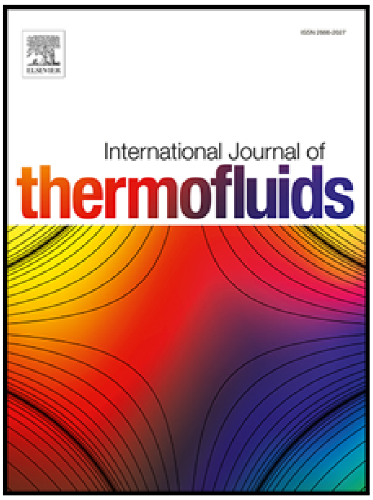

Advancements and prospects of thermal management and waste heat recovery of PEMFC

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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

$$q'' = (V_{max} - V_{cell})\, i \qquad 1$$

Where V_{th} is the thermal voltage; V_{cell} is the cell operating voltage; and i is the current density. V_{max} represents the imaginary maximum possible cell potential assuming full conversion of the chemical energy into electrical power. V_{max} 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'' 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

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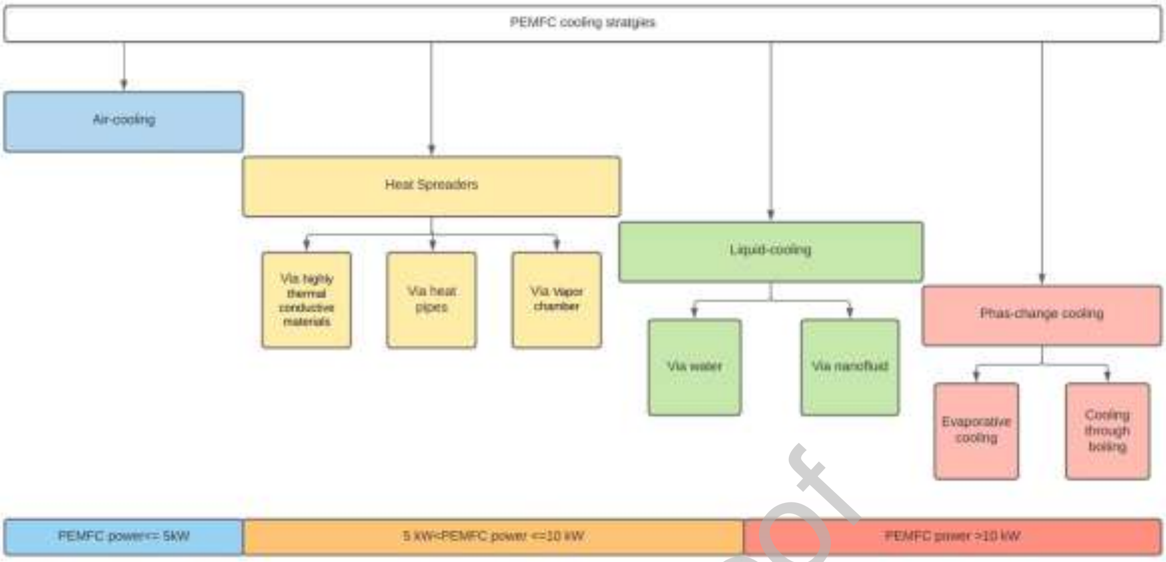


Figure 1: Main cooling strategies of PEMFC

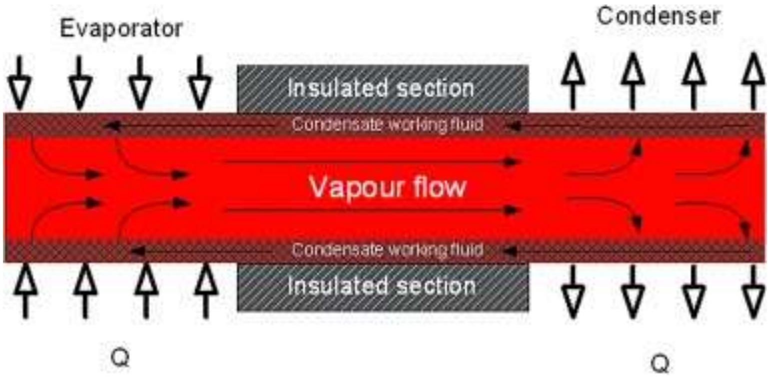


Figure 2: Heat pipe working concept [42]

