LT-PEMFC system requires external air to participate in the reaction within the fuel cell, and an air compressor and air filter are usually used to supply air to the positive electrode. The air must be humidified before entering the positive electrode for reaction, either externally using a humidifier or internally within the fuel cell. The most common fuel for LT-PEMFC is hydrogen, which must be supplied at the correct pressure and temperature. For the reactions within the fuel cell to be more efficient, the hydrogen needs to be evenly distributed and adequately humidified. LT-PEMFCs are less tolerant to impurities contained in the fuel. This is mainly due to their relatively low operating temperature, which results in the solid adsorption of impurities on the platinum catalyst at the cathode. To prevent the accumulation of pollutants or contaminants in the fuel at the anode compartment, the fuel needs to be cleaned, which results in a slight loss of fuel (<1%) [17]. Hydrogen produced from natural gas carries sulphur and carbon monoxide, which can seriously affect the lifetime and performance of the LT-PEMF. Carbon dioxide can also have an adverse effect through the formation of carbon monoxide in the side reactions. Ammonia contamination can also lead to rapid degradation as well as membrane poisoning [18]. Most LT-PEMFC systems today use high-purity hydrogen to achieve a satisfactory lifetime with minimal loading of the platinum catalyst. In principle, however, LT-PEMFC can be operated on modified hydrocarbon fuels and cracked ammonia, provided that the concentrations of sulphur, ammonia and carbon monoxide are all well below 1 ppm. Fuel cells with fuel handling systems have been built and demonstrated [19].

Bipolar plates are another vital part of the LT-PEMFC system and integrate many functions. Bipolar plates are usually designed with a complex hydrodynamic structure that allows them to perform the tasks of homogeneous distribution of fuel and air, separation of air and fuel, management of water and heat inside the fuel cell and conduction of current. Bipolar plates can be made of graphite, metal or composite materials [20]. The choice of bipolar plate material can significantly impact the system's cost, functionality, lifetime, weight and size; for example, metal plates have a higher energy density but a shorter lifetime than graphite. The correct bipolar plate material for each application and an excellent structural design are essential.

The heat management of the LT-PEMFC is also an important aspect. Usually, a liquid cooling system is generally used, where the coolant is a mixture of water and anti-freeze additives. The liquid cooling system usually consists of a coolant pump and a radiator. To prevent ions in the coolant from causing leakage currents in the battery stack, a Raisin filter should also be installed to filter out the ions in the coolant.

2.4.2 HT-PEMFC

To solve the problems of LT-PEMFC, the first attempts have been made to increase the operating temperature of PEMFCs. Therefore, it is vital to change the performance of proton exchange membranes so that they can be used in a broader range of temperatures to meet the requirements of both low-temperature cold start and high performance after start-up, which will become an important direction in the future, that is, high-temperature proton exchange membrane fuel cells (HT-PEMFC).

High-temperature proton exchange membrane fuel cells (HT-PEMFCs), which operate at 100–200°C, have more key advantages than ordinary LT-PEMFCs: (1) the catalytic activity of the electrodes is highly active; (2) the catalyst has high resistance to impurity gases; (3) there is only gas phase mass transfer, which is simple and efficient [21]; (4) the hydrothermal management is simple; (5) the methanol permeation problem of methanol fuel cells is solved at high temperatures; (6) there is no need to consider separation and purification devices, and the reforming gas can be matched with online hydrogen production [17], making it possible to produce inexpensive liquid reforming hydrogen (e.g. methanol and acetic acid), and it is easy to store, transport and refill, etc.

As a core component of HT-PEMFC, the proton exchange membrane has an important impact on the lifetime and performance of the fuel cell, and the development of HT-PEM is of very positive significance. However, the technology has some unavoidable challenges: ① The proton conductivity of existing membranes at high temperatures in the temperature range of $100 \sim 200$°C is severely reduced, and the perfluorosulphonic acid proton exchange membranes currently in use are heavily dependent on the water content of At high temperatures, the water content in the membrane is low, and the proton carriage mechanism is severely weakened [22]; ② the stability of existing membranes at high temperatures is poor; ③ the performance degradation of fuel cells at high temperatures such as carbon corrosion and platinum dissolution will be exacerbated and durability and lifetime will be reduced [23]; ④ how to solve the compatibility between high-temperature membranes and catalysts [21].

LT-PEMFC systems are already widely used in many areas such as automotive, submarines, portable power supplies, specialist UAV areas and aircraft propulsion. Low operating temperatures offer many advantages, such as lower manufacturing costs, longer service life, high reliability and short start-up times. However, the design of the heat management system of the LT-PEMFC is also a significant challenge due to the operating temperature requirements. The energy-to-weight ratio of the LT-PEMFC is relatively low compared with fuel cell systems operating at higher temperatures. Still, the lower operating temperature and the materials used result in better service life and lower manufacturing costs.

3. Aviation PEM fuel cells

3.1 Aviation challenges

Civil aviation has always held a relatively large share of transport, especially for medium- and long-haul passenger transport, where the aviation industry holds a significant market share and is growing at a rate of around 3–4% per year. It also brings the problem of contributing to a large amount of greenhouse gas emissions, such as carbon dioxide. According to statistics today, the aviation industry accounts for 3% of global CO_2 emissions; by 2050, this will be 24% [4]. So how to reduce greenhouse gas emissions and achieve the goal of green flight has become an urgent issue for the aviation industry.

Hydrogen fuel cell systems are widely considered a new type of aviation propulsion system that can replace conventional fuel engines in the future. With its lower noise level, clean, sustainable energy (hydrogen) use and more efficient energy conversion, it is perfect for achieving the goal of truly green flight.

However, there are still many hurdles to overcome before hydrogen fuel cell systems can truly replace conventional fuel engines as the primary propulsion system in large civil aircraft. Firstly, to meet the power requirements of large passenger aircraft, fuel cell systems need to have an output of megawatts or even tens of megawatts. Take the DLR study as an example, a fuel-cell-powered four-seater aircraft (HY4) flown by DLR in 2016. This prototype was equipped with a hybrid power system consisting of an LT-PEMFC and a lithium-ion battery, with the LT-PEMFC acting as the primary output for the main power and the lithium-ion battery as an auxiliary for the aircraft during take-off and climb. The power system has an output of 80 kW [24], and the successful test flight of this aircraft represents the possibility of hydrogen fuel cells as a propulsion system for small manned aircraft. However, for application on large passenger aircraft, a large number of fuel cell units would need to be connected in series to achieve the required power.

To ensure the proper functioning of many fuel cell stacks connected in series, extremely high demands are placed on all system parts. The first is the thermal management of the entire system. As the LT-PEMFC is sensitive to the operating temperature requirements, an efficient and stable thermal management system is necessary. The thermal management of a fuel cell system of this power level is also a severe challenge. Due to the characteristics of the proton exchange membrane used in the LT-PEMFC, a water management system is also required to cope with a large number of cells in the fuel cell system to prevent each fuel cell from being dehydrated and flooded, causing power reduction or even failure, to ensure the regular operation of the whole system.

In aircraft design, weight is always a priority. The overall mass of the aircraft affects the energy consumption; the heavier the mass, the more fuel is required, and the more powerful the propulsion system needs to be to overcome the drag in flight and meet the required lift. This is why the lightweight design of fuel cell systems is also a challenge (**Figure 3**).

There are two ideas for reducing the weight of a fuel cell system. One is to reduce the number of fuel cell stacks, which means increasing the fuel cell unit's efficiency of the fuel cell unit, that is, increasing the power-to-weight ratio. The efficiency of the LT-PEMFC can be effectively improved by developing new types of proton exchange membranes, optimising the design of the flow field inside the fuel cell, etc. The second idea is to simplify and lighten the creation of the system, for example, by developing new fuel cell thermal management systems and using lightweight materials.

For large passenger aircraft, safety always comes first; each new aircraft must undergo rigorous certification before servicing. This requires a higher level of safety redundancy for essential systems. For fuel cell systems, increasing the redundancy of the fuel cell may significantly reduce the specific power of the entire system. A fuel cell system's specific power and lifetime are also considered essential factors for its application in aviation. While the specific power of fuel cells has been increasing over the last decade through the optimisation of components and manufacturing processes, the reliability required in aviation has been significantly less.

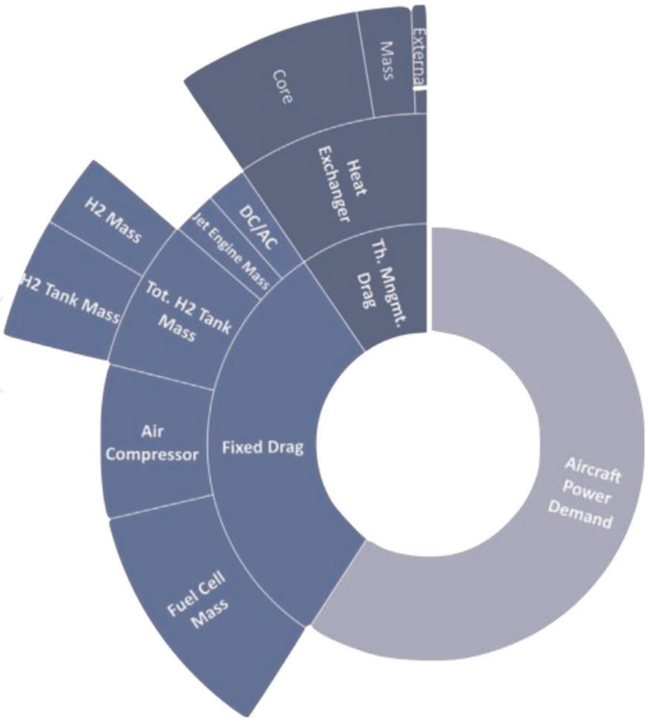


Figure 3.
The drag power of the hybrid PEMFC-jet.

