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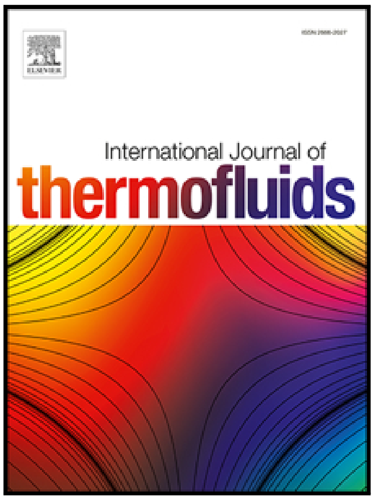

Advancements and prospects of thermal management and waste heat recovery of PEMFC

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Highlights

- The thermal management strategies of PEMFC are reviewed
- The waste heat recovery pathways of PEMFC are presented
- The challenges and prospects of the aforementioned areas are discussed

Advancements and prospects of thermal management and waste heat recovery of PEMFC

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Abstract

Despite that the Proton Exchange Membrane Fuel Cell (PEMFC) is considered to be an efficient power device; around half of the energy produced from the electrochemical reaction is dissipated as heat due to irreversibility of the cathodic reaction, Ohmic resistance, and mass transport overpotentials. Effective heat removal from the PEMFC, via cooling, is very important to maintain the cell/stack at a uniform operating temperature ensuring the durability of the device as excessive operating temperature may dry out the membrane and reduces the surface area of the catalyst hence lowering the performance of the cell. In addition to cooling, capturing the produced heat and repurposing it using one of the Waste Heat Recovery (WHR) technologies is an effective approach to add a great economic value to the PEMFC power system. Global warming, climate change, and the high cost of energy production are the main drivers to improve the energy efficiency of PEMFC using WHR.

This paper presents an overview of the recent progress concerning the cooling strategies and WHR opportunities for PEMFC. The main cooling techniques of PEMFCs are described and evaluated with respect to their advantages and disadvantages. Additionally, the potential pathways for PEMFC-WHR including heating, cooling, and power generation are explored and assessed. Furthermore, the main challenges and the research prospects for the cooling strategies and WHR of PEMFCs are discussed.

Keywords: Waste heat recovery, thermal management, cooling, CHP, CCP, PEMFC, Hydrogen

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1. Introduction

The unfavourable environmental impact of fossil fuel and its role in global warming and pollution continue to receive public and government attention where finding an alternative energy source is at the centre of any new legislation and a hot discussion topic in the parliament. Hydrogen was always regarded as an alternative to the traditional fossil fuel which can be burned, in the internal combustion engines, or used in the fuel cells, such as PEMFC, to generate power; virtually without producing any Greenhouse Gas (GHG) emissions [1], [2]. PEMFCs are promising power generation devices which were suggested for a wide range of applications such as automotive [3], railway [4], aviation and aerospace [5], maritime [6], portable devices [7], power plants [8], and energy storage systems [9]. PEMFC produces electricity as a result of the electrochemical reaction between hydrogen and oxygen [10]–[12]. Along with the electricity, heat and water are also produced as by-products in the PEMFC. Effective management of the produced heat and water is extremely important to enhance the energy efficiency and the durability of the device [13]. Heat/thermal management of the PEMFC is normally achieved via employing a suitable cooling strategy depending on the power and application of the stack. Cooling the fuel cell device can be either passive or active. In the passive cooling, the heat is dissipated via natural convection, conduction and radiation modes without using any external device. Such cooling is normally secured through the use of heat spreader and heat pipes. Passive cooling is simple, inexpensive, easy to implement, and has high energy efficiency and low noise due to the absence of fan. However, it has very low cooling capacity and can only be used for small PEMFCs [14]. Active cooling utilizes an external device, such as a fan or blower, to enhance heat transfer and to achieve the required amount of heat rejection. Normally in the active cooling, the PEMFC heat is transferred to a cooling fluid which passes through the stack increasing its temperature. The temperature of the cooling fluid is then decreased actively in the radiator which releases the heat to the environment. In some cases, the thermal management via active cooling requires controlling the main operation parameters of the system, such as coolant flow rate and coolant inlet temperature, using a proper control system such as proportional integral (PI) controller [15]–[17].

Improving the energy efficiency of the PEMFC is the key for making the technology more economically viable while maintaining its sustainability. Waste heat recovery (WHR) has emerged as an effective strategy for enhancing the energy efficiency of the PEMFC and reducing its operational cost while minimizing GHG emissions. WHR means capturing the heat loss within the system and utilizing it instead of discharging it to the environment [18], [19]. The captured waste heat can be converted back to electricity, mechanical power, or additional heat for use in targeted functions allowing for energy-saving [20]. The viability and limitations of WHR for a particular system depend on the temperature of the waste heat source [21]. Thus, the temperature of the waste heat is the main factor that determines the possible exploiting routes of it. In the context of an industrial process, waste heat temperature ranges from as low as 30°C to more than 1000°C [22]. Accordingly, waste heat is normally classified into high, medium and low-grade heat corresponding to the temperature level of >400 °C, 100–400 °C, and < 100 °C, respectively [23], [24]. Generally, the higher the temperature of the waste heat, the better its quality, and the easier to be retrieved. Recovering low-grade heat is more challenging and less feasible than recovering high and medium grade heat [22]. The temperature of waste heat from both low temperature (LT) and high temperature (HT) PEMFCs is between 60°C and 200°C [25]–[27]. Generally, the waste heat of HT-PEMFC has better quality than that of LT-PEMFC since it has a higher temperature levels of up to 200 °C [28]. However, the waste heat of both LT-PEMFC and HT-PEMFC falls within the low-medium grade category imposing some WHR difficulties.

Due to their significant impacts on the performance, energy efficiency, and sustainability, the thermal management and WHR of PEMFCs have gained a great deal of studies in the recent years leading to dramatic and interesting developments in the field. This paper aims to presents the latest trends in those interconnected areas highlighting the main challenges and identifying related prospects.

2. Mechanisms of heat generation and heat transfer in a PEMFC

Generally, the heat in a PEMFC is generated from different sources including electrochemical reactions between the hydrogen and oxygen, Ohmic resistance of the membrane, and condensation of water vapour [29]. As it is known, the fuel cell generates electrical power from an electrochemical reaction between hydrogen and oxygen; hence the chemical energy of the fuel which is not converted into electricity is released as heat. Heat accounts for around 50% of the total energy produced by the electrochemical reactions [30]. Thus, the heat flux of a fuel cell can be quantified as shown in equation 1

$$q^{\cdot\cdot} = (E_{total} - E_{cell}) \times i \quad (1)$$

Where E_{max} is the thermal voltage; E_{cell} is the cell operating voltage; and i is the current density. E_{total} represents the imaginary maximum possible cell potential assuming full conversion of the chemical energy into electrical power. E_{total} equals either to 1.25 V if it is calculated based on higher heating value (HHV) with liquid water as a by-product of the reaction or 1.48 V if it is calculated based on lower heating value (LHV) with water vapour as the by-product of the reaction. It is clear from the equation that $q^{\cdot\cdot}$ increases as the current density increases and the cell voltage decreases.

The heat of the PEMFC is generated in certain regions of the cell leading to non-homogenous temperature distribution within the device. The local heat flux greatly affects the performance and the durability of PEMFCs. Accurate estimation of the local heat generation within each region of the cell is somewhat complex. According to Ramousse et al [31], part of PEMFC heat is generated due to Joule effects, i.e. the protonic resistance of the electrolyte, and it is localized in the membrane region. Another part of the heat is produced at the electrodes and it is due to the electrochemical reactions taking place at those regions. Additionally, part of the heat is generated due to water sorption phenomena and it is localized at the membrane–electrode interfaces. Finally, some heat might be generated in the GDL layer due to the condensation of water. The generated heat within the PEMFC is transferred via different modes. Convective heat transfer occurs between the solid surfaces of the cell components and the flowing reactants; and conductive heat transfer occurs in the solid and/or porous materials of the device including electrolyte, electrodes and current interconnect layers [32].

3. Thermal management strategies of PEMFC stacks

Thermal management of the PEMFC means removing the heat produced by the device and maintaining an acceptable working temperature for it. The thermal management is achieved via applying one of four main cooling strategies including heat spreader, air cooling, liquid cooling, and phase change cooling as shown in Figure 1. Choosing a suitable cooling strategy for a specific PEMFC depends mainly on its power level. Each cooling method employs specific cooling materials which must be non-toxic, non-flammable, and chemically compatible with the materials used for the PEMFC components [33].

3.1 Heat spreaders

The heat spreader is one of the passive cooling techniques for PEMFC. This cooling method provides many advantages including the simple design, low parasitic loses, and no need for coolant circulation systems; thereby improving the overall efficiency of the stack [34]. The heat spreaders of the PEMFC can be in the form of a highly thermally conductive material, heat pipes, or vapour chamber.

3.1.1. Heat spreader in the form of highly thermally conductive material

In this method, highly thermally conductive materials are used as spreaders that absorb the heat from the central region of PEMFC stack and then transfer it to the edge of the cells and finally dissipate it to the surrounding air through natural convection [35]. Copper, with its excellent thermal conductivity (about 400 W/m K), is the most commonly used material for fabricating heat spreaders. Aluminium is another suitable material for application as heat spreaders for lightweight PEMFC stack due to its combined high thermal conductivity (about 200 W/m K) and low-density characteristics. Additionally, carbon nanotube (CNT) and graphene, with their thermal conductivities in the range of 3000–5000 W/m K, may also be employed as high-rate heat spreader materials [36]. Furthermore, low-density graphite-based material such as expanded graphite and pyrolytic graphite with thermal conductivity of 600–1000 W/mK could also be used [34].

The feasibility of applying a highly thermal conductivity pyrolytic graphite sheet (PGS) as heat spreaders for the thermal management of single-cell and small-to-medium-sized PEMFC stack was investigated by many researchers [37]–[39]. Wen and Huang [37] used a PGS heat spreader for single

PEMFC. It was shown that using PGS can enhance cell performance at high cathode flow rates. Also, PGS allowed for achieving a more uniform temperature distribution with less maximum temperature than those observed without using PGS. Wen et al. [38] extended the previous work by using the PGS for thermal management of PEMFC stack. It was reported that the using of PGS as heat spreader can increase the maximum power and improve the performance of the stack as well as addressing the water flooding issue at the low cathode flow rates.

3.1.2.Heat-pipe based heat spreader

Heat pipes are passive and very efficient heat transfer devices with high thermal conductivity in the range of 2100–50000 W/mK [34]. The Conventional Heat Pipe (CHP) can be simply described as an evacuated tube containing a working fluid in both vapour and liquid phases and a wick structure to return the condensed working fluid to the evaporator section, as shown in Figure 2 [40], [41].

Over the past years, heat pipes were successfully employed as cooling elements for different types of electronic devices [43]. Many studies have proved the suitability of different types of heat pipes including Loop Heat Pipe (LHP), Pulsating Heat Pipe (PHP), and micro Heat Pipe (μHP) for thermal management of PEMFC. μHPs can be used for PEMFC with low power output (<10 W) [44]. LHPs are suggested for PEMFCs with output power in the range of 10–100 W [44]. PHPs are suitable for PEMFC having high power (>100 W) [44]. The heat pipes can be embedded into the bipolar plates of the PEMFC stack to meet the different heat dissipation requirements [45]. Oro and Bazzo [46] proposed a thin flat heat pipe, which employs microgrooves for capillary pumping of the working fluid, as a cooling device for PEMFC. It was shown that the heat pipe can provide sufficient cooling for PEMFC rejecting up to 12 W at the evaporator section and maintaining the operating temperature within the desirable range. LHP with flat bifacial evaporator was proposed as a heat exchanger for PEMFC [47]. Planar bifacial made of sintered stainless steel (AISI 316) porous plates were used as wick while methyl alcohol was employed as working fluid. It was shown that for the applied power in the range of 10-30 W, the operating temperature of the LHP was less than 85 °C for the horizontal position which confirms its suitability for many PEMFC heat removal applications. A cooling system composed of heat pipes and Capillary Pumped Loop (CPL) was used for thermal control of PEMFC stack [48]. The heat pipes were made of seamless stainless steel (316L) tubes with stainless steel mesh as wicks and deionized water as working fluid. The proposed cooling system was capable of dissipating the heat and maintaining the suitable operation temperature for PEMFC. Clement and Wang [49] designed and analysed PHP as a heat dissipation device for PEMFC. The heat pipe was constructed from a copper tube and tested with three different working fluids including acetone, methanol, and deionized water. The best performance was obtained from PHP with methanol occupying a filling ratio of 45%. The aforementioned heat pipe reached the steady-state stage within a short time and exhibited the smallest temperature differences during the transient stage. PHP was capable of dissipating around 120 W at the evaporator section which proves its potential to be used as a passive cooling device for PEMFC.

3.1.3. Vapour chamber

Vapour chamber (VC) is another passive heat transfer device that can be used as a heat spreader in PEMFC. VCs have the same working concepts of heat pipes but they are different in shape, processing, and heat transfer patterns [45]. Zhao et al. [45] proposed an innovative VC concept for cooling of PEMFC stack. The proposed VC consists of two etched copper shell plates as the evaporation and the condensation sections and employs sintered copper powder and deionized water as a wick structure and working medium, respectively. The obtained results showed that the vapour chamber has excellent cooling characteristics including quick thermal response and high thermal conductivity. It was reported that VC can satisfy the cooling requirements of low-power PEMFCs.