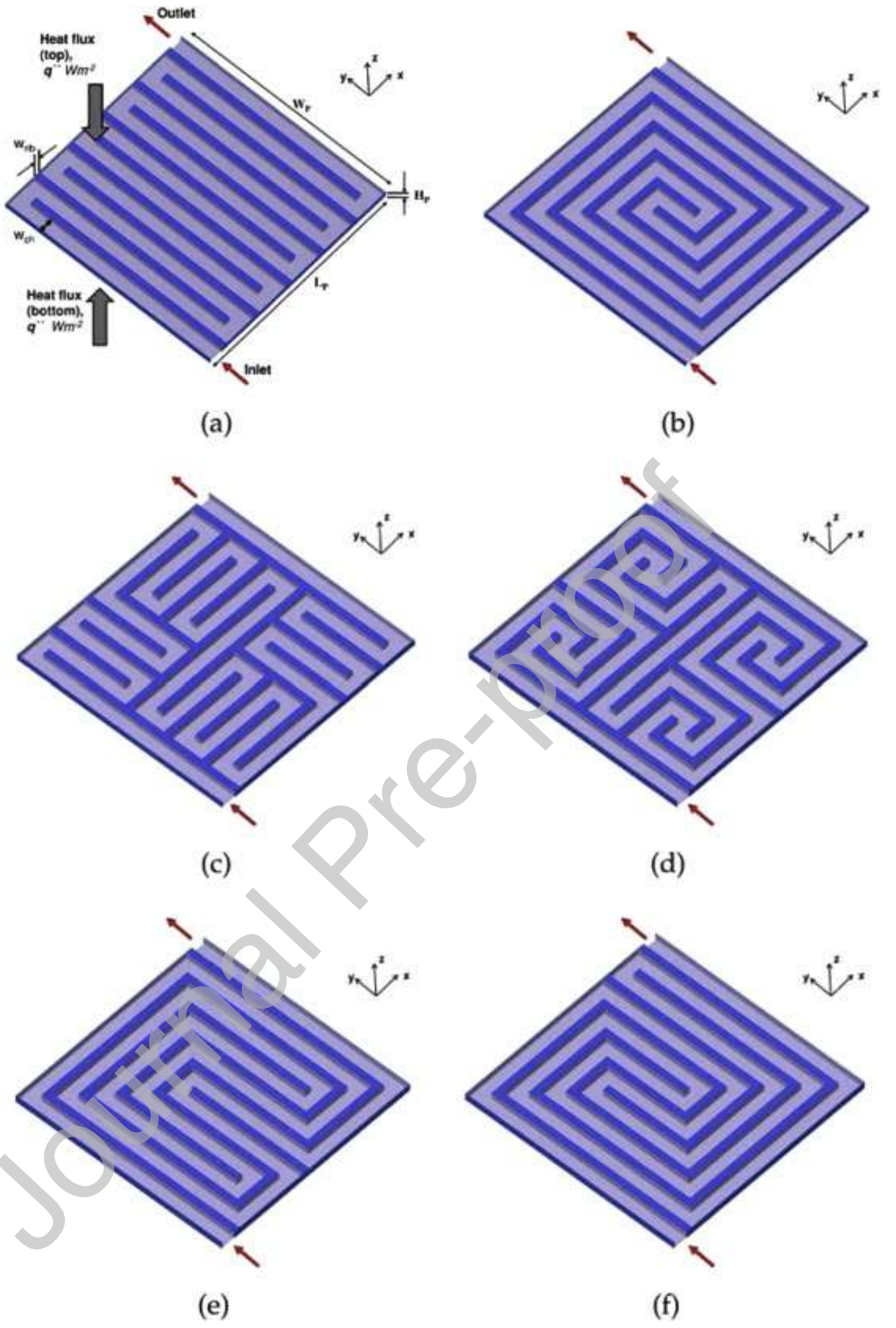


Figure 3: Air-flow cooling channels design [56]