In this chapter, the increase in specific power for sizeable civil aircraft fuel cell systems was sought from a different approach rather than focusing on the design of the fuel cell system.

3.2 Cooling systems

The cooling of a small LT-PEMFC can rely on air cooling, which is usually sufficient to keep the cell stack at a suitable temperature with the air involved in the reaction. However, when applied to megawatt-class LT-PEMFC systems, huge heat exchangers are required to maintain their operating temperature. This solution is not suitable for practical use. A large heat exchanger increases the air resistance of the aircraft in not only flight but also its weight is enormous, which adds additional drag to the plane. Liquid cooling systems are more widely used in automobiles due to their simple construction and better cooling capacity. But for aerospace applications, where the power of the system has been increased from kW to MW level, phase change cooling (PC) systems seem to have an advantage over liquid-cooled systems. Phase change cooling not only reduces weight but also increases cooling capacity by tens of percentages (**Figure 4**).

Therefore, a heat pump (HP) between the fuel cell system and the heat exchanger is proposed. According to Newton's law of cooling, the heat pump is used to increase the temperature of the coolant by the required heat exchanger capacity (surface area, volume and weight), that is, the flight drag can be effectively reduced. This PCHP (phase change–heat pump) cooling concept was first conceived for LT-PEMFC aeronautical applications in all published literature and the field of hydrogen propulsion in general, referring to Ref. [25].

To study and analyse the above-proposed PCHP cooling system, modelling and analysis were carried out based on a proven aircraft design and a typical flight mission.

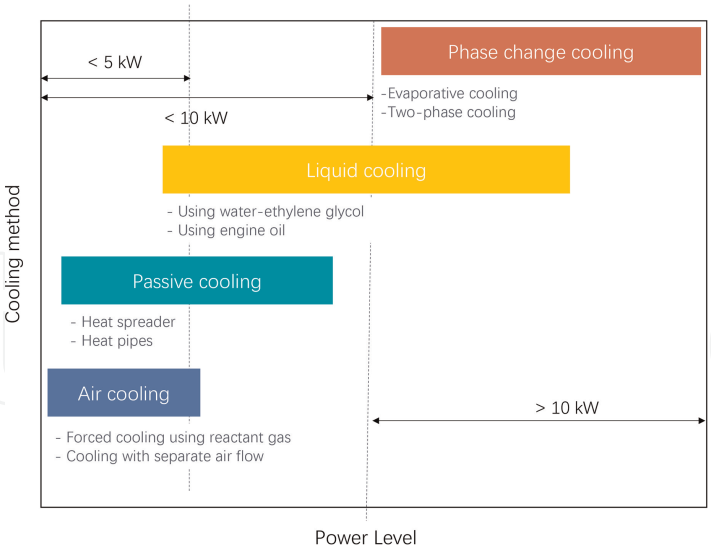


Figure 4.
Cooling methods for LT-PEMFC vs. power level.

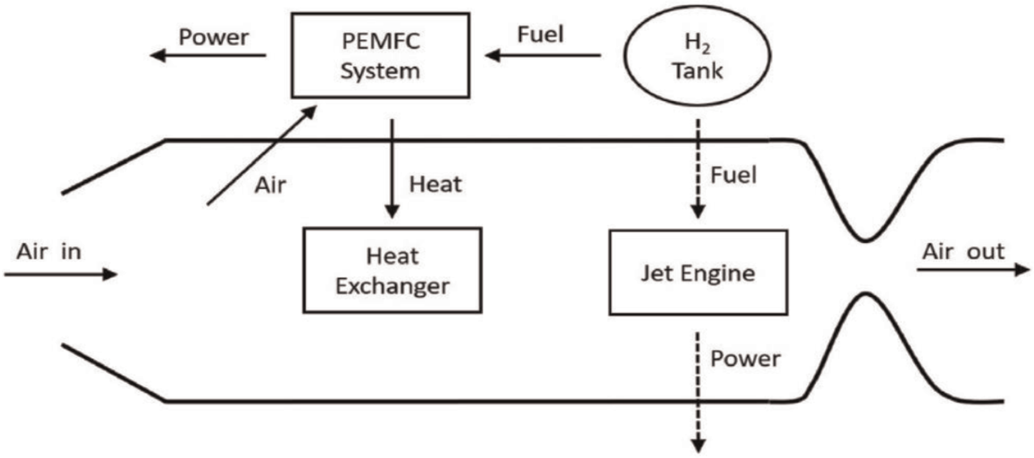


Figure 5.
Schematic presentation of the hybrid PEMFC-jet engine layout.

A hybrid LT-PEMFC-jet engine layout was chosen and then fine-tuned in size under two different PEMFC cooling schemes. Key performance indicators, including two drag items, are extracted and compared. Finally, they are discussed and summarised.

The Airbus A320–200 jetliner was chosen for this study. The hybrid PEMFC-jet engine system consists of a fuel cell system and a hydrogen internal combustion engine (i.e., a hydrogen-fuelled turbine engine). **Figure 5** shows the entire layout.

To facilitate the study, the fuel cell system in the model consists of a fuel cell stack, a hydrogen tank and a heat exchanger. The hydrogen tank feeds the stored hydrogen to the fuel cell and the jet engine, which provides additional power during take-off by burning the hydrogen directly. The thermal management system and the fuel cell system compressor are not shown as they are included in the 'PEMFC System' block. **Figure 6** shows the propulsion power requirements for the different flight phases of a mission, and it can be seen that an enormous amount of power is required during the take-off phase. During the cruise phase, the operating environment is more stable, and propulsion is provided by the fuel cell. For the specific aeroplane, based on data from Kadyk et al [26]., the data also shows us the power requirements of the A320–200 at various stages, as detailed in **Table 1**.

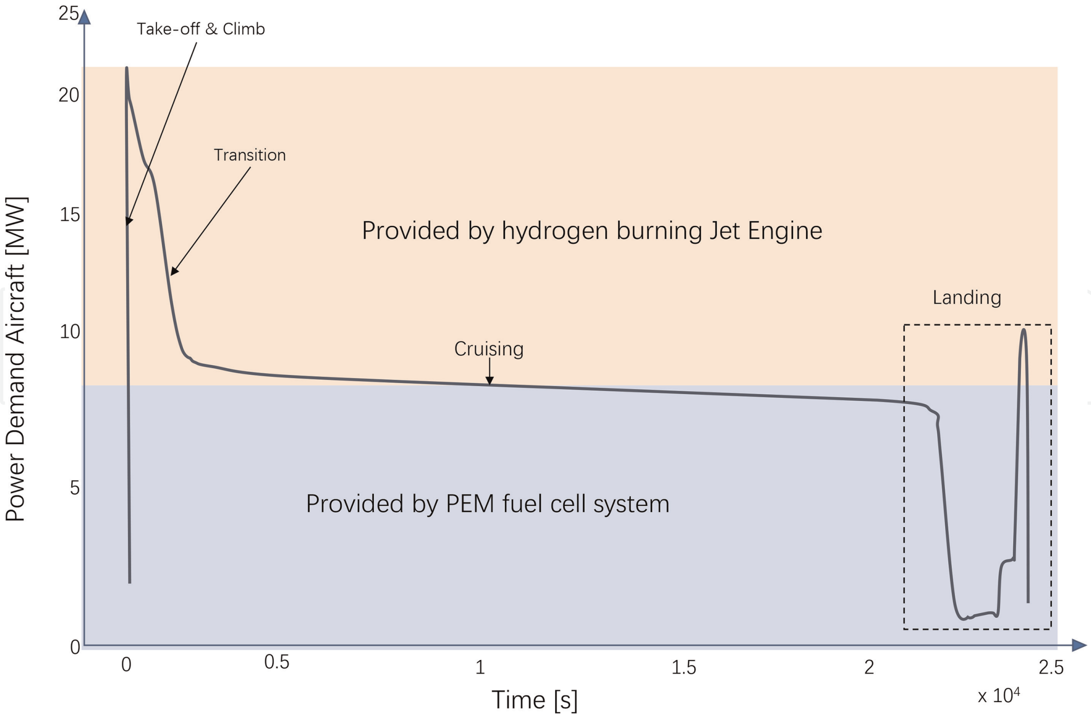


Figure 6.
Analysed flight mission for hybrid PEMFC-jet engine.

Description	Variable	Value	Unit
Average take-off power demand	$P_{TaO;ave}$	20.7256	MW
Maximum take-off power demand	$P_{TaO;max}$	20.8698	MW
Average cruising power demand	$P_{Cru;ave}$	7.7441	MW
Maximum cruising power demand	$P_{Cru;max}$	8.0646	MW
Fuel cell system power supply	P_{FC}	9.6775	MW
Jet engine power supply	P_{JE}	11.1923	MW
Maximum fuel cell system energy demand	E_{FC}		MJ
Average jet engine energy demand	$E_{JE;ave}$	6501	MJ

Table 1.
Power demand of the A320–200 aircraft for take-off and cruising based on data from Kadyk et al. and resulting provided power by the jet engine and the fuel cell system.