3.2 Air-cooling

In this cooling strategy, heat dissipation is achieved via air which is passing either in the cathode or in dedicated cooling plates [50]. The air-cooling method has received a good deal of interest due to its simplicity and potential to integrate the cooling channels into the cathode allowing for reducing the size, weight, cost, and control complexity of the device [51], [52]. Air-cooling is only suitable for small PEMFCs with low power while it is deemed not efficient for large PEMFC due to the significant increase in the parasitic losses [28], [53].

The main parameters that affect the performance of air-cooling are the inlet temperature and the mass flow rate of air as well as the configuration of the flow field [54]. Proper design of the coolant flow field is an important aspect of air-cooling to achieve uniform temperature distribution within the cell. The performance of the coolant flow field is normally assessed via different performance metrics such as average (T_{avg}) and maximum (T_{max}) temperatures, pressure drop (ΔP), and Index of Uniform Temperature (IUT). IUT measures the deviation of the surface temperature from the average temperature (T_{avg}) of the heat transfer surface. Generally, a smaller IUT indicates a more uniform distribution of the temperature and a better cooling performance where the surface with perfectly uniform temperature distribution has an IUT of 0 [55]. Using Computational Fluid Dynamic (CFD) tool, Ravishankar and Prakash [56] investigated the influence of channels configurations on the thermal characteristics of an air-cooled PEMFC. Six different designs were considered for air flow channels including serpentine, spiral, divided serpentine, divided spiral, distributed serpentine and distributed spiral, as sketched in Figure 3. ΔP, T_{max}, and IUT metrics were used to compare the different channels configurations. Divided spiral design, with the greater number of channels bends, exhibited a greater pressure drop among all designs. On the other side, distributed serpentine design was the one which showed the best performance in terms of temperature distribution uniformity. According to this study, there is no single design that satisfies well all the desirable performance metrics. Shahsavari et al. [57] numerically investigated the thermal behaviour of a PEMFC with combined oxidant and cooling channels as shown in Figure 4. It was revealed that the air velocity and in-plane thermal conductivity of the bipolar plate are the key factors that affect the temperature distribution in the cell. Matian et al. [58] investigated the influence of air channel size on the performance of the air-cooling system for PEMFC stack. The suggested designs integrate the air-channels and the reactants channels on the same plate, as shown in Figure 5. It was shown that the plate with bigger air channels provides more uniform temperature distribution due to the greater amount of air that can pass through these channels and the greater amount of heat that can be removed from the system.

The possibility of using open-pore cellular foam (OPCF) made of metals as air flow passages in air-cooled PEMFCs was also investigated in the literature [14], [59]. OPCF is characterized by high surface to volume ratio and randomly distributed tortuous ligaments creating randomly interrupted flow passages and a greater degree of coolant re-circulation thus enhancing the temperature uniformity and heat transfer in both axial and transverse directions [14]. Additionally, the low electrical resistance and the lightweight of the metallic OPCF can enhance the electrical performance of the cell while reducing its weight [14]. Odabaee et al. [59] used thin-layer of aluminium OPCF as cooling plates which are inserted at the back of the bipolar plates and in between the cells. The reported results revealed that air-cooling using OPCF as cooling plates requires half of the pumping power compared to water-cooling. Lee et al [60] employed foam material on the cathode in air-cooled PEMFC to prevent the membrane dehydration and associated unstable performance issues. It was found that the foam material can improve the water retention in the membrane and provide more uniform distribution of the temperature and current density leading to higher overall cell performance.

3.3 Liquid cooling

3.3.1 Via water

Since the specific heat for water is almost four times greater than that of air, using water as a coolant, instead of air, enhances the cooling effectiveness and reduces the heat exchanger size. The water-cooling is preferred over the air-cooling for high cooling loads and it is mostly used for large PEMFC stack with a power greater than 5 kW, such as those used in Fuel Cell Electric Vehicle (FCEV) [29], [61]. The working fluid in this type of cooling is mostly deionized water which flows in the cooling channels within the bipolar plates or in dedicated cooling plates [61]. The typical cooling cycle using water is shown in Figure 6. The water passes through the PEMFC absorbing its heat and then goes through a radiator which rejects its heat to the environment reducing its temperature and finally it is pumped back to the PEMFC to repeat the cooling cycle. The primary aim of the PEMFC cooling plates is to reduce the maximum temperature achieved within the cell preventing the overheating of the membrane. Additionally, the cooling plates play an important role in creating more uniform temperature distribution within the cell with less local hot spots. The local hot spots with very high temperature may dry out the membrane reducing its proton conductivity and deteriorating the performance of PEMFC [34]. Generally speaking, the uniform temperature distribution allows for better performance and durability of PEMFCs as well as easier operational control [61].

Similar to air-cooling, the geometrical configuration of the coolant flow passages plays a significant role in the heat removal effectiveness of water-cooling systems. Chen et al. [62] studied the influence of coolant flow field configuration on the performance of water cooling plates by assessing IUT and ΔP responses. The modified serpentine-type flow field was found to exhibit the best cooling performance in terms of IUT. However, the parallel flow field showed a lower ΔP meaning that it requires less power to transmit the cooling fluid. Baek et al. [61] investigated numerically, using CFD, the cooling performance of six different coolant flow field designs shown in Figure 7. ΔP, T_{max}, and IUT were calculated for all presented designs and compared. It was noted that the multi-pass serpentine flow field (MPSFF) designs, models C and D in Figure 7, yield a more uniform temperature distribution without compromising the pressure drop. Using numerical simulations, Afshari et al. [63] examined the cooling behaviour of straight and zigzag-shaped water flow channels illustrated in Figure 8. The obtained results indicated that the zigzag configuration is better than the straight one providing a more uniform temperature distribution but with higher pressure drop. Ghasemi et al. [64] numerically examined the performance of six cooling flow fields namely; serpentine, multi-pass serpentine, serpentine, parallel-serpentine, spiral, and parallel as sketched in Figure 9. The spiral flow field was found to offer the lowest IUT and highest ΔP compared to the other designs.

In the numerical simulations of the aforementioned investigations, the generated heat in PEMFC was idealized as a constant uniform heat flux and applied to the CFD model of the cooling plate. However, in the actual PEMFC, the heat generated by the cell is not uniformly distributed. To address the aforementioned issue, Rahgoshay et al. [65] adopted the electrochemistry model within ANSYS-FLUENT to capture the actual heat generated within the PEMFC as a result of the electrochemical reaction. A 3D model of PEMFC with cooling plates is constructed. The cooling performance of serpentine and parallel flow fields with water coolant was compared numerically and it was found that the serpentine configuration can provide a 24% improvement in IUT and better overall cooling behaviour.

3.3.2 Via nanofluids

Nanofluids have received increased research attention for different heat transfer applications due to their superior thermal properties [66]. Benefitting from nanotechnology, nanofluids are prepared by dispersing nanoscale metallic and non-metallic particles into a heat transfer liquid such as water, ethylene glycol, propylene glycol, and oils [67]. Using nanofluids as coolants for PEMFC provides several advantages [68]. First, the suspended nanoparticles, with their very large specific surface areas, enhance substantially the thermal characteristics of the nanofluids including thermal conductivity, convective heat transfer coefficient, and thermal diffusivity and viscosity. Additionally, the nanoparticles can immobilize the negative and positive ions from the base fluid eliminating the need for using deionizing filter within the cooling cycle [68]. Furthermore, some types of nanofluids have very low freezing points and this can be considered as an advantage for those fuel cells operating in extremely cold weather. Finally, nanofluids, with their enhanced heat transfer properties, allow for reducing the size of the heat exchanger and the parasitic losses of the cooling system. Islam et al. [69] demonstrated that the frontal area of the heat exchanger for a 2.4 kW PEMFC can be reduced by 21% when using 0.05% volume concentration of nanoparticles in 50/50 water (W)/ethylene glycol (EG) base fluid. Zakaria et al. [70] adopted Al_2O_3 nanofluid for cooling the PEMFC. Different volume concentrations of Al_2O_3 nanoparticles were dispersed in water and 60/40 W/EG mixture. The authors reported that the cooling rate was increased by 187% when using 0.5% volume concentration of Al_2O_3 in water. However, despite the excellent cooling performance, higher pressure drop and voltage drop were observed when using the aforementioned concentration of Al_2O_3. Thus, 0.1% volume concentration of Al_2O_3 dispersed either in water or in 60/40 W/EG was reported to be the preferred nanofluids for PEMFCs [70], [71]. Zakaria et al. [72] also investigated the performance of SiO_2/water nanofluids in cooling PEMFCs employing a cooling plate with parallel flow field for the proposed nanofluid. The results confirmed the cooling superiority of SiO_2 nanofluids as the average temperatures of the cooling plate with the nanofluids was 15% - 20% less than that observed when using conventional water coolant.

Similar to water cooling, the nanofluids coolants need to flow in mini/micro channels to deliver the required cooling for the device. Several studies have analysed the flow and thermal behaviour of nanofluids in mini/micor channels similar to those used in the cooling plates of PEMFC and all reported promising findings in terms of exceptional heat transfer behaviour [73], [74].

3.4 Phase change cooling

This cooling technique uses a Phase Change Material (PCM) as a coolant and employs its latent heat to dissipate the heat of a PEMFC stack [50], [75]. Such method is attractive for PEMFC with high cooling demands as it offers some advantages over the water-cooling strategy in terms of enhancing the heat removal rate, reducing the coolant flow rate and flow parasitic losses, decreasing pumping requirements, and providing more uniform temperature distribution [29], [33], [76]. The phase change cooling can be either evaporative cooling or two-phase cooling with boiling. Instead of circulating the liquid water in separate cooling channels/plates as in the water-cooling system, evaporative cooling is achieved through injecting the liquid water directly with the reactants, i.e. air and hydrogen, in their flow channels [50], [77]–[79]. During the process, the injected liquid water evaporates removing the heat and humidifying the cells of the PEMFC stack. The exhaust water vapour is then directed to a condenser to be cooled down and converted back to liquid water which is stored in a tank for future use. The distinct advantages of this cooling method are that the injected water serves a dual function of cooling and humidify the cells without the need for external humidifiers and separate cooling plates. Fly and Thring [50] compared a conventional water-cooled PEMFC to the evaporative-cooled ones. It was found that the evaporation cooling allows for reducing the radiator frontal area by around 27%. Using porous bipolar plates is another way of the evaporative cooling in PEMFCs. In this method, the porous bipolar plates allow for both thermal and water management of the PEMFC preventing the drying out or flooding of the membrane [80].

The two-phase cooling with boiling provides very high cooling capacity and it is applied using a working fluid with relatively low boiling temperature such as HFE-7100 for LT-PEMFC and water for HT-PEMFC [81], [82]. HFE-7100, which has a boiling temperature of 61^{o}C, was regarded as a promising boiling coolant for LT-PEMFC [33], [83], [84]. Choi et al [83] compared the performance of two-phase HFE-7100 and single-phase water cooling systems and reported a better overall thermal management of the two-phase cooling method in terms of providing more uniform temperature distribution and higher thermal stability.

4. Waste heat recovery in PEMFC

Recently, WHR in PEMFCs has attracted increased research interest and many studies have explored the possible options for the useful utilization of the generated heat using different conversion systems [85]. The main WHR routes of PEMFC are categorised into internal usage within the PEMFC system to either preheat the reactants or release hydrogen from Metal hydrides (MH) tank, provide heating in Combined Heat and Power (CHP) system, drive chillers in Combine Cooling and Power (CCP) system, and power generation as summarized in Figure 10.

4.1 Internal usage within the PEMFC system

Metal hydrides (MH), such as MgH_2, Mg_2NiH_4 and $LaNi_5H_6$, are promising hydrogen storage materials for on-board hydrogen applications such as FCEV. Such materials discharge hydrogen through an endothermic reaction known as dehydrogenation. One of the possible usages of the PEMFC waste heat is to improve the hydrogen discharge rate of MH. In order to deliver adequate amounts of hydrogen from MH, the temperature of MH should be maintained in the range of 20-30 ^{o}C. However, sometimes it is challenging to keep the temperature of MH within the suitable range without using an external heat source. Thus, the waste heat of the PEMFC can be used to increase the temperature of MH and improve the hydrogen release rate. Tetuko et al. [86] developed a mathematical model, using Mathlab, to simulate the thermal coupling of 500 W PEMFC and $LaNi_5$ based MH hydrogen storage system using heat pipes. The model results revealed that less than 20% of the PEMFC waste heat is needed by MH canister to deliver the required discharge rate of the hydrogen. Similar findings were reported by Tetuko et al. [87] who also established a thermal coupling between the PEMFC and MH using heat pipes to transfer the heat from the fuel cell to canister. It was proved through experimental and theoretical analysis that a 30% of the heat generated by a 130 W fuel cell is sufficient to keep the MH canister at the desirable temperature for effective release of hydrogen. Mahmoodi and Rahimi [88] optimized the geometrical configuration of the heat pipes that can be used for thermal coupling of PEMFC and MH tank. It was reported that the best performance of the hydrogen releasing process at 25 bar can be obtained by using four heat pipes covered by 10 fins. MH based thermal energy storage system was proposed by Nasri et al. [89] to recover the waste heat from FCEV powertrain and reuse it for heating the battery or the cabin during the start-up or during the drive, respectively. The MH tank, as a heat storage device, generates cooling during the hydrogen desorption process while produces heating during the hydrogen absorption. It was reported that the proposed WHR recovery system can increase the range of the FCEV from 152 km to 178 km.