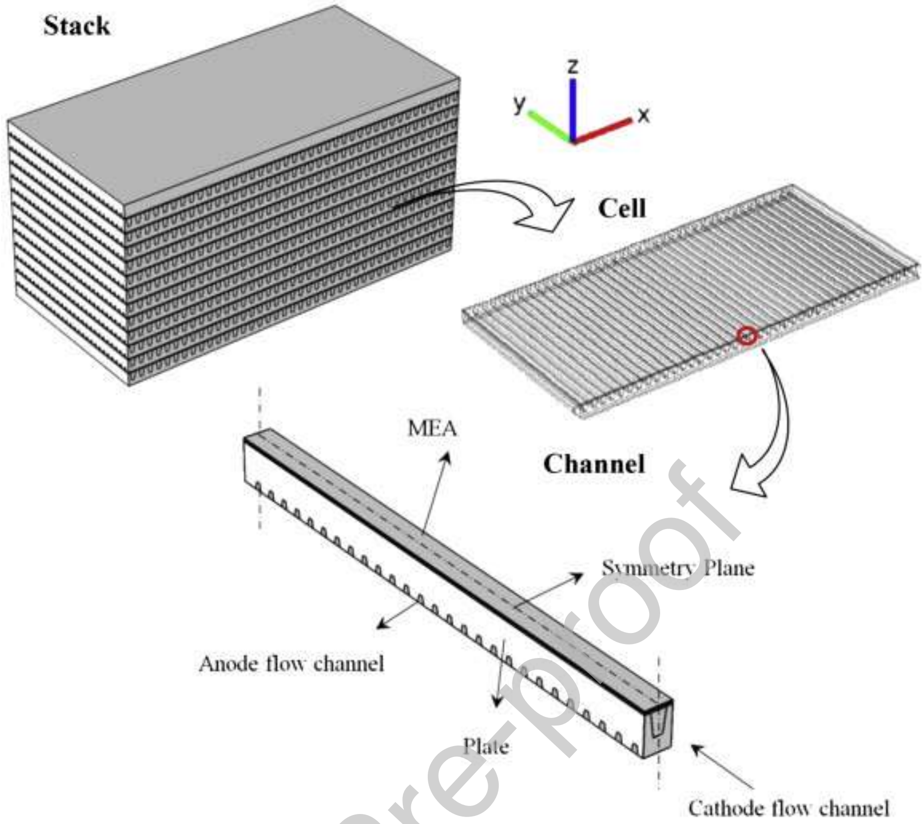


Figure 4: PEMFC design with combined oxidant and cooling channels [57]

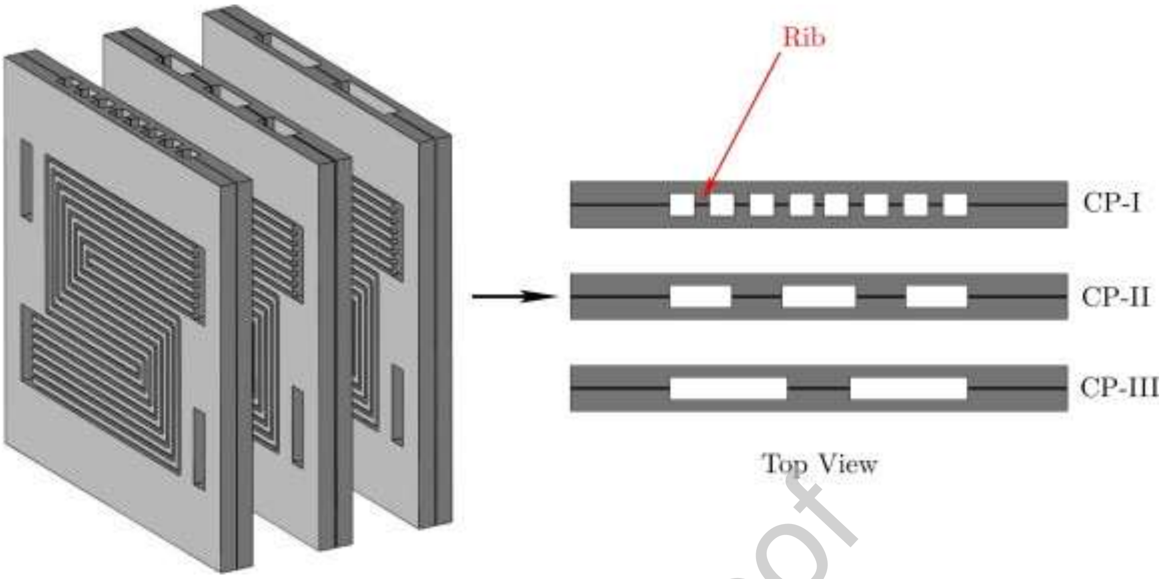


Figure 5: Cooling plates designs investigated by [58]