3.2.1 PEMFC cooling design

A schematic diagram of the PCHP cooling circuit proposed in this work is shown in **Figure 6**. The cooling course (excluding the PEMFC stack) consists of a heat exchanger, a compressor (HP), an expansion valve, ideal piping and a coolant. Water has been chosen as the phase change coolant. For water to evaporate in the operating temperature range of the fuel cell stack, the coolant pressure must be lower than the ambient pressure (0.2 bar). The low-pressure water (vapour mass of 0.153) evaporates, thus cooling the PEMFC stack and leaving a vapour mass of 0.950. Through the compressor, the pressure of the steam is increased by 5 bar, resulting in a significant temperature increase. Afterwards, the hot and pressurised steam (steam mass of 1.000) is transported to the heat exchanger, which removes heat into the ambient airflow around the aircraft. After passing through the heat exchanger, the steam is transformed into pressurised liquid water (vapour mass of 0.000). The heat exchanger model is implemented using the 'Condenser Evaporator (2P-MA)' module in Matlab/Simulink, and the minimum drag is determined using an optimisation algorithm. As the pressure drops through the expansion valve, the water is again mostly evaporated, that is, the vapour mass of the coolant returns to its original 0.153 at a pressure of 0.2 bar. Finally, the under-pressure cold water is piped into the PEMFC stack for a new cooling cycle. For comparison, we have also simulated conventional liquid cooling with the same cooling process as for the PCHP (**Figure 7**).

The reverse Rankine cycle of the coolant in the p-h diagram can be seen in **Figure 6**, where the blue line indicates the coolant cycle, the yellow line shows the isentropic process, and the red line indicates the isothermal process. The numbers 1–4 correspond to the states of the coolant in the PCHP cooling loop depicted in **Figure 8**.

3.2.2 PEMFC modelling

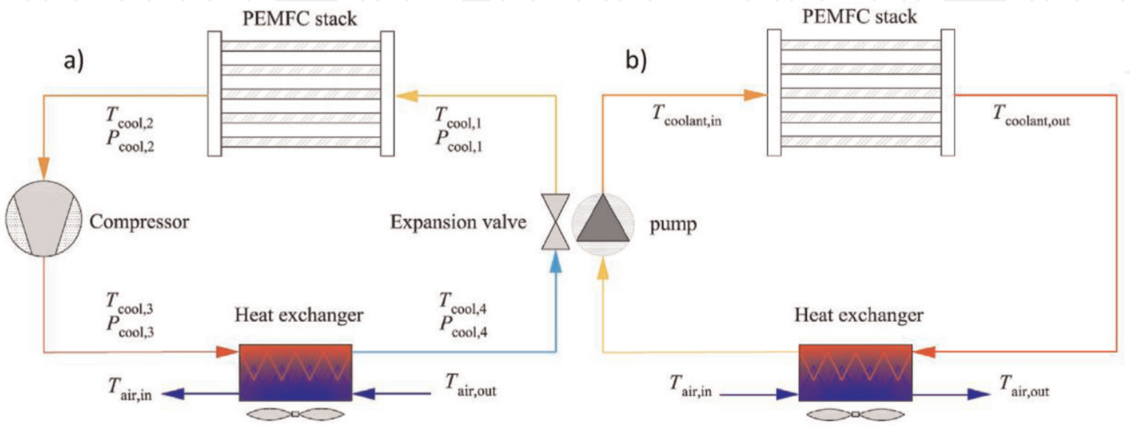
The PEMFC is modelled to calculate the heat generated by the PEMFC system during operation and to analyse the cooling system. The following assumptions have been adopted to simulate the PEMFC subsystem of the engine.

1. The operation of each flight phase is assumed to be steady state.

2. All components, except the heat exchanger, were simulated lumped.

3. The properties of hydrogen and air follow the ideal gas law

4. The ambient air properties for the cruise phase (7783 m above sea level) were taken from the International Standard Large Balloon (ISA) model [27].



(a) (b)

Figure 7.
a) the PCHP cooling loop proposed in this work for an aviation PEMFC system and b) schematic view of a conventional LC loop for the same PEMFC system.

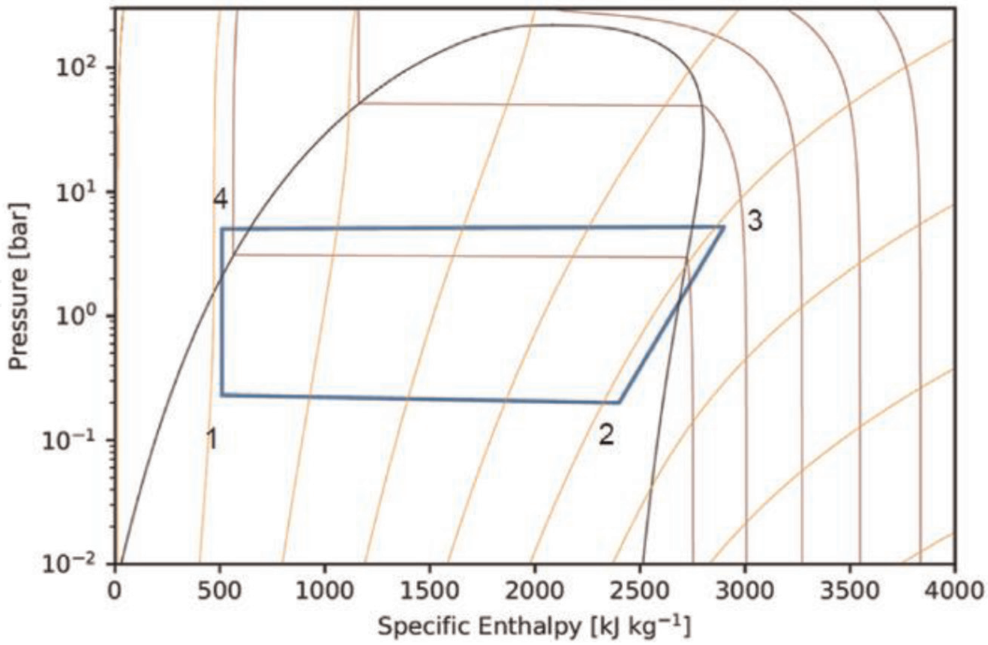


Figure 8.
Heat pump cycle of the coolant inside the PCHP model. Blue lines: Coolant cycle; yellow lines: Isentropic process; red lines: Isothermal process. The numbers 1–4 correspond to the respective state of the coolant in the cooling loop.

The subsystem-generated waste heat flow is [27],

$$\dot{Q}_{gen} = (V_{th} - V_{out}) \cdot i \cdot A_{cell} \cdot N_{cell} \tag{1}$$

To remove the waste heat flow ·Qgen to the ambient air, the two cooling designs mentioned above use the same aluminium louvre-fin heat exchanger and are of the same size [28].

3.2.3 Drag power

The drag generated by the PEMFC subsystem consists mainly of the system mass and aerodynamic friction caused by the heat exchanger, with some drag forces mitigated by the Meredith ramming effect [29]. This is because the air expands within the heat exchanger and leaves the nacelle faster than it entered, generating thrust. The overall drag is expressed as follows:

$$P_{d,tot} = v_{air,0} \times (D_{d,mass} + Dd, aero) + P_{comp,r} + P_{misc} - P_{ram} \tag{2}$$

where $v_{air,0}$ is the free flow velocity of air (m/s); $D_{d,\ mass}$ and $D_{d,\ aero}$ are the mass and aerodynamic induced drag (N), respectively; $P_{comp,r}$ is the power consumption of the turbo compressor supplying fresh air from the environment to the fuel cell stack (W); P_{ram} is the ram thrust caused by the Meredith ramjet effect (W). P_{misc} is the miscellaneous drag power (W) depending on the other components in each cooling circuit. $D_{d;\ mass}$ is determined by the force balance to lift resistance ratio L/D during the cruise. This ratio is the amount of lift generated divided by the aerodynamic drag due to movement through the air. The expression for the drag caused by mass is $D_{d,mass} = \frac{m_{sys,tot} \times g}{L/D}$, where g is the gravitational constant (m/s^2); L/D is the lift-to-drag ratio; and $m_{sys,tot}$, is the sum of all components in the system taken into account, which can be expressed as

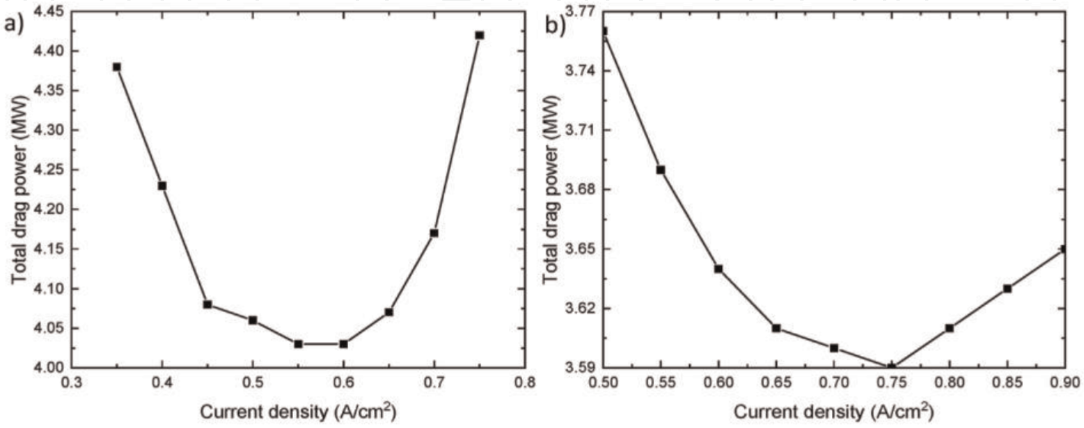
$$m_{sys,tot} = m_{HX} + m_{FC} + m_{JE} + m_{Tot,tank}, m_{Tot,tank} = m_{Tank} + m_{H_2} \tag{3}$$