In addition to using PEMFC waste heat for MH applications, some studies have shown the effectiveness of the PEMFC-WHR system for preheating the reactants of PEMFCs operating in an extremely cold environment. In very cold weather conditions, i.e. sub-zero temperatures, PEMFC undergoes freeze-thaw cycle operations which lead to ice formation, membrane dehydration, performance degradation, and start-up issues [90]. Nguyen et al. [91] conducted an exergy analysis for a PEMFC with WHR system which aims to increase the inlet temperature of the reactants above the freezing points. A comparison was made between the proposed WHR system and the traditional system which uses an external heater to increase the inlet temperature of the reactants. The modelling results, obtained using Mathlab, demonstrated that around 30% of the PEMFC output electrical power can be saved upon adopting the WHR system for preheating the reactants.

4.2 Provide heating in CHP system

PEMFCs can be used in a CHP system to simultaneously produce both heat and electrical power for residential applications as demonstrated in Figure 11. In such systems, PEMFC waste heat is captured during the operation and then used for heating the rooms or obtaining hot water for shower, laundry and washing [92]. CHP system increases the efficiency and sustainability of the power system by reducing the energy cost and minimizing the GHGs [85]. Fuel cell-based micro-CHP systems offer a significant saving in the primary energy consumption and a major reduction in the carbon emissions compared to conventional gas-fired boiler/central power stations [93]. Comparing with the conventional CHP systems, PEMFC based CHP systems are characterized by higher overall efficiency and higher power to heat ratio [94]. It should be noted that in PEMFC based CHP, part of the PEMFC waste heat is used in a fuel processor to produce hydrogen-rich feed streams from natural gas or methanol that then can be used as a fuel for the stack [92].

Chen et al. [95] assessed and optimized the performance of PEMFC based residential combined cooling, heating and power system (CCHP) consisting of 5 kW PEMFC stack, humidifier, compressor, heat exchanger for WHR, hot water tank, and a small absorption chiller. The proposed system aimed for simultaneous generation of electric power, space heating/cooling, and hot water. It was found that decreasing the operating temperature of PEMFC, and increasing both the relative humidity and the pressure of the reactants allows for enhancing the exergy efficiency of the CCHP system and reducing the GHG emissions. The thermal and economic performance of a PEMFC-based micro-CHP system for the household applications was investigated by Chang et al. [96]. The system compromised of a 2kW PEMFC and a lithium-ion battery as an energy storage device that can be charged by either PEMFC stack or commercial electricity during off-peak hours. The modelling results, obtained via MATLAB, indicated that the average total efficiency of the CHP system with battery storage can reach 81.24% which is 11.02% higher than that CHP system without the battery. It was also found that using battery storage system can reduce the daily hydrogen consumption and daily costs by 14.47% and 9.5%, respectively.

4.3 Drive chillers in CCP system

The waste heat of PEMFC can be used for cooling purposes by driving chillers that require low temperature to operate such as absorption and adsorption chillers. Some investigations showed the possibility of recovering the PEMFC waste heat in absorption chiller, i.e. absorption refrigerator, to desorb the refrigerant out of absorbent, as shown in Figure 12, for cooling purposes [97]. The most common absorption chiller systems use either lithium bromide-water (LiBr-water) or water-ammonia (water-NH_3) as absorbent-refrigerant pairs. Such chiller systems can be activated using heat sources with temperatures of 120–170 °C and 80-200 °C for LiBr-water and water-NH_3, respectively. HT-PEMFC with waste heat temperature of up to 200 °C is more suitable to drive the generator of the absorption chiller system. Yang and Zhang [98] numerically investigated the feasibility of combining a PEMFC with an absorption refrigerator to simultaneously generate cooling and electrical power. It was found that the PEMFC-chiller combined system outperformed the stand-alone PEMFC showing an increase of 5.3% and 6.8% in the maximum power density and the corresponding efficiency, respectively.

In addition to absorption chiller, adsorption chiller, that uses solid-vapour pairs, such as silica gel-water, zeolite-water and activated carbon-methanol, is another WHR option of PEMFC for Combined Cooling Power (CCP) generation. Adsorption chillers are considered to be more suitable for heat recovery from LT-PEMFC due to fact that they can be driven by heat sources with a temperature of 60-120 °C [34]. Oro el al. [99] studied the possibility of using chemisorption chiller, employing ammonia as refrigerant and NaBr impregnated in expanded graphite as adsorbent, as a heat recovery system for PEMFC stack. The mathematical modelling results confirmed the capability of the aforementioned CCP system to produce up to 400 W cooling that increased the overall efficiency of the system to around 63%

4.4 Power generation

The last WHR option for PEMFC is to employ special thermodynamic power cycles, such as Organic Rankine Cycle (ORC), and heat to power technologies, such as thermoelectricity generator, which can operate using low-grade heat sources to produce additional electrical power. ORC has the same working principles as the normal Rankine steam cycle but it employs working fluid with a low boiling point, most commonly Butane, Propane, R123, R245fa and R134a, which can operate within the temperature range of 65–250 °C in the evaporator [100]. The simple ORC cycle, as shown in Figure 13, consists of evaporator, condenser, turbine and pump. The PEMFC waste heat is used in the evaporator to heat the working fluid which turns into a gaseous state and then spins a turbine connected to an electrical generator. Zho et al. [101] employed mathematical models to evaluate the performance of a hybrid power system consisting of a PEMFC stack and ORC cycle. A parametric analysis was conducted to identify the influence of main factors, such as fuel flow rate, PEMFC operating pressure, turbine inlet pressure, and turbine backpressure, on the system performance. It was reported that the electrical efficiency of the hybrid system is 5% greater than that of the one without ORC heat recovery system. Sheshpoli et al [102], [103] performed a thermodynamic analysis of a multi-purposes hybrid PEMFC-WHR system. The proposed functions of the WHR system were releasing the hydrogen from MH tank; preheating the hydrogen to the stack temperature, and generating power using a recuperative ORC. It was reported that the overall thermal efficiency and the power of the system depend on turbine pressure ratio, type and mass flow rate of the working fluid.

Beside ORC cycle, using the other power cycles, such as Kalina cycle and transcritical carbon dioxide (CO_2), for recovering PEMFC waste heat was also presented in some studies. Ahmadi et al [104] proposed transcritical CO_2 cycle coupled with liquefied natural gas (LNG) cycle for PEMFC-WHR. Sensitivity analysis and optimization study were conducted to understand the influence of the main parameters and identify those that can maximize the energy efficiency. It was found that using the proposed WHR system can increase the output power and efficiency of the PEMFC by 39% and 33%, respectively.

In addition to power cycles, Thermoelectricity Generator (TEG) can be used to convert the waste heat of PEMFC to electrical power. TEG converts heat flux directly into electrical energy using semi-conductive materials with high electrical conductivity and low thermal conductivity through a seebeck effect. A standard TEG can operate with a hot plate temperature of 60–180 °C which is within the temperature range of PEMFC and therefore such generators were considered as a viable option to recover the PEMFC waste heat. Experimental and theoretical investigations were conducted by

Sulaiman et al. [105] on using TEG for WHR from a 2 kW PEMFC. It was shown that the TEG can produce up to 218 mW of maximum electrical power at 1 kW of PEMFC power. In another study, a thermal coupling system between PEMFC, TEG, and MH cylinder is proposed for efficient WHR from PEMFC [106]. The hot side of the TEG is connected to the PEMFC via an air duct while the cold side is connected to MH cylinder for heat dissipation without any active energy consumption. A dynamic mathematical model was developed to predict the characteristic performance of the proposed WHR system. The results revealed that the TEG power via this thermal coupling is limited to 20 mW for a PEMFC power of 1 kW. However, such system was reported to be more efficient than cooling the cold side of the TEG via natural or fan cooling.

5. Remaining challenges and prospects

5.1 Cooling strategies

A summary of the advantages and drawbacks of all cooling methods for PEMFC is presented in Table 1. For small portable and mobile PEMFC stacks, such as those used in electronic devices and drones, the ideal design is the one that requires minimum thermal management equipment. The heat spreader is the most suitable cooling strategies for such PEMFCs. In addition to the cooling capability, the size and weight of the cooling device are crucial factors that should be considered carefully when designing cooling surfaces for small PEMFCs. Developing compact, lightweight, and highly efficient heat transfer device is a challenging design task which requires using advanced multi-objective optimization techniques to satisfy the conflicting requirements of the design. The endeavour to enhance the performance of the cooling surface via applying optimization techniques might result in greatly complex geometrical shapes which are extremely expensive to manufacture using traditional methods. However, the design freedom feature of Additive Manufacturing (AM) opens up possibilities for building nonlinear complex shaped surfaces for tailored thermal management properties. Also, AM is a tool-less production method that enables consolidation of multiple components into one part to save space and weight as well as shortening the assembly time [107]–[109]. The recent advancements in AM technology allowed fabricating complex cooling surfaces made of highly thermally conductive materials, such as silver, for thermal management applications. For example, Selective Laser Melting (SLM) method of AM was successfully used to 3D printing of pure and alloyed silver components for various applications [110]–[112]. Also, complex-shaped lattice structures based on triply periodic minimal surfaces (TPMS) were successfully printed and used as heat exchanger materials in various applications [113]–[117]. Thus, adopting AM for thermal management applications of PEMFC is expected to receive increased attention in future research studies.

For liquid cooling method, water was the most used coolant and very limited attention was given to using other types of the working fluid. For this, researching alternative coolant suitable for PEMFC and their cooling performance could be a topic of interest for future work.

To achieve a well-balanced cooling capacity and energy efficiency, there might be a need to use multiple cooling techniques in one hybrid cooling system. However, such hybrid cooling systems have received no attention in the literature and for this, they are recommended for future investigations.

5.2 Waste heat recovery

The advantages and drawbacks of the different PEMFC-WHR technologies are summarized in Table 2. Generally, utilizing a WHR system involves additional overall construction cost and some environmental consequences but the overall gain from using it is still positive. Recovering the low-grade waste heat, such as the waste heat of PEMFC, is considered to be more challenging than recovering medium–high temperature waste heat [23]. One of the main obstacles when recovering PEMFC waste heat is the need to use a large heat exchanger to achieve optimum heat transfer due to the low heat transfer rate associated with recovering low-temperature waste heat.

Despite the research work done on investigating the PEMFC-WHR options, the majority of these studies only focused on parametric analysis and thermodynamic performance evaluations and no attention was paid for evaluating the economic feasibility. It is correct that all WHR options can improve the energy efficiency of the PEMFC system but not all of them are beneficial economically as some of them might require significant investment [118]. Identifying the most suitable WHR option, technically and economically, for a specific fuel cell system is not a straight forward task and therefore a further research work is needed to provide a comprehensive understanding of the WHR system performance from both thermodynamic and economic perspectives.

Additionally, assessing the environmental impact and sustainability of the PEMFC-WHR system, using Life cycle assessment (LCA) tool, is another area which requires further attention in order to provide valuable insights into the environmental performance of the proposed system and its environmental benefits and drawbacks.

In order to achieve the utmost outcome of the WHR system, different responses and features, such as size, cost, performance, and so on, need to be satisfied and balanced simultaneously and this cannot be achieved without employing advanced optimization approaches. Thus, the use of multi-objective optimization algorithms in this field is expected to grow and become a topic of future studies.

Also, the majority of PEMFC-WHR studies are conducted using modelling techniques and there is a lack of experimental work. Thus, more experimental investigations are required in order to confirm the conclusion drawn by the modelling studies.

The majority of studies on using thermodynamic cycles to recover the PEMFC waste heat have focused on using the ORC cycle. However, the other possible thermodynamic cycles, such as Kalina cycle, have received very limited attention [119]. Kalina cycles can be used effectively to recover low-grade waste heat with temperature ranging between 80 and 400°C which is suitable for both LT-PEMFC and HT-PEMFC [22]. Kalina cycles offer many advantages compared to ORC including superior performance, higher flexibility, and reduced heat transfer temperature difference between its working fluid and heat source. Thus, such cycle is another possible route that requires further investigation as WHR option for PEMFC.

6. Conclusion

Thermal management of PEMFC through maintaining its temperature at an appropriate level and limiting the uncontrolled elevation of it is critical for achieving the stable performance and high efficiency of the device. There are different cooling strategies for thermal management of PEMFC. Air-cooling and water-cooling circuits in which multi-channel cooling plates are used to circulate the coolants within the stack is the current practice in the fuel cell industry to remove the PEMFC heat. Water-cooling is the favourable option for PEMFC stacks with power capacity greater than 5 kW while air-cooling is used when the power output is less than 5 kW. Cooling using nanofluids is a promising new trend allowing for greater cooling capacity while minimizing the size and weight of the cooling system. Also, phase change cooling is another strategy to achieve higher heat removal capacity suitable for large PEMFC with high power. Phase-change cooling is particularly beneficial in terms of reducing the size of the cooling system compared to the water cooling one. Passive cooling devices including heat spreaders and heat pipes were also used as heat management devices.

PEMFCs are considered among the promising technologies driving the transformation towards decarbonised and more sustainable societies. However, increasing the energy efficiency of a PEMFC continues to remain a challenge for this technology. Energy prices are increasing globally so there is an urgent necessity for any emerging energy technology, such as PEMFC, to increase efficiency and reduce the cost in order to remain competitive. WHR of PEMFC is among the promising options to improve the efficiency of a PEMFC power system. The waste heat recovered from the PEMFC can be used to generate power meaning that less hydrogen fuel is required to operate a given energy consuming terminal. The suggested WHR options for the PEMFC are: i) producing electrical power using appropriate thermodynamic power cycles, such as ORC, or direct heat to power approach, such as TEG; ii) simultaneous generation of heating, cooling, and electricity using CHP and CCP systems; iii) improving the hydrogen discharge rate from a MH; and iiii) preheating the reactants in cold weather.