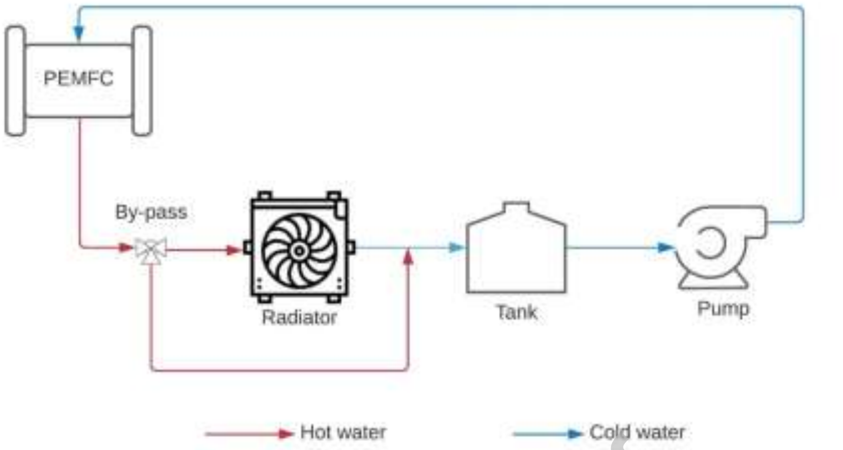


Figure 6: Typical cooling system of PEMFC using water