The lift-to-drag ratio of an A320–200 airliner at cruise is [30]

$$L/D = 16.3$$

An analysis comparing the cooling effect and the dragging force of the powertrain of a PEMFC with two cooling systems shows that with a fixed cruise power requirement for the aircraft, all drag power items were found to rise monotonically with increasing current density based on simulations of the model. This is because the current density increase amplifies the heat flow through the system, amplifying the heat exchanger's capacity. This leads to an increase in absolute values for all resistance sources in the interval analysed. At higher current densities, the core drag and the drag caused by the heat exchanger mass rise more rapidly, while the ramjet thrust and external drag follow an almost linear trend. The relationship between the drag source and the size of the heat exchanger can explain this. While the external drag depends on the frontal area of the heat exchanger, the mass and core drag depend on the volume of the heat exchanger, which does not follow a linear trend. The total resistance of the liquid-cooled cooling loop and the phase-change heat pump cooling loop at different current densities is shown in **Figure 8** without accounting for the stack and hydrogen storage mass. It can be seen that the drag resistance first decreases and then increases through increasing current densities, indicating that there is a minimum drag resistance point for which the corresponding current density of the combustion link cell can be identified as the optimum operating point for the fuel cell. It can also be observed that the total drag force of the phase change heat pump cooling system is significantly lower than that of the liquid cooling system for both cold de-circuit designs. For the minimum total drag corresponding to the optimum current density, 0.5781 A/cm^2 for the liquid-cooled system and 0.7313 A/cm^2 for the phase-change heat pump system, it can be concluded that the phase-change heat pump system is advantageous in reducing the drag force during flight and increasing the efficiency of the fuel cell (**Figure 9**).

The combined performance of the hybrid system with its two different cooling systems is also worth discussing. The first thing to say is the total drag power of the



(a) (b)

Figure 9.
a) the total drag of the LC loop. b) the total drag of the PCHP loop vs. stack current density.

two systems: 6.648 MW for the LC system is 1.528 MW more than the PCHP cooling system, representing 15.79% of the aircraft's total propulsion power. As the coolant temperature in the PCHP system is much higher than in the LC system (324.4°C for the PCHP and 56.4°C for the LC), according to Newton's law of cooling and assuming other variables are inconvenient, the PCHP requires about 1/5 the area of the heat exchanger of the LC system. The use of a small-area heat exchanger also allows a further reduction in flight resistance and overall system mass. More drag requires more energy consumption, that is, more fuel needs to be carried to ensure range. At the same time, the current density of the LC system is also relatively low, which exacerbates the gap between the two systems.

Another point worth noting is the effect of the thrust generated by the Meredith Ramjet effect on the overall system for both systems. According to model calculations, the Ramjet effect of the LC cooling system provides an additional 1.773 MW of thrust, approximately three times that of the PCHP system. Still, it only counteracts 53.2% of the drag generated by the LC system, whereas the Ramjet effect in the PCHP cooling circuit counteracts 96.8% of the drag caused by itself. So the drag generated by the PCHP cooling system is entirely negligible, reducing the drag overcome by the propulsion system by 23%, which can also be seen as a 16% increase in airspeed.

3.3 Efficiency

From the current research, it is clear that the performance of PEMFC itself still needs to be improved to be used in civil aviation. Previous sections have described the study of a sub-system of the PEMFC system, namely the cooling system. The performance of the entire hybrid PEMFC propulsion system has been optimised by employing a new phase change heat pump performance of the PEMFC [31]. To improve the performance of PEMFC, design optimisation of GDL is often considered an effective approach. Pore-scale simulations are generally regarded as one of the most effective tools for optimising the microscopic performance of porous media, such as GDL [32, 33]. In the last few decades, the rapid development of computer modelling and analysis, X-ray computed tomography and scanning electron microscope has provided a variety of effective modelling methods, simulating and studying GDLs at the microscopic level, such as pore-scale modelling (PSM), which is used below cooling system. This section will discuss how the performance of the PEMFC itself can be further optimised by design (**Figure 10**).

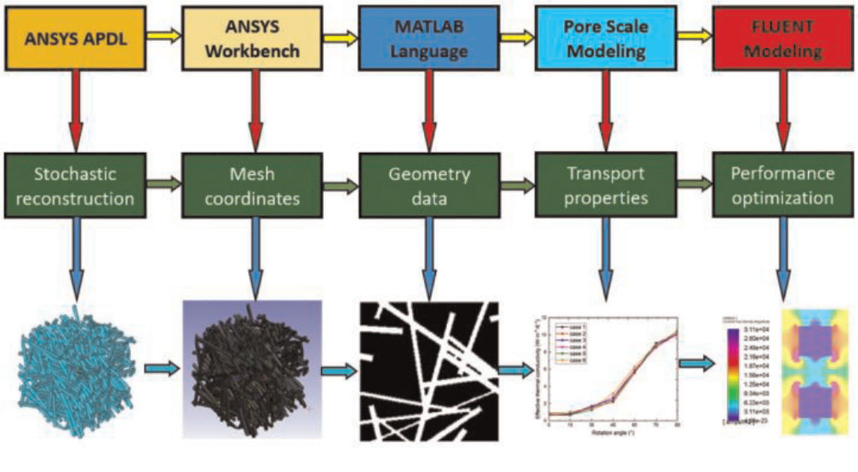


Figure 10.
Schematic of this multiscale modelling study approach.

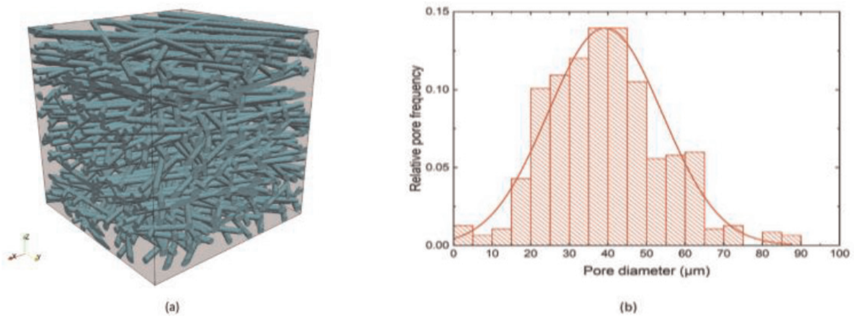
The Gas Diffusion Layer (GDL) is a critical component of the PEMFC structure and is responsible for managing water and heat and transporting substances in the PEMFC [34, 35]. The GDL transports the reactants to the catalyst layer (CL) and transports the products from the CL efficiently and uniformly, a link that impacts the performance of the PEMFC.

To design a new GDL, a 3D GDL model with a specific structure is first generated by the stochastic reconstruction method of the ANSYS Para-metric Design Language (APDL). The stochastic reconstruction method utilises a stochastic algorithm which allows the fibres to be placed randomly in a specified space. To facilitate the study, the following restrictions are imposed on the model: the generated GDL consists only of solid carbon fibres and pore scale, all carbon fibres on the same diameter and is entirely allocated on every single x-y plane, allowing for stacking between fibres. As a result, a numerical GDL is generated with only solid carbon fibres on the same diameter and is entirely allocated on every single x-y plane, allowing for the stacking of fibres. As a result, a numerical GDL is reconstructed, with a domain of size $304 \times 304 \times 304 \mu m^3$ and a resolution of which the porosity is 0.78 and the fibre diameter is $8 \mu m$. **Figure 11 b**) analyses the pore size distribution to validate the reconstructed geometry. It demonstrates that the structure is ready for the GDL study.

ANSYS Workbench then carried out pre-processing to obtain the mesh coordinates. To improve its electrical and hydrothermal properties, the reconstructed GDL was rotated by different angles to form a new GDL. This step was transformed and tilted using MATLAB scripts and matrix transformation functions to obtain matrices with different degrees of GDL phase data. PSM, including gas diffusivity and electrical and thermal conductivities, extracted the effective transport properties of these angled GDLs. It should be noted that anisotropy is evident in common GDL materials. Calculating fluxes in the in-plane direction (x and y) and across the plane direction (z) is necessary. Finally, these properties were applied to a CFD model to investigate the performance of the PEMFC using this new design.

For ease of calculation, the simulation of the 3D macroscale model covers only one channel of the PEMFC, as shown in **Figure 12**. It consists of seven components: the anode current collector (ACC), the cathode current collector (CCC), the anode catalyst layer (ACL), the cathode catalyst layer (CCL), the anode gas diffusion layer (AGDL), the cathode gas diffusion layer (CGDL) and the membrane. Thermal and electrical conductivities at different GDL fibre angles were used in this model. Based on our PSM results, the effect of compression on the GDL has been considered.

In this macro model, the following assumptions are taken.



(a)

(b)

Figure 11.
Stochastic reconstruction of the GDL.