Despite the recent intensive work presented in the literature on the cooling and WHR of PEMFC, the majority of the work is based on modelling approach and more reliable experimental investigations and comprehensive environmental assessment are still required to confirm the effectiveness, sustainability and economic viability of the proposed cooling and WHR systems. Also, widening the adoption of modern manufacturing technique, such as 3D printing, and developing more innovative materials will definitely address some of the challenges and allow for the development of effective cooling and WHR systems.

Conflict of interest statement

None.

References

[1] A. G. Olabi *et al.*, "Large-vscale hydrogen production and storage technologies: Current status and future directions," *Int. J. Hydrogen Energy*, Nov. 2020.

[2] M. Milani *et al.*, "Experimental and Numerical Analysis of a Liquid Aluminium Injector for an Al-H2O based Hydrogen Production System," *Int. J. Thermofluids*, vol. 7–8, p. 100018, Jan. 2020.

[3] T. Wilberforce *et al.*, "Developments of electric cars and fuel cell hydrogen electric cars," *Int. J. Hydrogen Energy*, vol. 42, no. 40, pp. 25695–25734, 2017.

[4] R. A. Varin, T. Czujko, and Z. S. Wronski, *Nanomaterials for Solid State Hydrogen Storage*. Boston, MA: Springer US, 2009.

[5] A. Baroutaji, T. Wilberforce, M. Ramadan, and A. G. Olabi, "Comprehensive investigation on hydrogen and fuel cell technology in the aviation and aerospace sectors," *Renew. Sustain. Energy Rev.*, vol. 106, pp. 31–40, May 2019.

[6] L. van Biert, M. Godjevac, K. Visser, and P. V. Aravind, "A review of fuel cell systems for maritime applications," *Journal of Power Sources*, vol. 327. Elsevier B.V., pp. 345–364, 30-Sep-2016.

[7] P. P. Kundu and K. Dutta, "Hydrogen fuel cells for portable applications," in *Compendium of Hydrogen Energy*, M. Ball, A. Basile, and T. N. Veziroğlu, Eds. Oxford: Woodhead

Publishing, 2016, pp. 111–131.

[8] T. Wilberforce, A. Alaswad, A. Palumbo, and M. Dassisti, "Advances in stationary and portable fuel cell applications," *Int. J. Hydrogen Energy*, vol. 41, no. 37, pp. 16509–16522, 2016.

[9] B. Paul and J. Andrews, "PEM unitised reversible/regenerative hydrogen fuel cell systems: State of the art and technical challenges," *Renewable and Sustainable Energy Reviews*, vol. 79. Elsevier Ltd, pp. 585–599, 01-Nov-2017.

[10] T. Wilberforce *et al.*, "A comprehensive study of the effect of bipolar plate (BP) geometry design on the performance of proton exchange membrane (PEM) fuel cells," *Renew. Sustain. Energy Rev.*, vol. 111, pp. 236–260, Sep. 2019.

[11] A. Baroutaji, J. G. Carton, A. M. Oladoye, J. Stokes, B. Twomey, and A. G. Olabi, "Ex-situ evaluation of PTFE coated metals in a proton exchange membrane fuel cell environment," *Surf. Coatings Technol.*, vol. 323, pp. 10–17, 2016.

[12] A. Alaswad, A. Baroutaji, H. Achour, J. Carton, A. Al Makky, and A. G. Olabi, "Developments in fuel cell technologies in the transport sector," *Int. J. Hydrogen Energy*, vol. 41, no. 37, pp. 16499–16508.

[13] A. Baroutaji, J. G. Carton, M. Sajjia, and A. G. Olabi, "Materials in PEM Fuel Cells," in *Reference Module in Materials Science and Materials Engineering*, Saleem Hashmi (editor-in-chief), Ed. Oxford: Elsevier, 2016, pp. 1–11.

[14] M. Sajid Hossain and B. Shabani, "Metal foams application to enhance cooling of open cathode polymer electrolyte membrane fuel cells," *J. Power Sources*, vol. 295, pp. 275–291, Nov. 2015.

[15] J. Han and S. Yu, "Ram air compensation analysis of fuel cell vehicle cooling system under driving modes," *Appl. Therm. Eng.*, vol. 142, pp. 530–542, Sep. 2018.

[16] J. Han, J. Park, and S. Yu, "Control strategy of cooling system for the optimization of parasitic power of automotive fuel cell system," *Int. J. Hydrogen Energy*, vol. 40, no. 39, pp. 13549–13557, Oct. 2015.

[17] S. Yu and D. Jung, "A study of operation strategy of cooling module with dynamic fuel cell system model for transportation application," *Renew. Energy*, vol. 35, no. 11, pp. 2525–2532, Nov. 2010.

[18] D. Brough, J. Ramos, B. Delpech, and H. Jouhara, "Development and validation of a TRNSYS type to simulate heat pipe heat exchangers in transient applications of waste heat recovery," *Int. J. Thermofluids*, vol. 9, p. 100056, Feb. 2021.

[19] D. Brough and H. Jouhara, "The aluminium industry: A review on state-of-the-art technologies, environmental impacts and possibilities for waste heat recovery," *International Journal of Thermofluids*, vol. 1–2. Elsevier B.V., p. 100007, 01-Feb-2020.

[20] H. Jouhara and A. G. Olabi, "Editorial: Industrial waste heat recovery," *Energy*, vol. 160. Elsevier Ltd, pp. 1–2, 01-Oct-2018.

[21] M. Poerner and A. Rimpel, "Waste heat recovery," in *Fundamentals and Applications of Supercritical Carbon Dioxide (SCO2) Based Power Cycles*, Elsevier Inc., 2017, pp. 255–267.

[22] J. Ling-Chin, H. Bao, Z. Ma, W. Taylor, and A. Paul Roskilly, "State-of-the-Art Technologies on Low-Grade Heat Recovery and Utilization in Industry," in *Energy Conversion - Current Technologies and Future Trends*, IntechOpen, 2019.

[23] H. Jouhara, N. Khordehgah, S. Almahmoud, B. Delpech, A. Chauhan, and S. A. Tassou, "Waste heat recovery technologies and applications," *Thermal Science and Engineering Progress*, vol. 6. Elsevier Ltd, pp. 268–289, 01-Jun-2018.

[24] A. G. Olabi, K. Elsaid, M. K. H. Rabaia, A. A. Askalany, and M. A. Abdelkareem, "Waste heat-driven desalination systems: Perspective," *Energy*, vol. 209, p. 118373, Oct. 2020.

[25] A. Baroutaji *et al.*, “Materials for Fuel Cell Membranes,” in *Reference Module in Materials Science and Materials Engineering*, Elsevier, 2020.

[26] J. G. Carton and A. Baroutaji, “Developments of Foam Materials for Fuel Cell Technology,” in *Reference Module in Materials Science and Materials Engineering*, Elsevier, 2016.

[27] A. Baroutaji, J. G. Carton, J. Stokes, and A. G. Olabi, “Application of Open Pore Cellular Foam for air breathing PEM fuel cell,” *Int. J. Hydrogen Energy*, vol. 42, no. 40, pp. 25630–25638, Oct. 2017.

[28] R. E. Rosli *et al.*, “A review of high-temperature proton exchange membrane fuel cell (HT-PEMFC) system,” *Int. J. Hydrogen Energy*, vol. 42, no. 14, pp. 9293–9314, Apr. 2017.

[29] G. Zhang and S. G. Kandlikar, “A critical review of cooling techniques in proton exchange membrane fuel cell stacks,” *Int. J. Hydrogen Energy*, vol. 37, no. 3, pp. 2412–2429, Feb. 2012.

[30] W. R. W. Daud, R. E. Rosli, E. H. Majlan, S. A. A. Hamid, R. Mohamed, and T. Husaini, “PEM fuel cell system control: A review,” *Renew. Energy*, vol. 113, pp. 620–638, Dec. 2017.

[31] J. Ramousse, O. Lottin, S. Didierjean, and D. Maillet, “Heat sources in proton exchange membrane (PEM) fuel cells,” *J. Power Sources*, vol. 192, no. 2, pp. 435–441, Jul. 2009.

[32] J. Yuan, M. Faghri, and & B. Sundén, “On heat and mass transfer phenomena in PEMFC and SOFC and modeling approaches,” in *Transport Phenomena in Fuel Cells*, 2005, pp. 133–174.

[33] E. J. Choi, J. Y. Park, and M. S. Kim, “Two-phase cooling using HFE-7100 for polymer electrolyte membrane fuel cell application,” *Appl. Therm. Eng.*, vol. 148, pp. 868–877, Feb. 2019.

[34] H. Q. Nguyen and B. Shabani, “Proton exchange membrane fuel cells heat recovery opportunities for combined heating/cooling and power applications,” *Energy Conversion and Management*, vol. 204. Elsevier Ltd, p. 112328, 15-Jan-2020.

[35] A. Faghri and Z. Guo, “Challenges and opportunities of thermal management issues related to

fuel cell technology and modeling," *International Journal of Heat and Mass Transfer*, vol. 48, no. 19–20. Pergamon, pp. 3891–3920, 01-Sep-2005.

[36] Y. Wang, D. F. Ruiz Diaz, K. S. Chen, Z. Wang, and X. C. Adroher, "Materials, technological status, and fundamentals of PEM fuel cells – A review," *Materials Today*, vol. 32. Elsevier B.V., pp. 178–203, 01-Jan-2020.

[37] C. Y. Wen and G. W. Huang, "Application of a thermally conductive pyrolytic graphite sheet to thermal management of a PEM fuel cell," *J. Power Sources*, vol. 178, no. 1, pp. 132–140, Mar. 2008.

[38] C. Y. Wen, Y. S. Lin, and C. H. Lu, "Performance of a proton exchange membrane fuel cell stack with thermally conductive pyrolytic graphite sheets for thermal management," *J. Power Sources*, vol. 189, no. 2, pp. 1100–1105, Apr. 2009.

[39] C. Y. Wen, Y. S. Lin, C. H. Lu, and T. W. Luo, "Thermal management of a proton exchange membrane fuel cell stack with pyrolytic graphite sheets and fans combined," *Int. J. Hydrogen Energy*, vol. 36, no. 10, pp. 6082–6089, May 2011.

[40] H. Jouhara, A. Chauhan, T. Nannou, S. Almahmoud, B. Delpech, and L. C. Wrobel, "Heat pipe based systems - Advances and applications," *Energy*, vol. 128. Elsevier Ltd, pp. 729–754, 01-Jun-2017.

[41] W. Srimuang and P. Amatachaya, "A review of the applications of heat pipe heat exchangers for heat recovery," *Renewable and Sustainable Energy Reviews*, vol. 16, no. 6. Pergamon, pp. 4303–4315, 01-Aug-2012.

[42] H. Jouhara, V. Anastasov, and I. Khamis, "Potential of heat pipe technology in nuclear seawater desalination," *Desalination*, vol. 249, no. 3, pp. 1055–1061, Dec. 2009.

[43] H. Tang *et al.*, "Review of applications and developments of ultra-thin micro heat pipes for electronic cooling," *Applied Energy*, vol. 223. Elsevier Ltd, pp. 383–400, 01-Aug-2018.

[44] L. Vasiliev and L. Vasiliev, "Heat Pipes in Fuel Cell Technology," Springer, Dordrecht, 2008, pp. 117–124.

[45] J. Zhao, Q. Jian, and Z. Huang, "Experimental study on heat transfer performance of vapor chambers with potential applications in thermal management of proton exchange membrane fuel cells," *Appl. Therm. Eng.*, vol. 180, p. 115847, Aug. 2020.

[46] M. V. Oro and E. Bazzo, "Flat heat pipes for potential application in fuel cell cooling," *Appl. Therm. Eng.*, vol. 90, pp. 848–857, 2015.

[47] W. Joung, T. Yu, and J. Lee, "Experimental study on the loop heat pipe with a planar bifacial wick structure," *Int. J. Heat Mass Transf.*, vol. 51, no. 7–8, pp. 1573–1581, Apr. 2008.

[48] A. P. Silva, R. M. Galante, P. R. Pelizza, and E. Bazzo, "A combined capillary cooling system for fuel cells," in *Applied Thermal Engineering*, 2012, vol. 41, pp. 104–110.

[49] J. Clement and X. Wang, "Experimental investigation of pulsating heat pipe performance with regard to fuel cell cooling application," *Appl. Therm. Eng.*, vol. 50, no. 1, pp. 268–274, Jan. 2013.

[50] A. Fly and R. H. H. Thring, "A comparison of evaporative and liquid cooling methods for fuel cell vehicles," *Int. J. Hydrogen Energy*, vol. 41, no. 32, pp. 14217–14229, Aug. 2016.

[51] A. De las Heras, F. J. Vivas, F. Segura, M. J. Redondo, and J. M. Andújar, "Air-cooled fuel cells: Keys to design and build the oxidant/cooling system," *Renew. Energy*, vol. 125, pp. 1–20, Sep. 2018.

[52] C. D'souza *et al.*, "Thermal characteristics of an air-cooled open-cathode proton exchange membrane fuel cell stack via numerical investigation," *Int J Energy Res*, 2020.

[53] R. Mosdale and S. Srinivasan, "Analysis of performance and of water and thermal management in proton exchange membrane fuel cells," *Electrochim. Acta*, vol. 40, no. 4, pp. 413–421, Mar. 1995.

[54] M. Ramezanizadeh, M. Alhuyi Nazari, M. Hossein Ahmadi, and L. Chen, “A review on the approaches applied for cooling fuel cells,” *International Journal of Heat and Mass Transfer*, vol. 139. Elsevier Ltd, pp. 517–525, 01-Aug-2019.

[55] E. Alizadeh, S. M. Rahgoshay, M. Rahimi-Esbo, M. Khorshidian, and S. H. M. Saadat, “A novel cooling flow field design for polymer electrolyte membrane fuel cell stack,” *Int. J. Hydrogen Energy*, vol. 41, no. 20, pp. 8525–8532, Jun. 2016.