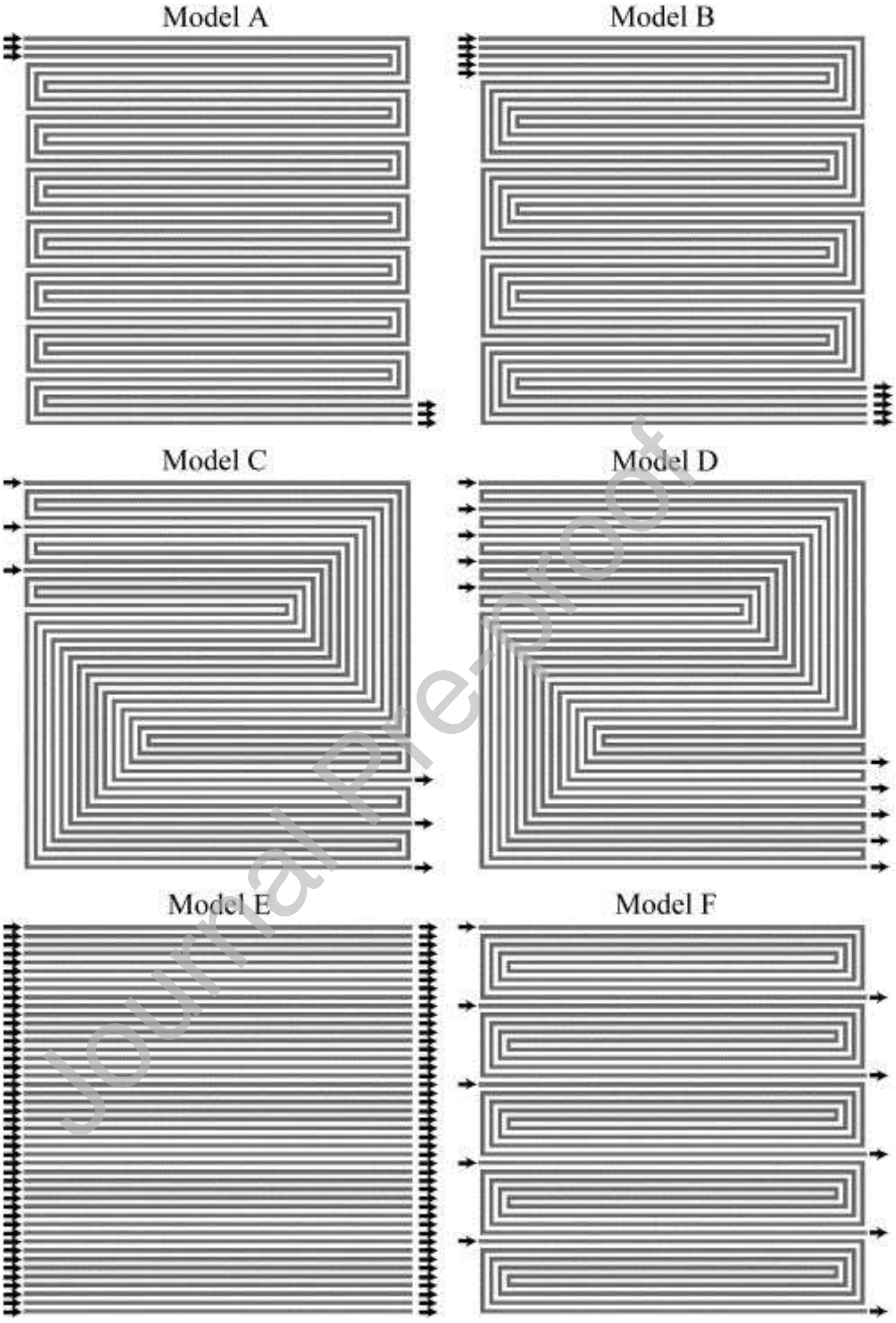
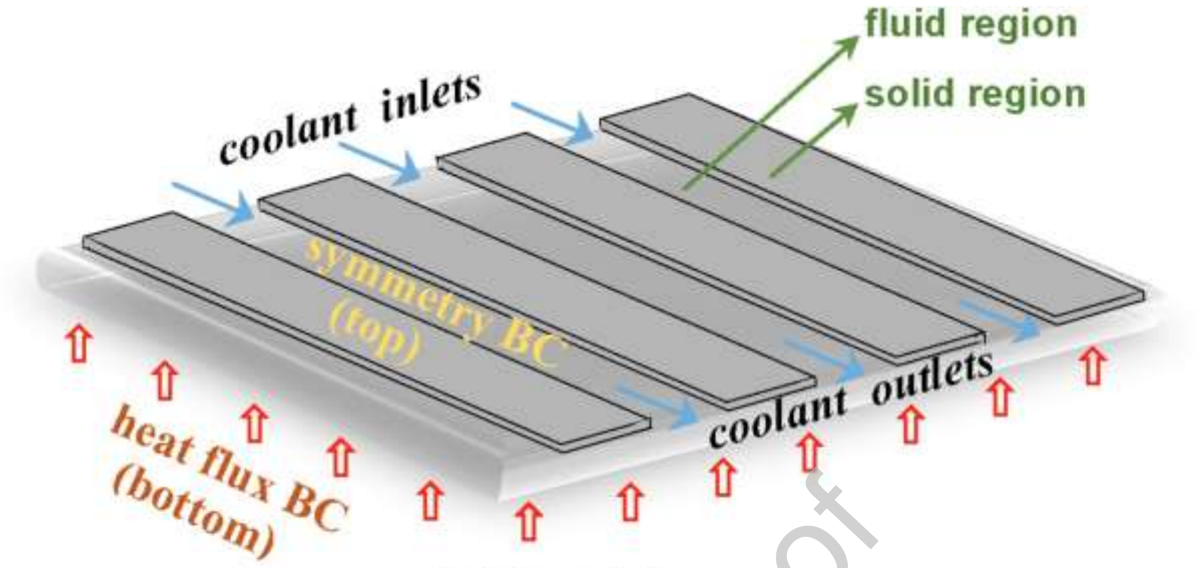
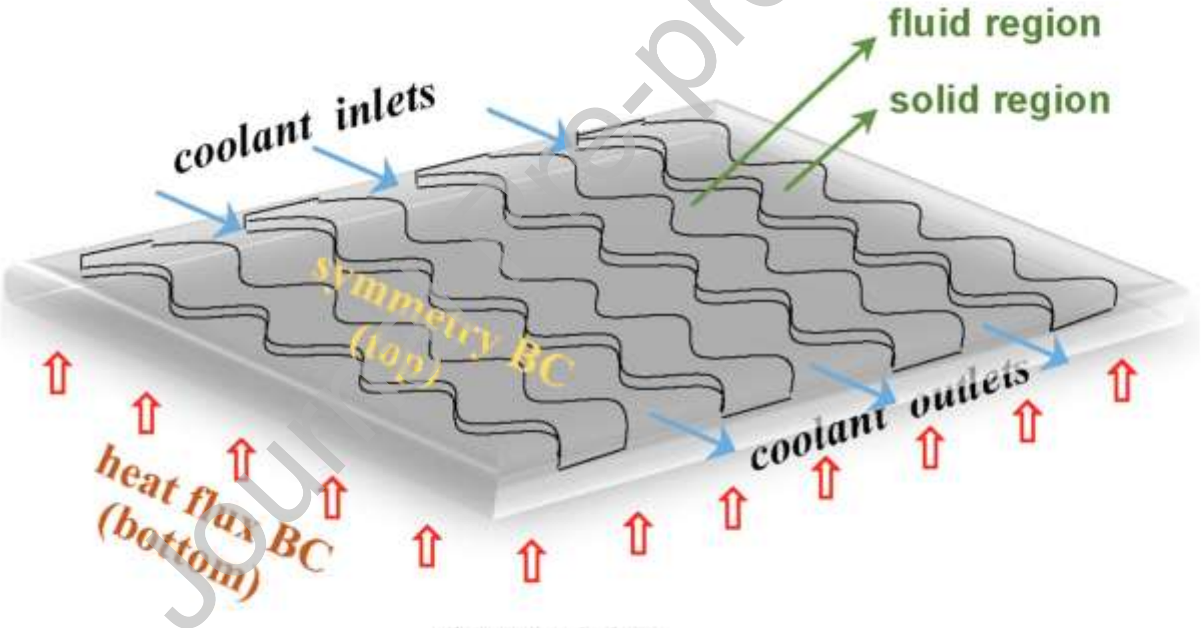