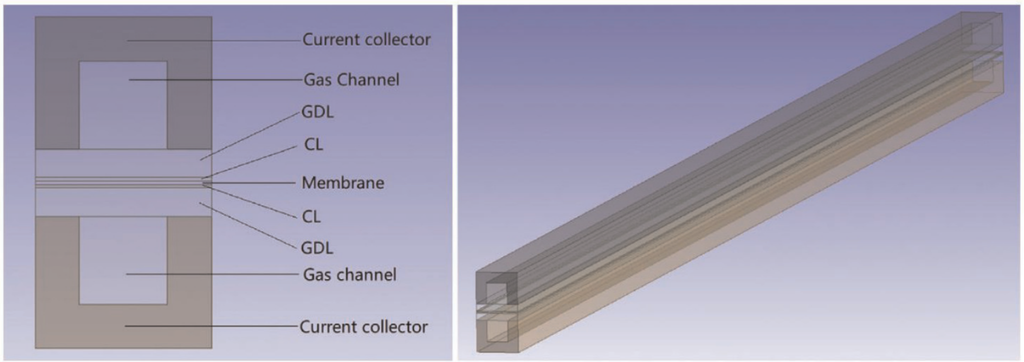


Figure 12.
Schematics of the PEMFC model, 2-D view (left) and 3-D view (right).

a. The fuel cell operates under steady-state conditions, and gravitational effects are neglected.

b. The properties of the GDL are considered to be anisotropic, and the other components of the fuel cell are isotropic.

c. Thermal and electrical contact resistances are neglected.

d. The gases in this model are considered ideal.

e. The membrane is impermeable to all gases.

The conservation of mass governs this macroscopic PEMFC model, conservation of momentum, conservation of energy and electrochemical reaction equations [36–38].

With the help of the constructed micro and macro models, the properties of GDL, such as gas diffusivity, and electrical and thermal conductivity, are analysed.

The GDL was set at 15-degree intervals around the y-axis from 0 to 90 degrees, as shown in **Figure 13** and then rotated around the z-axis from 0 to 90 degrees. It can be observed that the porosities of the GDL appear to become more uniform as the angle increases. By calculating the effective gas diffusivity (EGD) using PSM, it was found that the effective gas diffusivity increased with increasing rotation angle.

To understand this phenomenon, relative gas diffusivity (RED) was introduced. As shown in **Figure 14a**, the RED increases with increasing angle. According to the

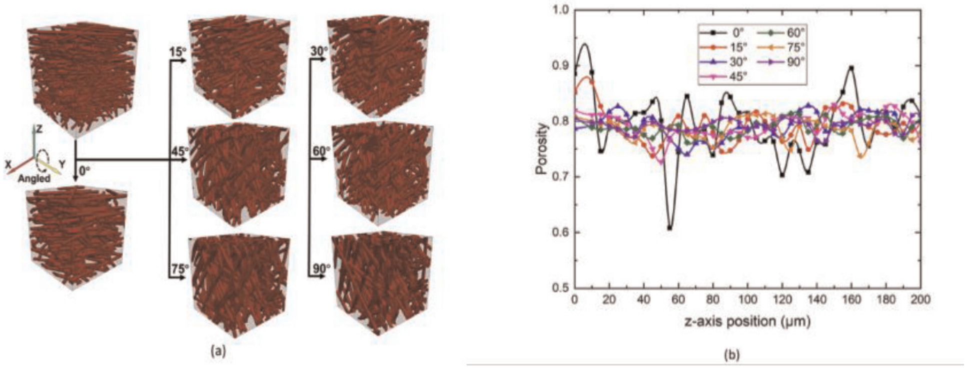


Figure 13.
GDL angling, a) schematics of the angling around the y-axis and (b) porosity distributions through the z-axis direction of these angled GDLs.

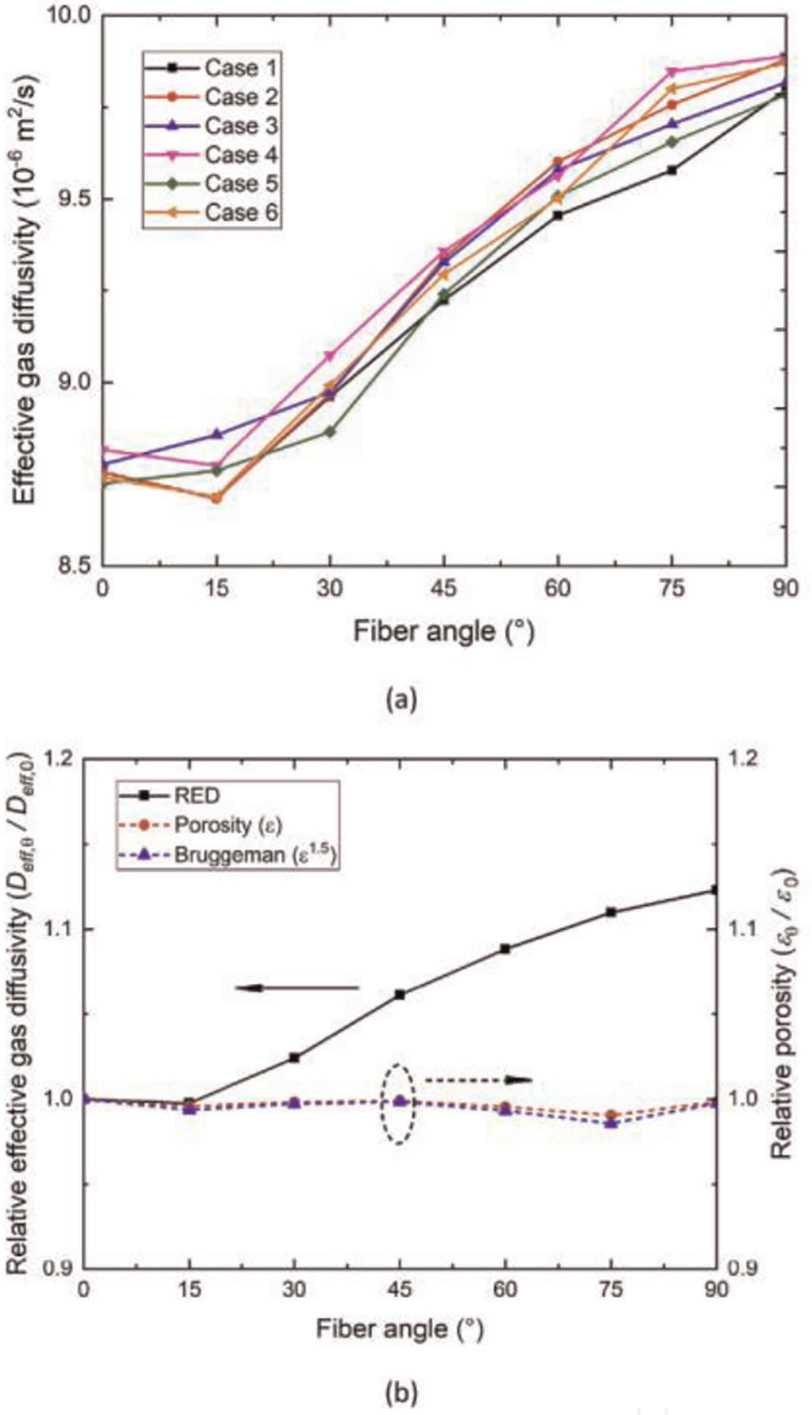


Figure 14.
Effects of the fibre angle on the EGD, (a) the EGD with the angle, (b) the RGD and relative porosity with the angle, including the calculation results and Bruggeman function.

Bruggeman function, it can be concluded that EGD is correlated with porosities. This also shows that porosities are one of the determinants of EGD. However, we can also see from **Figure 14b** that the relative porosities are almost unity, which indicates that porosities' effect on EGD can be neglected. Research reveals that it is not porosity but tortuosity that causes EGD to increase with angle [39, 40]. Tortuosity is inversely proportional to EGD, with tortuosity decreasing as the angle increases, which is reflected in EGD increasing with the angle.

For carbon fibres, effective electrical conductivity (EEC) and effective thermal conductivity (ETC) increase with the angle but show an S-shaped curve as more electrons/heat is conducted through the fibres and less through the contact points between the fibres. This would result in less resistance to electrical/heat conduction through the planar direction [41, 42]. The difference between REEC and RETC is illustrated in **Figure 15** mainly because heat is also conducted through air, while electricity is only conducted through carbon fibres [43].

From the macroscopic model, the fuel cell performance has been dramatically improved by the optimised design of the GDL. The benefits of the new GDL design translate into performance gains of up to approximately 80% for the macroscopic PEMFC due to the significant improvements in EEC and ETC. In addition, the increase in ETC leads to a reduction in membrane temperature, leading to a higher membrane water content. The result is an increase in membrane proton conductivity, which increasingly reduces the ohmic overpotential and dramatically improves the fuel cell performance.

3.4 Hydrogen storage

As the bridge between the production and utilisation of hydrogen, hydrogen storage technology runs through the hydrogen end of the industry chain to the fuel cell end. It is an important link in controlling the cost of hydrogen.

How hydrogen is stored is of great concern. Hydrogen has a high energy density, three times that of petrol; it is light, weighing only 1 kg for $11.2m^3$; it is very easy to dissipate because it is far less dense than air; and since hydrogen is a liquid with a density of $70.78kg/m^3$ at $-253°C$, it is nearly 850 times denser than hydrogen under standard conditions (approx. $0.08342kg/m^3$). Therefore, cryogenic liquid hydrogen storage is a highly desirable form of hydrogen storage in terms of energy storage density alone. However, there are still some problems with low-temperature liquid hydrogen storage technology. Firstly, the process of hydrogen liquefaction consumes much energy, with the actual energy consumption being equivalent to 30% of the total hydrogen energy; secondly, liquid hydrogen storage tanks require high selection criteria for insulation materials and tank design due to issues such as sealing, insulation and safety, leading to increased manufacturing difficulties and high costs.