[56] S. Ravishankar and K. Arul Prakash, “Numerical studies on thermal performance of novel cooling plate designs in polymer electrolyte membrane fuel cell stacks,” *Appl. Therm. Eng.*, vol. 66, no. 1–2, pp. 239–251, May 2014.

[57] S. Shahsavari, A. Desouza, M. Bahrami, and E. Kjeang, “Thermal analysis of air-cooled PEM fuel cells,” *Int. J. Hydrogen Energy*, vol. 37, no. 23, pp. 18261–18271, Dec. 2012.

[58] M. Matian, A. Marquis, and N. Brandon, “Model based design and test of cooling plates for an air-cooled polymer electrolyte fuel cell stack,” *Int. J. Hydrogen Energy*, vol. 36, no. 10, pp. 6051–6066, May 2011.

[59] M. Odabaee, S. Mancin, and K. Hooman, “Metal foam heat exchangers for thermal management of fuel cell systems-An experimental study,” 2013.

[60] N. Lee *et al.*, “Metal-foam-based cathode flow-field design to improve H2O retention capability of passive air cooled polymer electrolyte fuel cells,” *Int. J. Therm. Sci.*, p. 106702, Nov. 2020.

[61] S. M. Baek, S. H. Yu, J. H. Nam, and C. J. Kim, “A numerical study on uniform cooling of large-scale PEMFCs with different coolant flow field designs,” *Appl. Therm. Eng.*, vol. 31, no. 8–9, pp. 1427–1434, Jun. 2011.

[62] F. C. C. Chen, Z. Gao, R. O. O. Loutfy, and M. Hecht, “Analysis of Optimal Heat Transfer in a PEM Fuel Cell Cooling Plate,” *Fuel Cells*, vol. 3, no. 4, pp. 181–188, Dec. 2003.

[63] E. Afshari, M. Ziaei-Rad, and M. M. Dehkordi, “Numerical investigation on a novel zigzag-shaped flow channel design for cooling plates of PEM fuel cells,” *J. Energy Inst.*, vol. 90, no. 5, pp. 752–763, Oct. 2017.

[64] M. Ghasemi, A. Ramiar, A. A. Ranjbar, and S. M. Rahgoshay, “A numerical study on thermal analysis and cooling flow fields effect on PEMFC performance,” *Int. J. Hydrogen Energy*, vol. 42, no. 38, pp. 24319–24337, Sep. 2017.

[65] S. M. Rahgoshay, A. A. Ranjbar, A. Ramiar, and E. Alizadeh, “Thermal investigation of a PEM fuel cell with cooling flow field,” *Energy*, vol. 134, pp. 61–73, Sep. 2017.

[66] R. D. Plant and M. Z. Saghir, “Numerical and experimental investigation of high concentration aqueous alumina nanofluids in a two and three channel heat exchanger,” *Int. J. Thermofluids*, vol. 9, p. 100055, Feb. 2021.

[67] V. Sridhara and L. N. Satapathy, “Al2O3-based nanofluids: A review,” *Nanoscale Research Letters*, vol. 6, no. 1. Springer, pp. 1–16, 2011.

[68] M. R. Islam, B. Shabani, G. Rosengarten, and J. Andrews, “The potential of using nanofluids in PEM fuel cell cooling systems: A review,” *Renew. Sustain. Energy Rev.*, vol. 48, pp. 523–539, Aug. 2015.

[69] M. R. Islam, B. Shabani, and G. Rosengarten, “Nanofluids to improve the performance of PEM fuel cell cooling systems: A theoretical approach,” *Appl. Energy*, vol. 178, pp. 660–671, Sep. 2016.

[70] I. Zakaria, W. A. N. W. Mohamed, W. H. Azmi, A. M. I. Mamat, R. Mamat, and W. R. W. Daud, “Thermo-electrical performance of PEM fuel cell using Al2O3 nanofluids,” *Int. J. Heat Mass Transf.*, vol. 119, pp. 460–471, Apr. 2018.

[71] I. Zakaria *et al.*, “Thermal analysis of Al2O3ewater ethylene glycol mixture nanofluid for single PEM fuel cell cooling plate: An experimental study,” *Int. J. Hydrogen Energy*, vol. 41,

no. 9, pp. 5096–5112, Mar. 2016.

[72] I. A. Zakaria, W. A. N. W. Mohamed, M. B. Zailan, and W. H. Azmi, “Experimental analysis of SiO2-Distilled water nanofluids in a Polymer Electrolyte Membrane fuel cell parallel channel cooling plate,” *Int. J. Hydrogen Energy*, vol. 44, no. 47, pp. 25850–25862, Oct. 2019.

[73] M. R. Sohel, S. S. Khaleduzzaman, R. Saidur, A. Hepbasli, M. F. M. Sabri, and I. M. Mahbubul, “An experimental investigation of heat transfer enhancement of a minichannel heat sink using Al2O3-H2O nanofluid,” *Int. J. Heat Mass Transf.*, vol. 74, pp. 164–172, Jul. 2014.

[74] M. K. Moraveji and R. M. Ardehali, “CFD modeling (comparing single and two-phase approaches) on thermal performance of Al2o3/water nanofluid in mini-channel heat sink,” *Int. Commun. Heat Mass Transf.*, vol. 44, pp. 157–164, May 2013.

[75] H. Jouhara, A. Żabnieńska-Góra, N. Khordehgah, D. Ahmad, and T. Lipinski, “Latent thermal energy storage technologies and applications: A review,” *Int. J. Thermofluids*, vol. 5–6, p. 100039, Aug. 2020.

[76] U. Soupremanien, S. Le Person, M. Favre-Marinet, and Y. Bultel, “Tools for designing the cooling system of a proton exchange membrane fuel cell,” *Appl. Therm. Eng.*, vol. 40, pp. 161–173, Jul. 2012.

[77] S. H. Hwang and M. S. Kim, “An experimental study on the cathode humidification and evaporative cooling of polymer electrolyte membrane fuel cells using direct water injection method at high current densities,” *Appl. Therm. Eng.*, vol. 99, pp. 635–644, Apr. 2016.

[78] D. L. Wood, J. S. Yi, and T. V. Nguyen, “Effect of direct liquid water injection and interdigitated flow field on the performance of proton exchange membrane fuel cells,” *Electrochim. Acta*, vol. 43, no. 24, pp. 3795–3809, Aug. 1998.

[79] A. Fly and R. H. Thring, “Temperature regulation in an evaporatively cooled proton exchange membrane fuel cell stack,” in *International Journal of Hydrogen Energy*, 2015, vol. 40, no. 35,

pp. 11976–11982.

[80] A. Z. Weber and R. M. Darling, “Understanding porous water-transport plates in polymer-electrolyte fuel cells,” *J. Power Sources*, vol. 168, no. 1 SPEC. ISS., pp. 191–199, May 2007.

[81] K. M. Oseen-Senda, F. Lundell, A. Hillenbach, and J. Pauchet, “The cooling of PEFC with pentane boiling in minichannels: A study of flow instabilities using neutron radiography visualization,” *Heat Transf. Eng.*, vol. 28, no. 1, pp. 49–57, Jan. 2007.

[82] T. W. Song, K. H. Choi, J. R. Kim, and J. S. Yi, “Pumpless thermal management of water-cooled high-temperature proton exchange membrane fuel cells,” *J. Power Sources*, vol. 196, no. 10, pp. 4671–4679, May 2011.

[83] E. J. Choi, J. Y. Park, and M. S. Kim, “A comparison of temperature distribution in PEMFC with single-phase water cooling and two-phase HFE-7100 cooling methods by numerical study,” *Int. J. Hydrogen Energy*, vol. 43, no. 29, pp. 13406–13419, Jul. 2018.

[84] P. T. Garrity, J. F. Klausner, and R. Mei, “A flow boiling microchannel evaporator plate for fuel cell thermal management,” *Heat Transf. Eng.*, vol. 28, no. 10, pp. 877–884, Oct. 2007.

[85] A. G. Olabi, T. Wilberforce, E. T. Sayed, K. Elsaid, and M. A. Abdelkareem, “Prospects of Fuel Cell Combined Heat and Power Systems,” *Energies*, vol. 13, no. 16, p. 4104, Aug. 2020.

[86] A. P. Tetuko, B. Shabani, and J. Andrews, “Thermal coupling of PEM fuel cell and metal hydride hydrogen storage using heat pipes,” *Int. J. Hydrogen Energy*, vol. 41, no. 7, pp. 4264–4277, Feb. 2016.

[87] A. P. Tetuko, B. Shabani, R. Omrani, B. Paul, and J. Andrews, “Study of a thermal bridging approach using heat pipes for simultaneous fuel cell cooling and metal hydride hydrogen discharge rate enhancement,” *J. Power Sources*, vol. 397, pp. 177–188, Sep. 2018.

[88] F. Mahmoodi and R. Rahimi, “Experimental and numerical investigating a new configured thermal coupling between metal hydride tank and PEM fuel cell using heat pipes,” *Appl.*

Therm. Eng., vol. 178, p. 115490, Sep. 2020.

[89] M. Nasri *et al.*, "Waste Heat Recovery for Fuel Cell Electric Vehicle with Thermochemical Energy Storage," in *2016 11th International Conference on Ecological Vehicles and Renewable Energies, EVER 2016*, 2016.

[90] A. P. Sasmito, T. Shamim, and A. S. Mujumdar, "Passive thermal management for PEM fuel cell stack under cold weather condition using phase change materials (PCM)," *Appl. Therm. Eng.*, vol. 58, no. 1–2, pp. 615–625, Sep. 2013.

[91] H. Q. Nguyen, A. M. Aris, and B. Shabani, "PEM fuel cell heat recovery for preheating inlet air in standalone solar-hydrogen systems for telecommunication applications: An exergy analysis," *Int. J. Hydrogen Energy*, vol. 41, no. 4, pp. 2987–3003, Jan. 2016.

[92] H. R. Ellamla, I. Staffell, P. Bujlo, B. G. Pollet, and S. Pasupathi, "Current status of fuel cell based combined heat and power systems for residential sector," *Journal of Power Sources*, vol. 293. Elsevier B.V., pp. 312–328, 30-May-2015.

[93] A. Arsalis, "A comprehensive review of fuel cell-based micro-combined-heat-and-power systems," *Renewable and Sustainable Energy Reviews*, vol. 105. Elsevier Ltd, pp. 391–414, 01-May-2019.

[94] G. Di Marcoberardino, G. Manzolini, C. Guignard, and V. Magaud, "Optimization of a micro-CHP system based on polymer electrolyte membrane fuel cell and membrane reactor from economic and life cycle assessment point of view," *Chem. Eng. Process. - Process Intensif.*, vol. 131, pp. 70–83, Sep. 2018.

[95] X. Chen *et al.*, "Multi-criteria assessment and optimization study on 5 kW PEMFC based residential CCHP system," *Energy Convers. Manag.*, vol. 160, pp. 384–395, Mar. 2018.

[96] H. Chang, X. Xu, J. Shen, S. Shu, and Z. Tu, "Performance analysis of a micro-combined heating and power system with PEM fuel cell as a prime mover for a typical household in

North China," *Int. J. Hydrogen Energy*, vol. 44, no. 45, pp. 24965–24976, Sep. 2019.

[97] M. Chahartaghi and B. A. Kharkeshi, "Performance analysis of a combined cooling, heating and power system with PEM fuel cell as a prime mover," *Appl. Therm. Eng.*, vol. 128, pp. 805–817, Jan. 2018.

[98] P. Yang and H. Zhang, "Parametric analysis of an irreversible proton exchange membrane fuel cell/absorption refrigerator hybrid system," *Energy*, vol. 85, pp. 458–467, Jun. 2015.

[99] M. V. Oro, R. G. de Oliveira, and E. Bazzo, "An integrated solution for waste heat recovery from fuel cells applied to adsorption systems," *Appl. Therm. Eng.*, vol. 136, pp. 747–754, May 2018.

[100] T. He, R. Shi, J. Peng, W. Zhuge, and Y. Zhang, "Waste Heat Recovery of a PEMFC System by Using Organic Rankine Cycle," *Energies*, vol. 9, no. 4, p. 267, Apr. 2016.

[101] P. Zhao, J. Wang, L. Gao, and Y. Dai, "Parametric analysis of a hybrid power system using organic Rankine cycle to recover waste heat from proton exchange membrane fuel cell," *Int. J. Hydrogen Energy*, vol. 37, no. 4, pp. 3382–3391, Feb. 2012.

[102] M. A. Sheshpoli, S. S. M. Ajarostaghi, and M. A. Delavar, "Thermodynamic analysis of waste heat recovery from hybrid system of proton exchange membrane fuel cell and vapor compression refrigeration cycle by recuperative organic Rankine cycle," *J. Therm. Anal. Calorim.*, vol. 135, no. 3, pp. 1699–1712, Feb. 2019.

[103] M. Alijanpour sheshpoli, S. S. Mousavi Ajarostaghi, and M. A. Delavar, "Waste heat recovery from a 1180 kW proton exchange membrane fuel cell (PEMFC) system by Recuperative organic Rankine cycle (RORC)," *Energy*, vol. 157, pp. 353–366, Aug. 2018.

[104] M. H. Ahmadi *et al.*, "Thermodynamic analysis and optimization of a waste heat recovery system for proton exchange membrane fuel cell using transcritical carbon dioxide cycle and cold energy of liquefied natural gas," *J. Nat. Gas Sci. Eng.*, vol. 34, pp. 428–438, Aug. 2016.