Figure 7: Coolant flow field designs studied by Baek et al. [61]



(a) Model A



(b) Model B

Figure 8: Straight and zigzag flow channels [63]

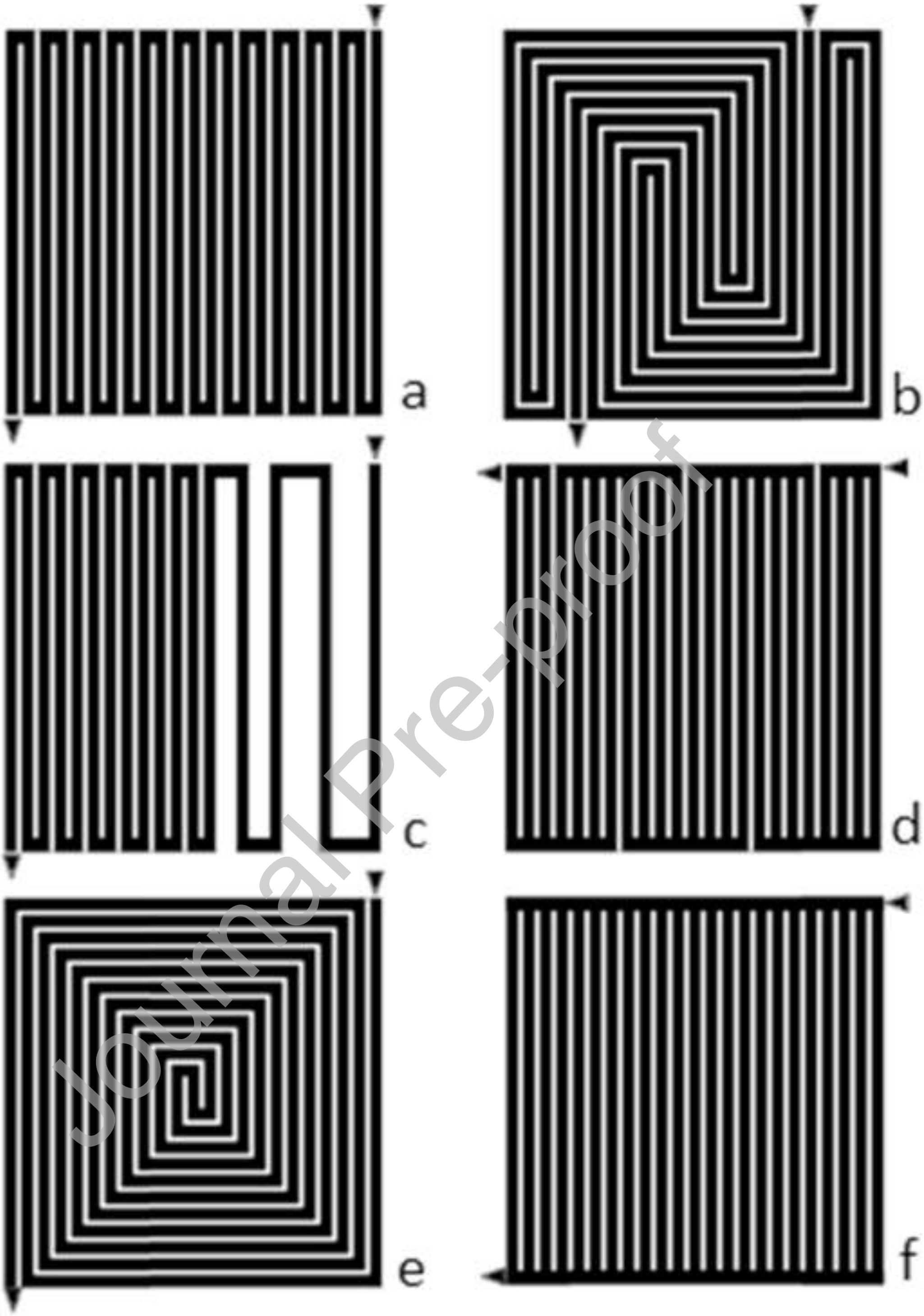


Figure 9: Coolant flow fields investigated by Ghasemi *et al.* [64]: (a) serpentine (b) multi-pass serpentine (c) serpentine with different distances between the channels (d) parallel-serpentine (e) spiral (f) parallel