The abovementioned problems limit the use of hydrogen as a fuel in aviation. A new hydrogen storage tank concept has been proposed to solve this problem, using cryogenic liquid nitrogen as an insulating layer. The structure is shown in **Figure 16**. This is a multi-layer isolation structure with a chamber between the tank walls that can be filled with cryogenic liquid nitrogen, which is used to maintain the temperature of the liquid hydrogen inside the tank. The liquid nitrogen can be replenished simultaneously as the fuel is refuelled.

To better analyse this concept and explore its actual performance, a modelling analysis of the structure of the hydrogen storage tank was carried out. It is first assumed that this tank is designed to meet the following mission requirements. A regional aircraft capable of carrying 32 passengers, with a required range of 2100 km, an altitude of 9144 m, a cruise speed of Mach 0.65 and a fuel load (liquid hydrogen) of 1150 kg. To compare with the original liquid hydrogen storage equipment, two more advanced types of hydrogen storage tanks (Polyurethane (PU) foam and vacuum-based multilayer insulation (MLI)) were also analysed.

The analysis of the thermodynamic properties, insulation capacity and adaptability to different environmental conditions of the three tanks leads to the conclusion that

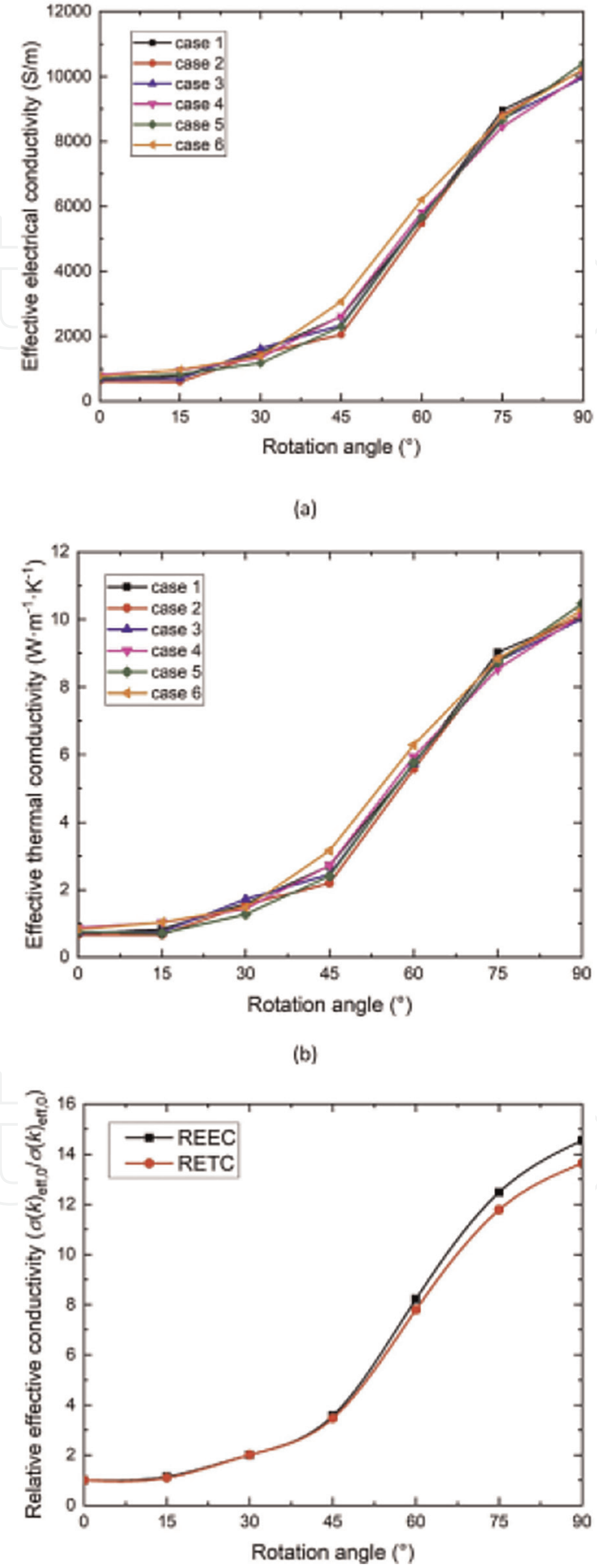


Figure 15.
Effects of the fibre angle on (a) the EEC, (b) the ETC and (c) the REEC and RETC.

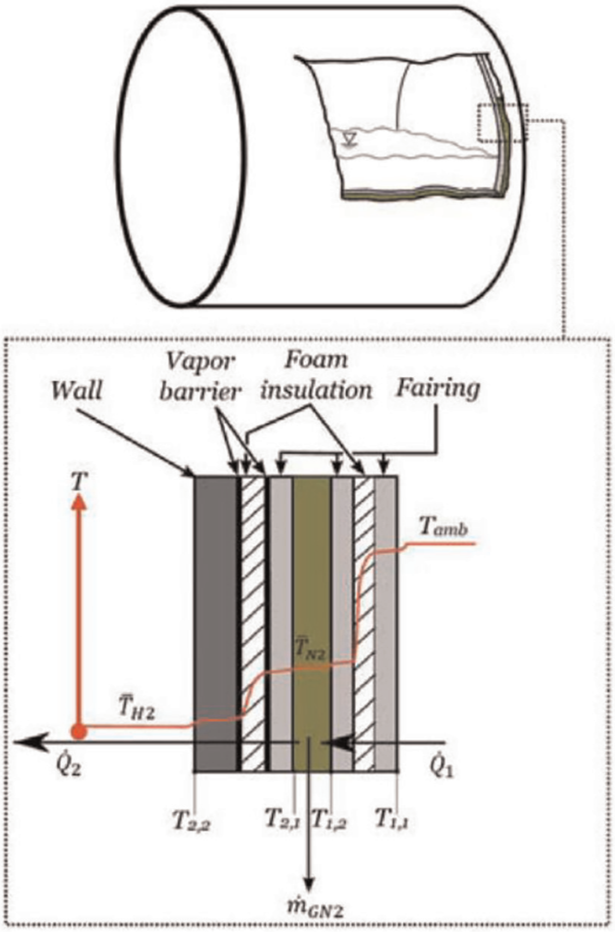


Figure 16.
Schematic description of the new concept of the hydrogen storage tank.

the novel concept hydrogen storage tank can significantly limit the tank's volume by introducing liquid nitrogen to limit the heat flux into the tank. The volume savings compared with foam materials increase with the reduction of the liquid hydrogen payload. For small tanks, the volume savings compared with pure foam insulation, as well as the increased adaptability and robustness, come at the cost of the tank weight, as additional structural walls are necessary. MLI is the best performer of all concepts in tank volume because it has the lowest insulation thickness. For larger tanks, however, the MLI has a comparative advantage over the novel concept in weight reduction. In the 12-hour overnight stop design, the MLI outperforms the other two concepts. But the novel concept still fulfils the challenge of the 12-hour stop. The novel concept is expected to be a reliable hydrogen storage system in the future because it does not need to maintain vacuum conditions and its reliability in the face of active thermal system failure.

3.5 Reliability

Safety is the most critical factor for a civil airliner; therefore, the safety requirements of such aeroplanes are extremely stringent according to national regulations. However, higher safety redundancy means lower specific power for the fuel cell. The increase in specific power for large civil aircraft fuel cell systems is sought from different approaches rather than focusing on the design of the fuel cell system. Having quantified the extent to which aviation safety specifications affect the specific power of fuel cell systems, strategies to reduce these effects need to be investigated.

The safety certification guidelines for aircraft guide the design of fuel cell systems. To meet the requirements of safety certification guidelines, it is necessary to design the fuel cell system with sufficient redundancy. However, the more redundancy there is in a system, the heavier it becomes, thus reducing the specific power of the fuel cell system and payload. The theoretical redundancy (DOR_{theo}) can be calculated using the following formula.

$$DOR_{theo} = log_{(1-W)}(p) \tag{4}$$

As the DOR follows a logarithmic function, a considerable increase in reliability is required to reduce the DOR significantly. The relationship between redundancy and failure rate is given in **Figure 17**. It can be seen that the sensitivity of DOR and the sensitivity of different powers to system reliability increase as system reliability increases.

Subsystem redundancy analysis of fuel cells helps reduce the overall system's mass, as less redundancy is required for reliable components than for the system as a whole. Further improvements in fault-tolerant systems are a good direction, such as the new PEMFC stacks, which can bypass faulty cells [44].

3.5.1 Time constant determined extended operations (TCD-ETOPS)

TCD-ETOPS is a newly introduced concept based on ETOPS (Extended Operations), which allows the aircraft to maintain a greater distance from diversionary airports, allowing shorter flight paths and operations over water and in remote areas [45]. And the purpose of TEC-ETOPS is to reduce the impact of safety certification on

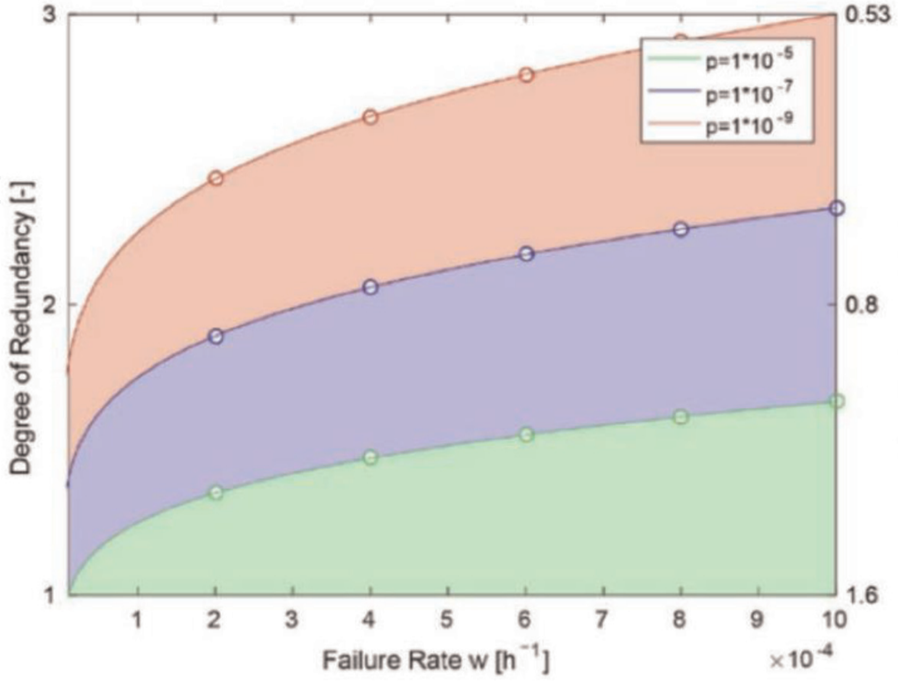


Figure 17.
Degree of redundancy as a function of failure rate. Area colours show different failure modes. Green: minor, blue: major, red: hazardous, white: catastrophic.