[105] M. Saufi Sulaiman, B. Singh, and W. A. N. W. Mohamed, "Experimental and theoretical study of thermoelectric generator waste heat recovery model for an ultra-low temperature PEM fuel cell powered vehicle," *Energy*, vol. 179, pp. 628–646, Jul. 2019.

[106] M. Alam, K. Kumar, and V. Dutta, "Dynamic modeling and experimental analysis of waste heat recovery from the proton exchange membrane fuel cell using thermoelectric generator," *Therm. Sci. Eng. Prog.*, vol. 19, p. 100627, Oct. 2020.

[107] A. Baroutaji, A. Arjunan, M. Stanford, J. Robinson, and A. G. Olabi, "Deformation and energy absorption of additively manufactured functionally graded thickness thin-walled circular tubes under lateral crushing," *Eng. Struct.*, vol. 226, 2021.

[108] A. Arjunan, M. Singh, A. Baroutaji, and C. Wang, "Additively manufactured AlSi10Mg inherently stable thin and thick-walled lattice with negative Poisson's ratio," *Compos. Struct.*, vol. 247, Sep. 2020.

[109] A. Arjunan, M. Demetriou, A. Baroutaji, and C. Wang, "Mechanical performance of highly permeable laser melted Ti6Al4V bone scaffolds," *J. Mech. Behav. Biomed. Mater.*, 2020.

[110] A. Arjunan, J. Robinson, E. Al Ani, W. Heaselgrave, A. Baroutaji, and C. Wang, "Mechanical performance of additively manufactured pure silver antibacterial bone scaffolds," *J. Mech. Behav. Biomed. Mater.*, vol. 112, p. 104090, Dec. 2020.

[111] J. Robinson, M. Stanford, and A. Arjunan, "Correlation between selective laser melting parameters, pore defects and tensile properties of 99.9 % silver," *Mater. Today Commun.*, vol. 25, p. 101550, Dec. 2020.

[112] J. Robinson, M. Stanford, and A. Arjunan, "Stable formation of powder bed laser fused 99.9% silver," *Mater. Today Commun.*, vol. 24, p. 101195, Sep. 2020.

[113] M. I. Hassan Ali, O. Al-Ketan, M. Khalil, N. Baobaid, K. Khan, and R. K. Abu Al-Rub, "3D printed architected heat sinks cooling performance in free and forced convection

environments," in *ASME 2020 Heat Transfer Summer Conference, HT 2020, collocated with the ASME 2020 Fluids Engineering Division Summer Meeting and the ASME 2020 18th International Conference on Nanochannels, Microchannels, and Minichannels*, 2020.

[114] M. I. Hassan Ali, O. Al-Ketan, A. Alhammadi, M. Khalil, K. Khan, and R. K. Abu Al-Rub, "Heat transfer characterization of 3D printable architected heat sinks," in *ASME International Mechanical Engineering Congress and Exposition, Proceedings (IMECE)*, 2019, vol. 8.

[115] D. W. Abueidda, R. K. Abu Al-Rub, A. S. Dalaq, D. W. Lee, K. A. Khan, and I. Jasiuk, "Effective conductivities and elastic moduli of novel foams with triply periodic minimal surfaces," *Mech. Mater.*, vol. 95, pp. 102–115, Apr. 2016.

[116] N. Thomas, N. Sreedhar, O. Al-Ketan, R. Rowshan, R. K. Abu Al-Rub, and H. Arafat, "3D printed triply periodic minimal surfaces as spacers for enhanced heat and mass transfer in membrane distillation," *Desalination*, vol. 443, pp. 256–271, Oct. 2018.

[117] W. Li, G. Yu, and Z. Yu, "Bioinspired heat exchangers based on triply periodic minimal surfaces for supercritical CO2 cycles," *Appl. Therm. Eng.*, vol. 179, p. 115686, Oct. 2020.

[118] E. Woolley, Y. Luo, and A. Simeone, "Industrial waste heat recovery: A systematic approach," *Sustain. Energy Technol. Assessments*, vol. 29, pp. 50–59, Oct. 2018.

[119] V. Rezaee and A. Houshmand, "Energy and exergy analysis of a combined power generation system using PEM fuel cell and kalina cycle system 11," *Period. Polytech. Chem. Eng.*, vol. 60, no. 2, pp. 98–105, 2016.

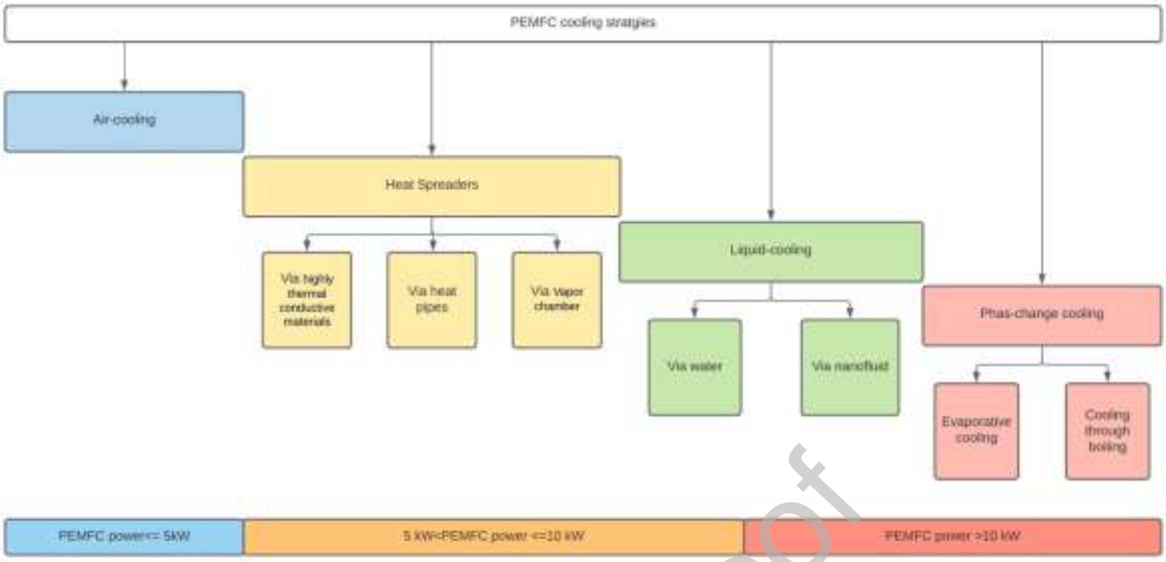

Figure 1: Main cooling strategies of PEMFC

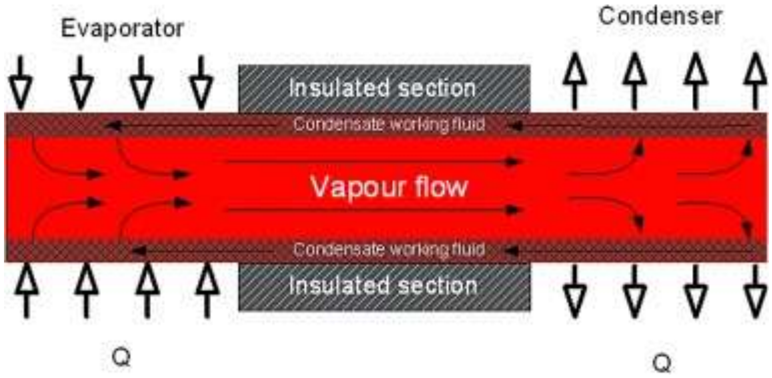

Figure 2: Heat pipe working concept [42]

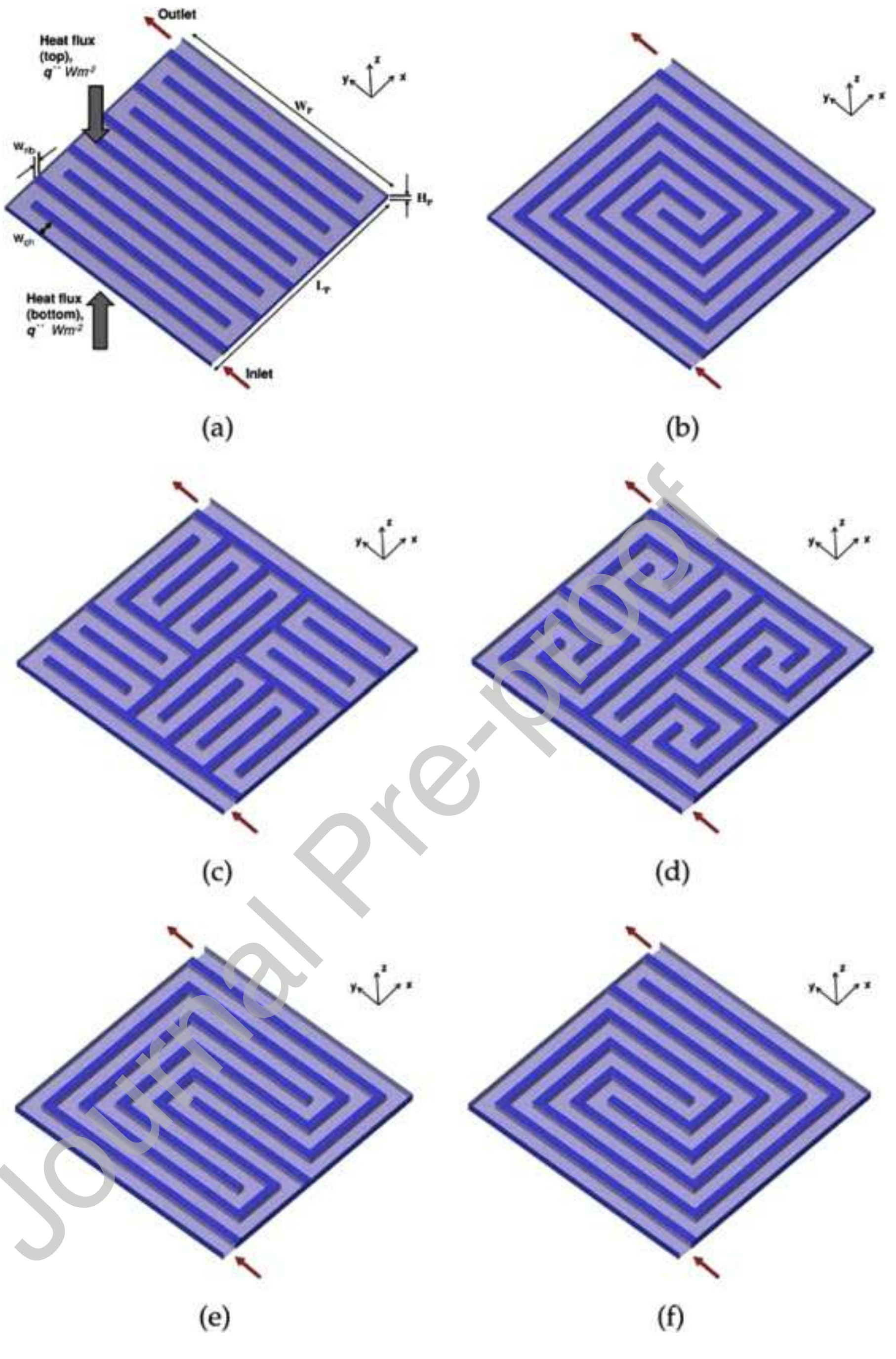

Figure 3: Air-flow cooling channels design [56]

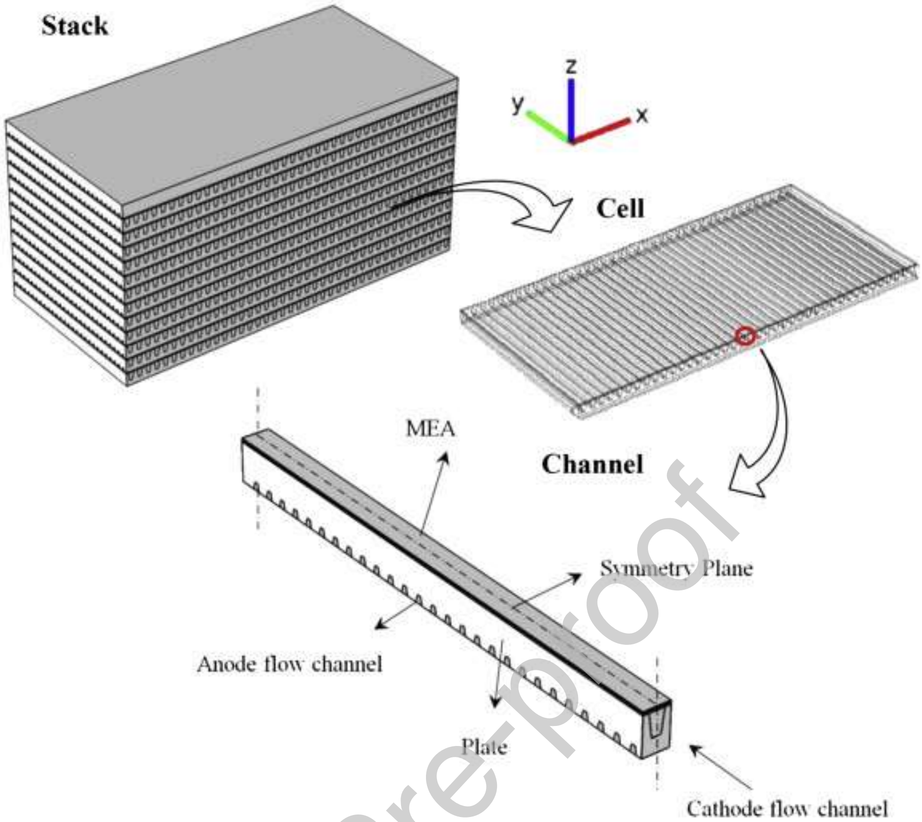

Figure 4: PEMFC design with combined oxidant and cooling channels [57]