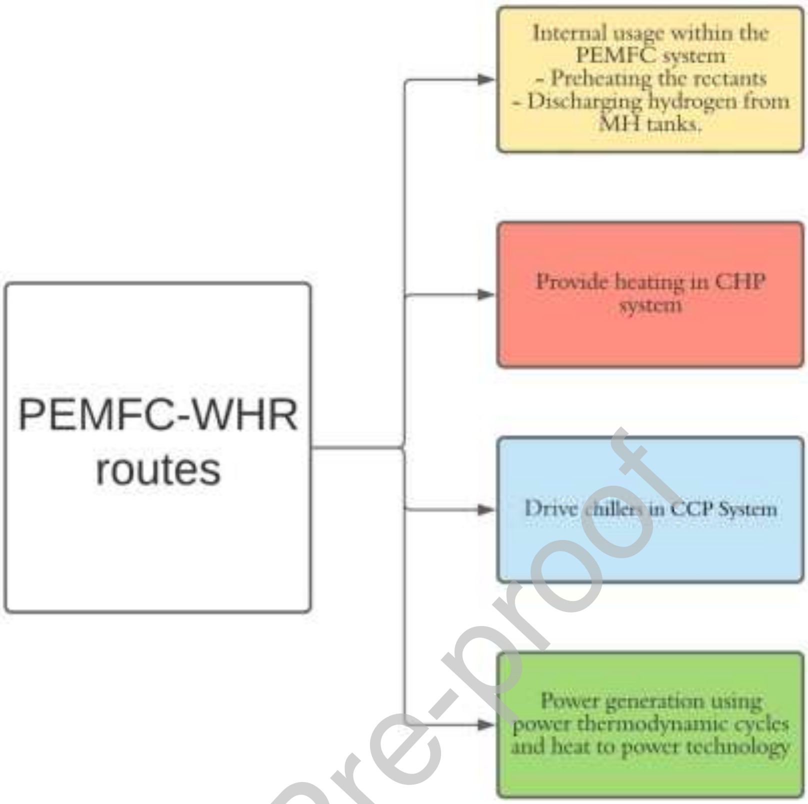


Figure 10: PEMFC waste heat recovery options

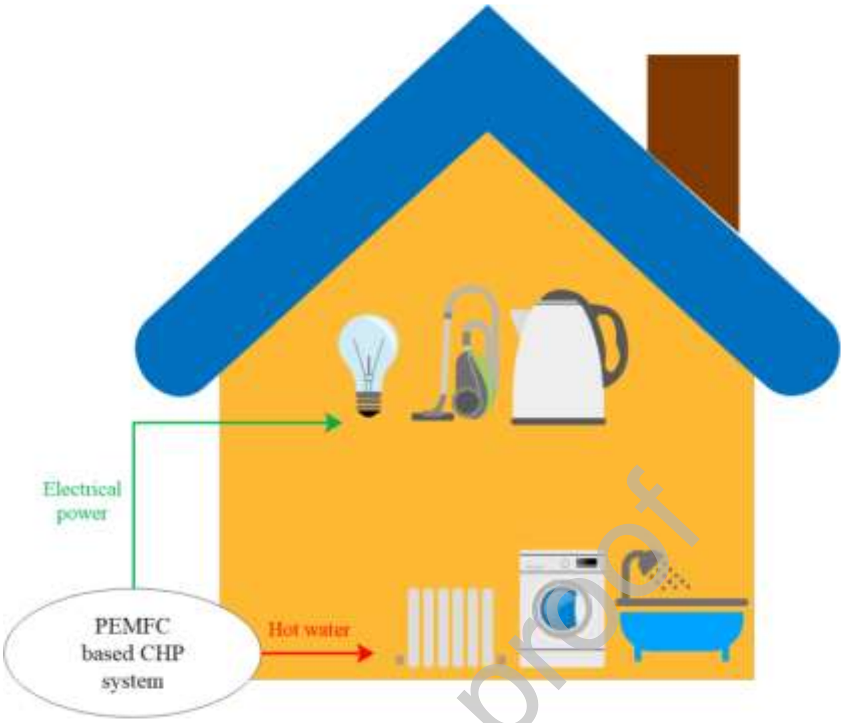


Figure 11: Illustration of PEMFC-based CHP system

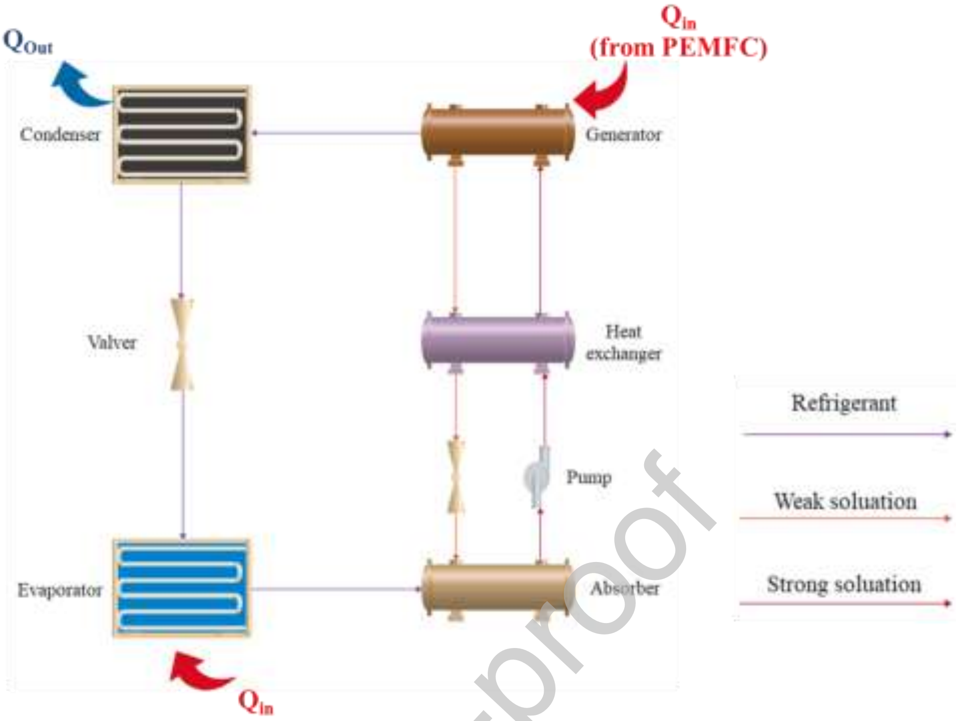