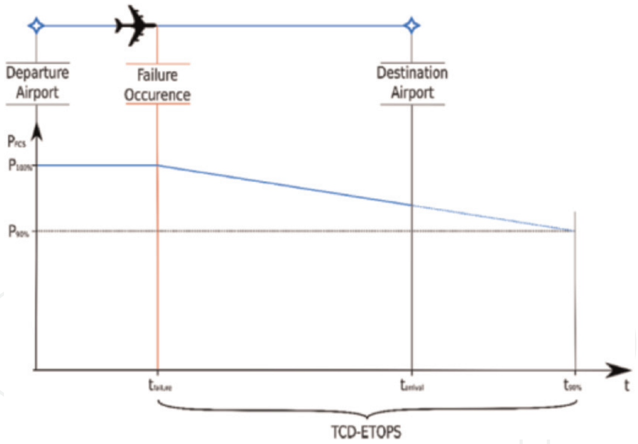


Figure 18.
Visualisation of the time constant determined extended operations (TCD-ETOPS). The failure condition is met at 10% initial power loss.

the specific power of the system. The time constant for a given degradation mechanism represents the time scale of power loss of the FC. If the diversionary airport is within the TEC-ETOPS range, the aircraft can continue flying and landing in the event of a subsystem failure. Suppose the time scale of degradation allows the aircraft to reach the destination airport without further deterioration of the failure. In this case, a greater incidence of failure can be allowed with a guarantee of safety; therefore, the system's redundancy can be reduced.

For example, as shown in **Figure 18**, the range of the aircraft's TCD-ETOPS after a failure encompasses the time the plane arrives at the destination airport. This failure has a minimal impact on the aircraft's operations, and then there is a possibility that the failure of this subsystem can be degraded to a lower failure level.

The PEMFC system can fail to power an aircraft due to several failure conditions, the 10 most serious being: overheating, leakage, fracture, extruded, stress corrosion cracking, erosion, deposition, cavitation, inadequate structural support and failure to perform its function [46]. But some of the degradations that occur are also reversible; for example, the loss of voltage due to low humidity in the ground is reversible to some extent [47], while the supply of pure hydrogen to the anode after carbon monoxide poisoning of the membrane restores the total voltage [48]. In this way, the failed FCs are restored after TCD-ETOPS, then repair or replacement of the FCs can be postponed or avoided, and if in flight, the range of TCD-ETOPS in flight can also be extended.

By proposing the TDC- ETOPS concept, the impact on the specific power of the fuel cell due to excessive redundancy requirements can be compensated. By analysing the fuel cell system at the component level, there is also the prospect of reducing the system's mass. In future research, it is also necessary to address the different failure modes of PEMFCs and the degradation relationships caused by failures, thus being a more detailed fuel cell system design.

4. Summary and outlook

As early as the 1960s, fuel cells were used in the NASA Gemini spacecraft, followed by the launch of fuel cell concept models by many internationally renowned car companies. In the twenty-first century, as the development of hydrogen energy technology has gradually matured, the world's major developed countries have attached great importance to the development of the hydrogen energy industry, and hydrogen energy has become an important strategic choice to accelerate energy transformation and upgrade and cultivate new economic growth points.

Fuel cells have the following advantages.

1. High efficiency. Since the chemical energy of the fuel is directly converted into electrical energy without thermal energy conversion in the middle, the conversion efficiency is not limited by the thermodynamic Carnot cycle; since there is no mechanical energy conversion, mechanical transmission losses can be dispensed with, plus the conversion efficiency does not vary according to the size of power generation, so the fuel cell has a high conversion efficiency.

2. Low noise and low pollution. In converting chemical energy into electrical energy, the fuel cell has no mechanical moving parts, only a part of the control system has small moving parts, so it is low noise. In addition, the fuel cell is also a low-pollution energy source. Take phosphoric-acid-type fuel cells as an example; the sulphur oxides and nitrogen compounds emitted by them are two orders of magnitude lower than the standard set by the United States.

3. High adaptability. Fuel cells can use a variety of hydrogen-containing fuels, such as methane, methanol, ethanol, biogas, LPG, natural gas and synthetic gas, and the oxidiser is inexhaustible air. Fuel cells can be made into standard modules of specific power (e.g. 40 kW) and assembled into different power and types according to the user's needs and installed in the most convenient place for the user. They can also be installed as large power stations if required and used in parallel with the conventional power supply system, which will help regulate the electrical load.

4. Short construction cycle and easy maintenance. After the fuel cell has been formed for industrial production, the various standard components of the power generation unit can be produced continuously at the factory. It is easy to transport and can also be assembled on-site at the power station. Some estimate that the maintenance of a 40 kW phosphate-type fuel cell is only 25% of that of a diesel generator of the same power.

Although the fuel cell presents many attractive advantages, it also has severe shortcomings. The main bottleneck for fuel cell applications is the high cost. Due to cost constraints, fuel cell technology is currently only economically competitive in a few specific applications (e.g. on space vehicles).

Power density is another significant limitation. Power density represents the power produced per unit volume (volumetric power density) or per unit mass (mass power density) of a fuel cell.

Although the power density of fuel cells has increased significantly over the last few decades, it needs to be increased further if they are to be competitive in portable electronics and the automotive sector. Internal combustion engines and ordinary batteries often outperform fuel cells in terms of volumetric power density, while they are very close in terms of mass power density.

The availability and storage of fuel pose an even more profound challenge. Fuel cells work best when fuelled by hydrogen, but hydrogen is not readily available, has a low bulk energy density and is challenging to store. Other alternative fuels are difficult to use directly and often require reforming. All of these issues reduce the performance of the fuel cell and increase the requirement for auxiliary equipment. Thus, although gasoline is an attractive fuel from an energy density point of view, it is not suitable for fuel cell use.

For the time being, the hydrogen energy sector is still in its early stages of development and is an integral part of the zero-carbon, low-carbon era. But hydrogen has strengths and weaknesses in equal measure, so it needs to be used for its strengths and avoided for its shortcomings.

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References

[1] Sharaf OZ, Orhan MF. An overview of fuel cell technology: Fundamentals and applications. Renewable and Sustainable Energy Reviews. 2014;**32**: 810-853

[2] European Commission, Directorate-General for Mobility and Transport, Directorate-General for Research and Innovation, Flightpath 2050: Europe's Vision for Aviation: Maintaining Global Leadership and Serving Society's Needs. Publications Office; 2011. DOI: 10.2777/50266

[3] CO2 emissions from Commercial Aviation. International Council on ... (no date). 2018. Available from: https://theicct.org/sites/default/files/publications/ICCT_CO2-commercl-aviation-2018_20190918.pdf. [Accessed: November 16, 2022]

[4] Noland JK. Hydrogen electric airplanes: A disruptive technological path to clean up the aviation sector. IEEE Electrical Insulation Magazine. 2021; **9**(1):92-e102. DOI: 10.1109/MELE.2020.3047173

[5] Castro AL, Lacava PT, Moura∼o CHB. Feasibility of using fuel cells in a small aircraft. In: AIAA Aviation 2021 Forum. Reston, Virginia: American Institute of Aeronautics and Astronautics; 2021

[6] Wang B et al. Current technologies and challenges of applying fuel cell hybrid propulsion systems in unmanned aerial vehicles. Progress in Aerospace Sciences. 2020;**116**:100620. DOI: 10.1016/j.paerosci.2020.100620

[7] Huang Y, Xiao X, Kang H, Lv J, Zeng R, Shen J. Thermal management of polymer electrolyte membrane fuel cells: A critical review of heat transfer mechanisms, cooling approaches, and advanced cooling techniques analysis. Energy Conversion and Management. 2022;**254**:115221. DOI: 10.1016/j.enconman.2022.115221

[8] Parent KE. Fuel Cells: Energy from Gases Instead of Gasoline [Internet]. acs.org. Available from: https://www.acs.org/content/dam/acsorg/greenchemistry/education/resources/fuel-cells-energy-from-gases-instead-of-gasoline.pdf. [Accessed: Nov 2022]

[9] Kurzweil P. Renaissance Der Brennstoffzelletechnik. In: Brennstoffzellentechnik Grundlagen, Komponenten, Systeme, Anwendungen. Wiesbaden, Germany: Springer Vieweg; 2013. pp. 8-9. DOI: 10.1007/978-3-658-00085-1