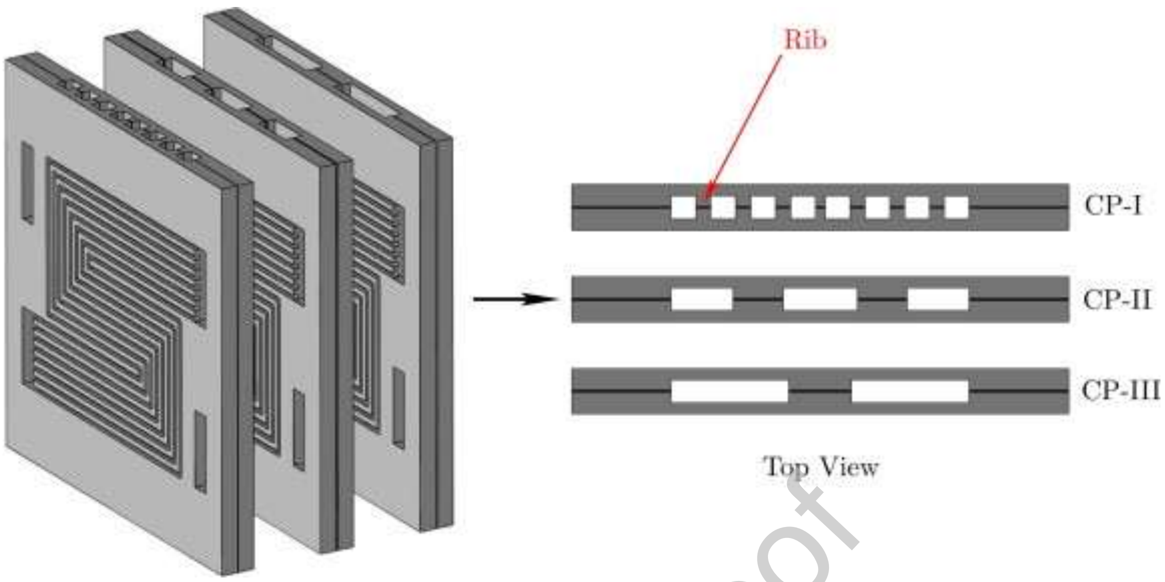

Figure 5: Cooling plates designs investigated by [58]

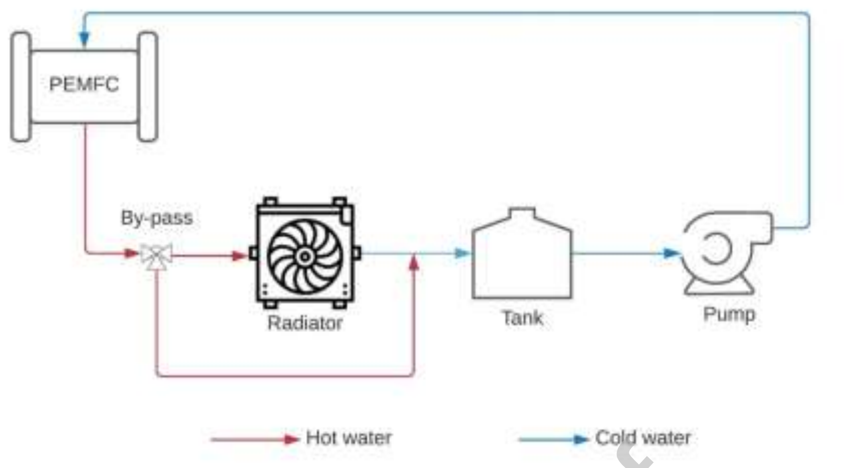

Figure 6: Typical cooling system of PEMFC using water

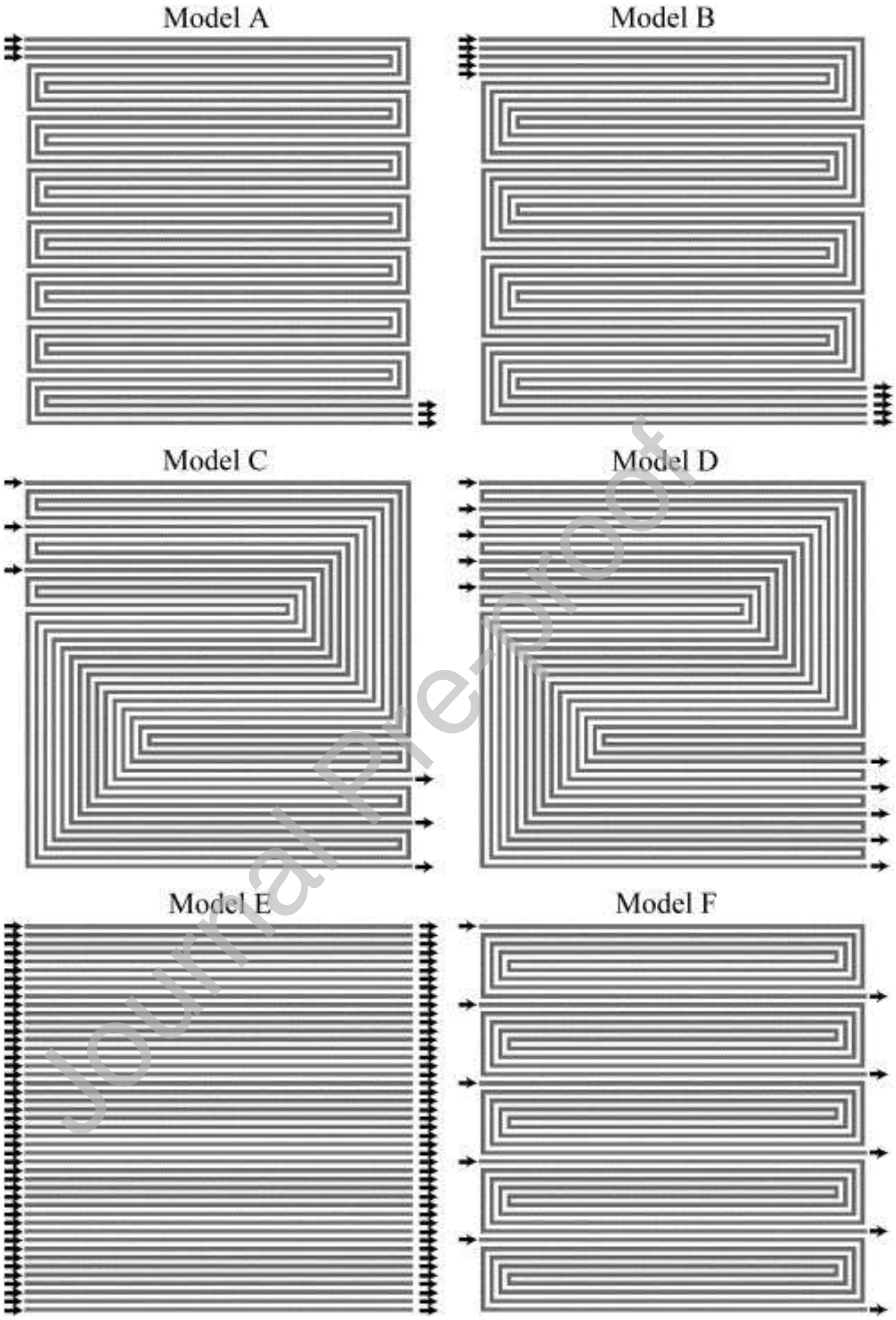

Figure 7: Coolant flow field designs studied by Baek et al. [61]

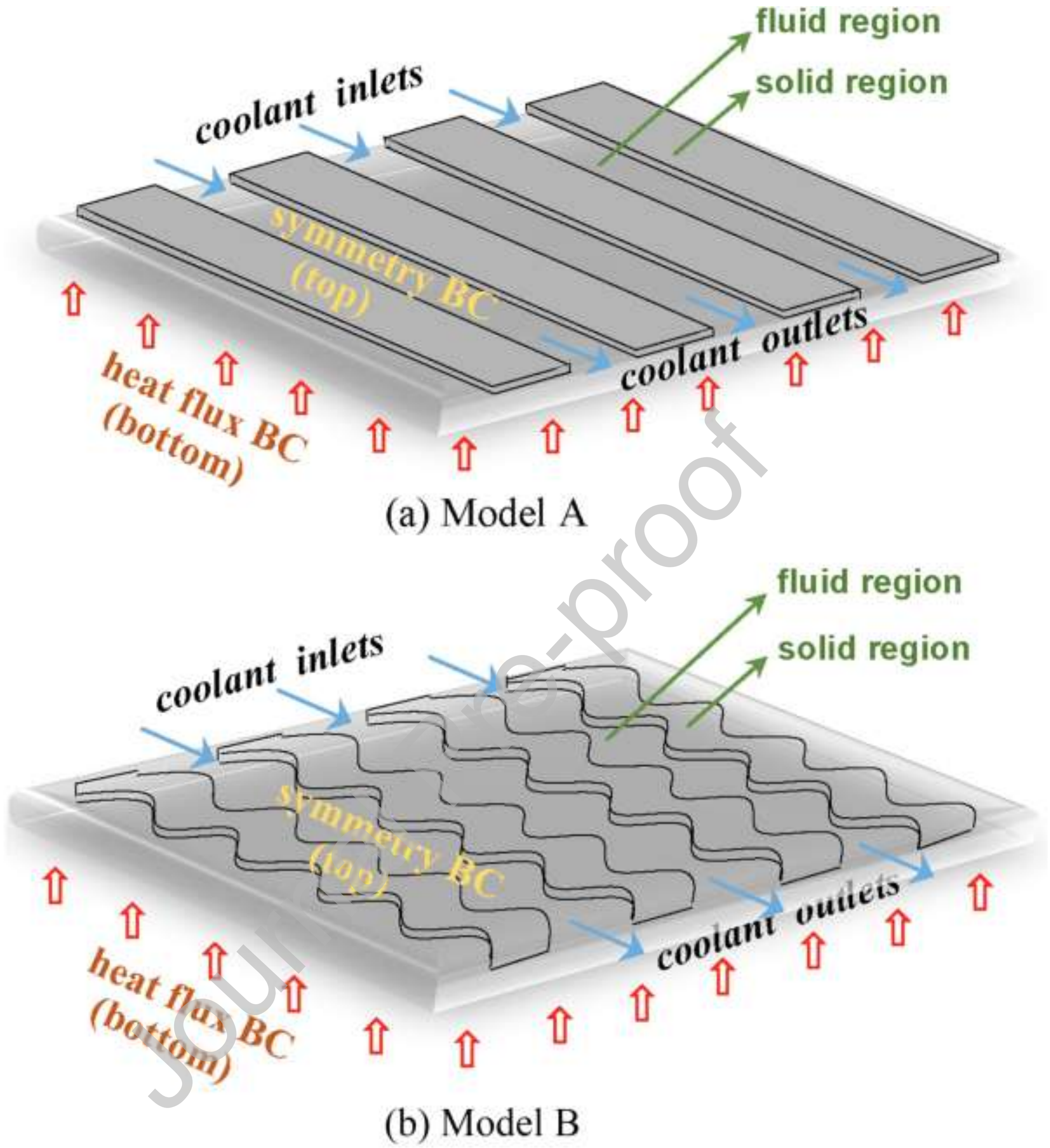

Figure 8: Straight and zigzag flow channels [63]

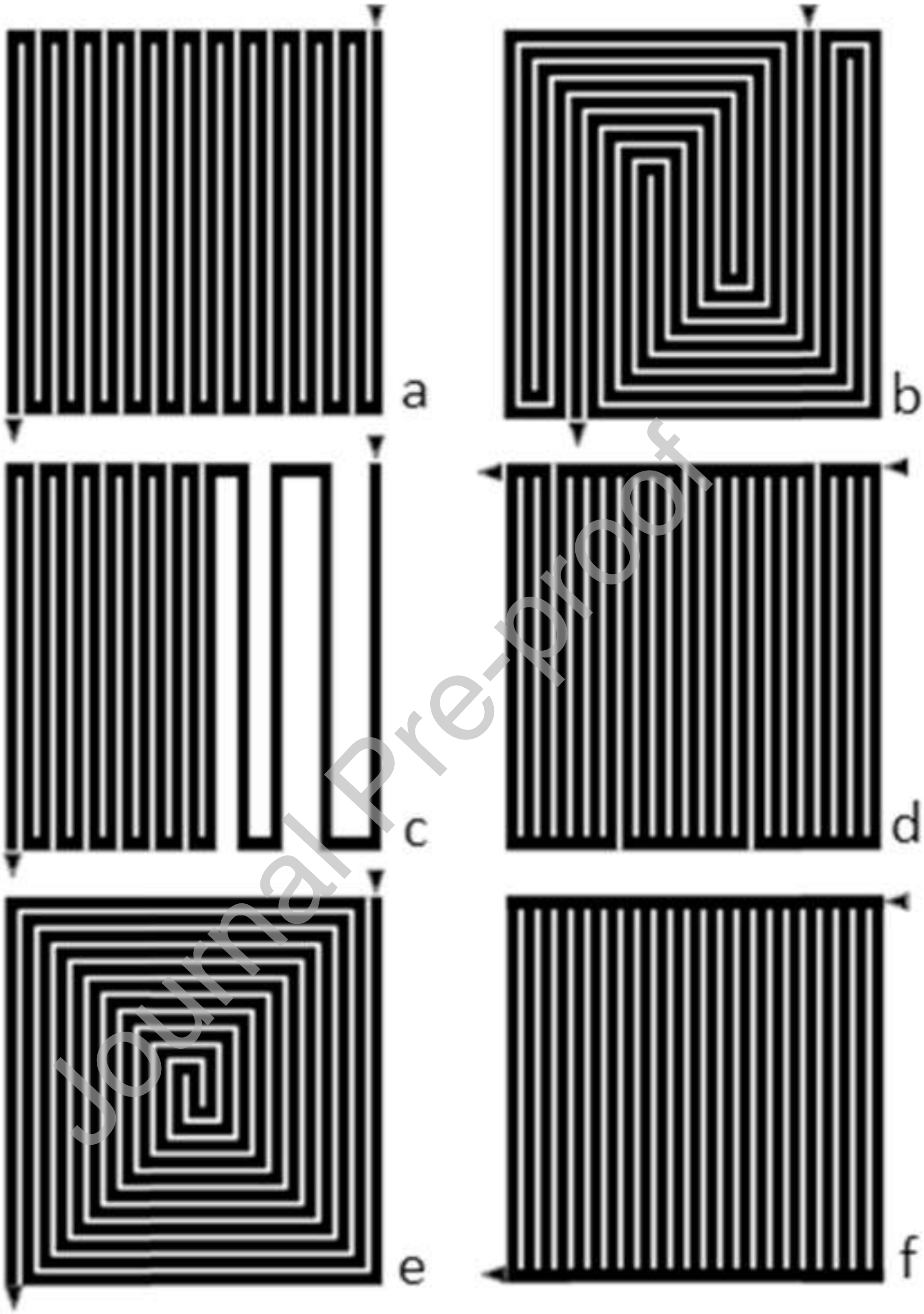

Figure 9: Coolant flow fields investigated by Ghasemi *et al.* [64]: (a) serpentine (b) multi-pass serpentine (c) serpentine with different distances between the channels (d) parallel-serpentine (e) spiral (f) parallel