Figure 12: Illustration of an absorption chiller system using PEMFC waste heat to drive the generator

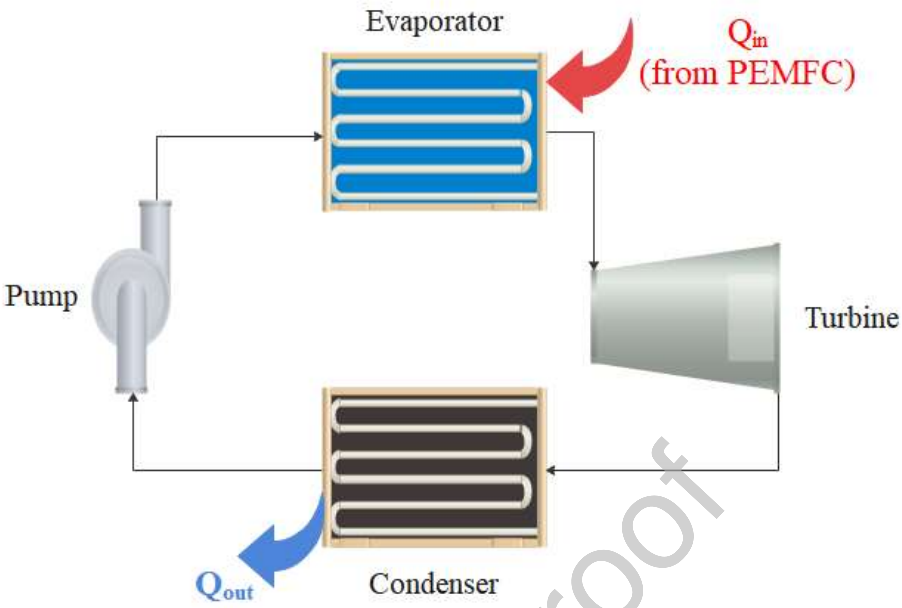


Figure 13: Illustration of ORC system using PEMFC heat in the evaporator

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