[10] Wee J-H. Which type of fuel cell is more competitive for portable application: Direct methanol fuel cells or direct borohydride fuel cells? Journal of Power Sources. 2006;**161**(1):1-10. DOI: 10.1016/j.jpowsour.2006.07.032

[11] https://en.wikipedia.org/wiki/Proton-exchange_membrane_fuel_cell#History

[12] Rathke P, Kallo J, Schirmer J, Stephan T, Waiblinger W, Weiss-Ungethu¨ m J. Antares DLR-H2 e flying test bed for aircraft fuel cell systems development. ECS Transactions. 2013; **51**(1):229-e41. DOI: 10.1149/05101.0229ecst

[13] DLR - zero-emission air transport [Internet]. DLRARTICLE DLR Portal. Available from: https://www.dlr.de/content/en/articles/news/2016/20160929_zero-emission-air-transport-first-flight-of-four-seat-passenger-airc

raft-hy4_19469.html. [Accessed: Nov 2022]

[14] Hydrogeit. Hy4 gets permit to fly [Internet]. H2. 2021. Available from: https://h2-international.com/2021/02/12/hy4-gets-permit-to-fly/. [Accessed: Oct 2022]

[15] Kandlikar S, Garofalo M, Lu Z. Water management in a pemfc: Water transport mechanism and material degradation in gas diffusion layers. Fuel Cells. 2011;**11**:814-823

[16] Chen J, Matsuura T, Hori M. Novel gas diffusion layer with water management function for pemfc. Journal of Power Sources. 2004;**131**:155-161

[17] Wang B, Deng H, Jiao K. Purge strategy optimisation of proton exchange membrane fuel cell with anode recirculation. Applied Energy. 2018;**225**: 1-13

[18] Halseid R, Vie PJ, Tunold R. Effect of ammonia on the performance of polymer electrolyte membrane fuel cells. Journal of Power Sources. 2006;**154**:343-350

[19] Imamura D, Ebata D, Hshimasa Y, Akai M, et al. Impact of Hydrogen Fuel Impurities on PEMFC Performance. SAE Technical Paper 2007-01-2010. 2007. DOI: 10.4271/2007-01-2010

[20] Wang H, Turner J. Reviewing metallic pemfc bipolar plates. Fuel Cells. 2010;**10**:510-519

[21] Haider R et al. High temperature proton exchange membrane fuel cells: Progress in advanced materials and key technologies. Chemical Society Reviews. 2021;**50**(2):1138-1187. DOI: 10.1039/d0cs00296h

[22] Araya SS, Zhou F, Liso V, Sahlin SL, Vang JR, Thomas S, et al. A comprehensive review of pbi-based high temperature pem fuel cells. International Journal of Hydrogen Energy. 2016;**41**: 21310-21344. [Accessed: Nov 2022]

[23] Hartnig C, Schmidt TJ. On a new degradation mode for high-temperature polymer electrolyte fuel cells: How bipolar plate degradation affects cell performance. Electrochimica Acta. 2011; **56**:4237-4242

[24] Deutsches Zentrum für Luft- und Raumfahrt. Emissionsfreier Antrieb für die Luftfahrt: Erstflug des viersitzigen Passagier- flugzeugs HY4. 2016. Available from: https://www.dlr.de/content/de/artikel/news/2016/20160929_emissionsfreier-antrieb-fuer-die-luftfahrt-erstf lug-des-viersitzigen-passagierflugzeugs-hy4_19469#/gallery/24480. [Accessed: November 26, 2020

[25] Srinath AN, Pena Lopez A, Miran Fashandi SA, Lechat S, Di Legge G, Nabavi SA, et al. Thermal management system architecture for hydrogen-powered propulsion technologies: Practices, thematic clusters, system architectures, future challenges, and opportunities. Energies. 2022;**15**(1):304. DOI: 10.3390/en15010304

[26] Kadyk T, Schenkendorf R, Hawner S, Yildiz B, Ro€mer U. Design of fuel cell systems for aviation: Representative mission profiles and sensitivity analyses. Front Energy Res. 2019;7:35. DOI: 10.3389/fenrg.2019.00035

[27] NASA. U.S. Standard Atmosphere. Available from: https://ntrs.nasa.gov/api/citations/19770009539/downloads/19770009539.pdf. [Accessed: May 31, 2022]

[28] Kozulovic D. Heat release of fuel cell powered aircraft. In: Proceedings of Global Power and Propulsion Society. 2020. DOI: 10.33737/gpps20-tc-99

[29] Piancastelli L, Frizziero L, Donnici G. The Meredith ramjet: An efficient way to recover the heat wasted in piston engine cooling. Journal of Engineering and Applied Science. 2015; **10**(12):5327-5333

[30] Martinez-Val R, Perez E, Palacin J. Historical perspective of air transport productivity and efficiency. In: 43rd AIAA Aerospace Sciences Meeting and Exhibit. 2005. DOI: 10.2514/6.2005-121

[31] Chen L, Kang Q, Tao W. Pore-scale study of reactive transport processes in catalyst layer agglomerates of proton exchange membrane fuel cells. Electrochimica Acta. 2019;**306**:454e65. DOI: 10.1016/j.electacta.2019.03.158

[32] Ryan EM, Mukherjee PP. Mesoscale modelling in electrochemical devicesda critical perspective. Progress in Energy and Combustion Science. 2019;**71**:118-e42. DOI: 10.1016/j.pecs.2018.11.002

[33] Chen Q, Niu Z, Li H, Jiao K, Wang Y. Recent progress of gas diffusion layer in proton exchange membrane fuel cell: Two- phase flow and material properties. International Journal of Hydrogen Energy. 2021;**46**:8640-8e71. DOI: 10.1016/j.ijhydene.2020.12.076

[34] Sui PC, Djilali N. Analysis of coupled electron and mass transport in the gas diffusion layer of a PEM fuel cell. Journal of Power Sources. 2006;**161**:294-e300. DOI: 10.1016/j.jpowsour.2006.03.079

[35] Bazylak A. Liquid water visualisation in PEM fuel cells: A review. International Journal of Hydrogen Energy. 2009;**34**: 3845e57. DOI: 10.1016/j.ijhydene. 2009.02.084

[36] Um S, Wang C-Y, Chen KS. Computational fluid dynamics modelling of proton exchange membrane fuel cells. Journal of the Electrochemical Society. 2000;**147**:4485. DOI: 10.1149/1.1394090

[37] Shen J, Tu Z, Chan SH. Performance enhancement in a proton exchange membrane fuel cell with a novel 3D flow field. Applied Thermal Engineering. 2020;**164**:114464. DOI: 10.1016/j. applthermaleng.2019.114464

[38] Kulikovsky AA, Divisek J, Kornyshev AA. Modeling the cathode compartment of polymer electrolyte fuel cells: Dead and active reaction zones. Journal of the Electrochemical Society. 1999;**146**:3981-3e91. DOI: 10.1149/ 1.1392580

[39] Wu W, Jiang F. Microstructure reconstruction and characterization of PEMFC electrodes. International Journal of Hydrogen Energy. 2014;**39**: 15894-1e906. DOI: 10.1016/J. IJHYDENE.2014.03.074

[40] Nabovati A, Hinebaugh J, Bazylak A, Amon CH. Effect of porosity heterogeneity on the permeability and tortuosity of gas diffusion layers in polymer electrolyte membrane fuel cells. Journal of Power Sources. 2014;**248**:83-e90. DOI: 10.1016/J.JPOWSOUR. 2013.09.061

[41] Zamel N, Li X, Shen J. Numerical estimation of the effective electrical conductivity in carbon paper diffusion media. Applied Energy. 2012;**93**:39-e44. DOI: 10.1016/J.APENERGY.2011.08.037

[42] Yablecki J, Bazylak A. Determining the effective thermal conductivity of compressed PEMFC GDLs through thermal resistance modelling. Journal of Power Sources. 2012;**217**:470-4e8. DOI: 10.1016/j.jpowsour.2012.06.011

[43] Lange KJ, Sui PC, Djilali N. Pore scale modeling of a proton exchange membrane fuel cell catalyst layer: Effects

of water vapor and temperature. Journal of Power Sources. 2011;**196**:3195-e203. DOI: 10.1016/j.jpowsour.2010.11.118

[44] Scott P, Chen Y, Calay R, Bhinder F. Experimental investigation into a novel modular PEMFC fuel cell stack. Fuel Cells. 2015;**15**:306-321. DOI: 10.1002/fuce.201200212

[45] Airbus: Getting to Grips with ETOPS: Flight Operations & Line Assistance. 1998. Available from: https://www.737ng.co.uk/AIRBUS%20ETOPS%20Guide.pdf. [Accessed: November 26, 2020]

[46] Bahrebar S, Blaabjerg F, Wang H, Vafamand N, Khoo-Ban M-H, Rastayesh S, et al. A novel type-2 fuzzy logic for improved risk analysis of proton exchange membrane fuel cells in marine power systems application. Energies. 2018;**11**:721. DOI: 10.3390/en11040721

[47] Knights SD, Colbow KM, St-Pierre J, Wilkinson DP. Aging mechanisms and lifetime of PEFC and DMFC. Journal of Power Sources. 2004;**127**:127-134. DOI: 10.1016/j.jpowsour.2003.09.033

[48] Le Canut J-M, Abouatallah RM, Harrington DA. Detection of membrane drying, fuel cell flooding, and anode catalyst poisoning on pemfc stacks by electrochemical impedance spectroscopy. Journal of Power Sources. 2006;**153**:A857. DOI: 10.1149/1.2179200