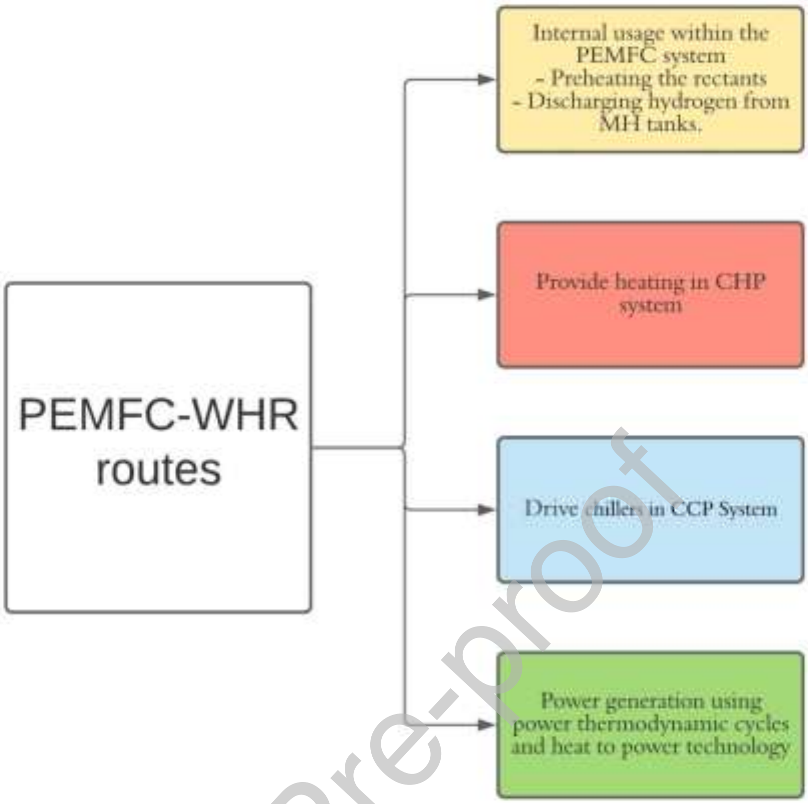

Figure 10: PEMFC waste heat recovery options

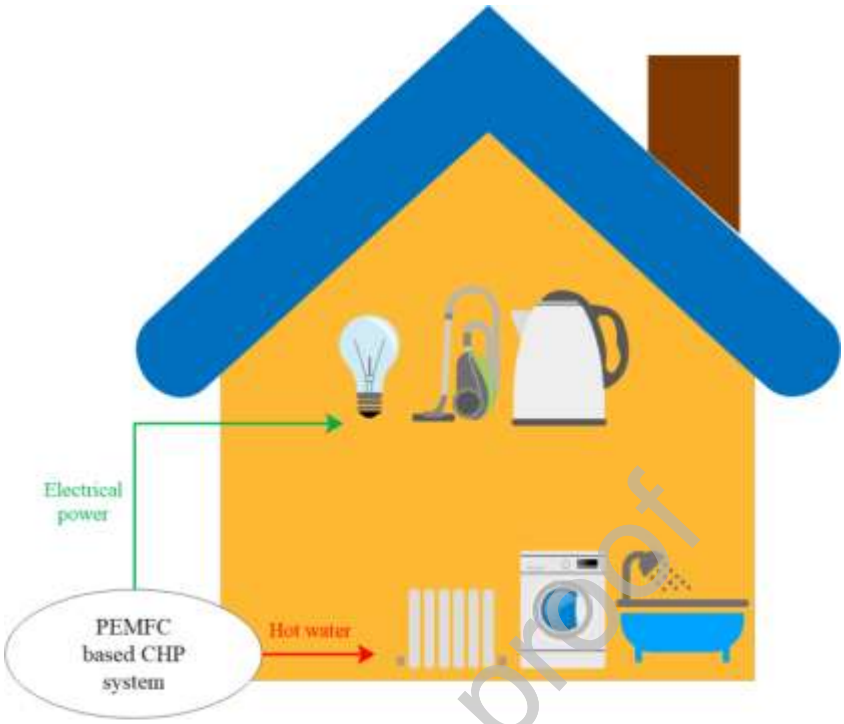

Figure 11: Illustration of PEMFC-based CHP system

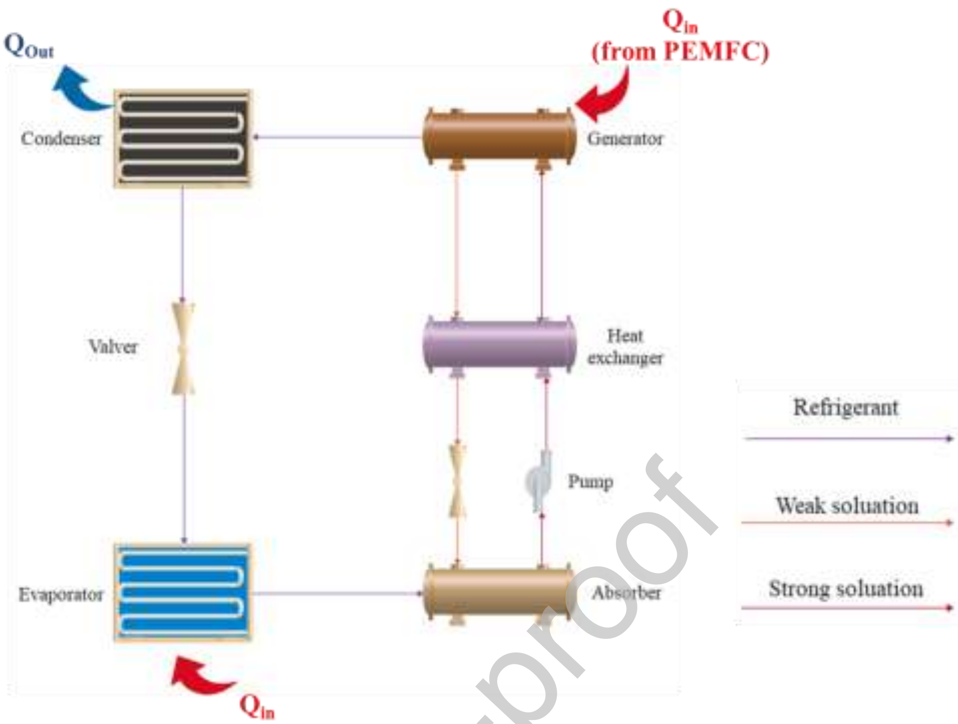

Figure 12: Illustration of an absorption chiller system using PEMFC waste heat to drive the generator

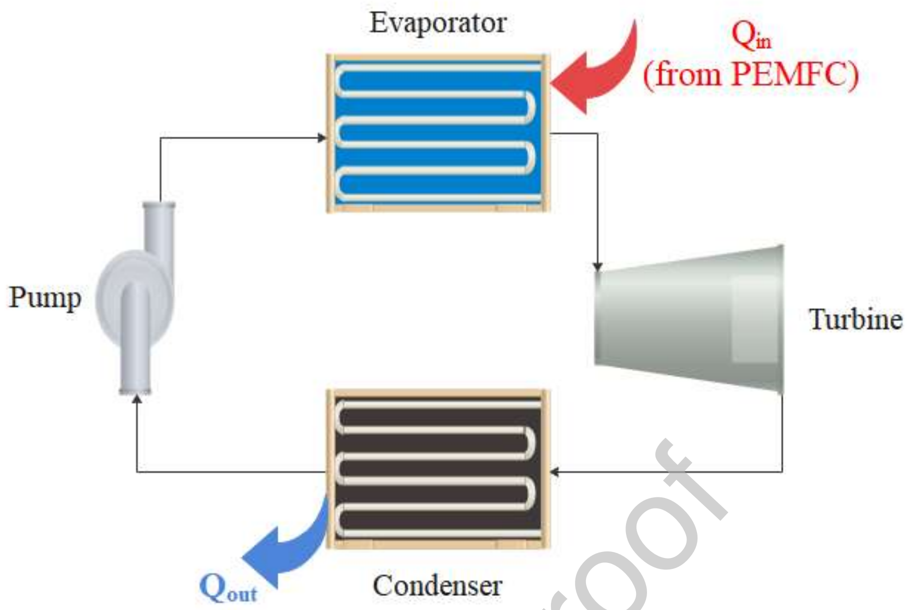

Figure 13: Illustration of ORC system using PEMFC heat in the evaporator

Table 1: Advantages and drawbacks of PEMFC cooling methods

PEMFC cooling method	Summary	Advantages	Drawbacks
Heat spreader	Passive cooling technique achieved using highly thermally conductive material or heat pipes	• Simple design and operation • Doesn't require a coolant circulation system	• Only suitable for PEMFC with a low power level
Air-cooling	Uses either extra amounts of air in the cathode or separate air channels to provide the required cooling for the device	• Low cost • Requires less maintenance • Has high reliability	• Low cooling performance, thus it is only suitable for small devices
Liquid cooling	Deionized water or nanofluids are used as coolants. The cooling channels can either be integrated into the bipolar plate or in dedicated cooling plates.	• Excellent cooling performance particularly when using nanofluids. • Can control and optimize the cooling capacity.	• Has low energy efficiency due to high parasitic losses. • Requires coolant circulation system and thus it needs greater space to accommodate the extra components.
Phase-change cooling	Uses the latent heat of the coolant to maintain the acceptable operating temperature of the PEMFC. It can be either boiling or evaporative cooling.	• Simple cooling system with high capacity and compact size • Doesn't require coolant circulation system	• More expensive compared to the other passive cooling. • The evaporation rate is hard to be controlled

Table 2: Advantages and drawbacks of PEMFC-WHR routes

PEMFC-WHR route	Advantages	Drawbacks
Releasing hydrogen from MH tanks	• Enhancing the hydrogen discharge rate from the MH tanks without the need for an external heat source or increasing the size of the MH tanks • Improving the efficiency of the PEMFC system by reducing the parasitic energy consumption required in case of using other sources of heat	• Additional components are required to facilitate the thermal coupling between the MH tank and the PEMFC which may increase the overall mass of the power system • Metal fins should be mounted on the external surface of MH tanks when it is coupled with air-cooled PEMFC to enhance the heat transfer coefficient. Those fins increase the MH tank volume.
Preheating the reactants	• Highly beneficial for PEMFC systems operating in cold weather • Can reduce the start-up time of the PEMFC system in cold weather • Decreasing the energy demand of the system by eliminating the need for an external heater.	• More complicated design of the PEMFC system.
Provide heating in CHP	• Reducing the overall GHG emissions. • Reducing electricity costs • PEMFC-based CHP has a shorter start-up time compared to SOFC-based CHP.	• High initial and investment cost.
Drive chillers in CCP system	• CCP allows for reducing demand on electricity supply required for cooling • Absorption and adsorption chillers have low environmental impact as they use environmentally friendly refrigerants • Suitable for WHR from both HT-PEMFC and LT-PEMFC using absorption and adsorption chillers, respectively.	• Relatively-high capital cost • The PEMFC waste heat is only suitable to drive absorption and adsorption chillers which have lower cooling performance and a lower coefficient of performance (COP) in comparison with the conventional vapour compression refrigeration systems
Power generation using ORC	• Generating additional power and improving the efficiency of the PEMFC system • ORC is suitable for low-grade waste heat because it uses working fluids with low evaporation temperature. • ORC has less erosion risk than that of the steam cycle as the working fluid within the ORC remains dry throughout the process	• ORC has higher cost and produces less power than a steam cycle operating with similar conditions. • Working fluids of ORC are combustible and this might cause a serious environmental hazard in case of leaking.

Power generation using TEG	• Environmentally friendly approach to enhance the efficiency of the PEMFC • TEG can convert low quality thermal energy into electricity • TEG has no moving parts and allows for silent operation • TEG doesn't require fuel or working fluids to operate. • TEG has smaller size than traditional engines • TEG has high durability	• TEG is expensive and less efficient than the other heat engines