

Design Considerations to Ensure a Safe and Effective Piping System for a Self-humidifying PEMFC

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Fuel cell systems, particularly in stationary power and transport applications, are becoming increasingly prevalent for hydrogen utilization. However, designing reliable and leak-tight hydrogen fuel cell vehicles and infrastructure presents significant challenges due to the small molecule nature of hydrogen, which can easily permeate through even the smallest fissures. Proton exchange membrane fuel cells (PEMFCs) operate at low temperatures and pressures, necessitating precise fuel flow control for optimal performance. Thus, the performance of fittings in high-pressure hydrogen fuel systems is crucial. This paper explores design considerations to ensure safety and efficiency in fuel cell systems, focusing on components and materials in fuel piping, while adhering to relevant standards and regulations. A proposed fluid system solution is also presented.

1. Introduction

A fuel cell (FC) is an electrochemical device that converts chemical energy into electrical energy. In a fuel cell, the fuel at the anode side is oxidized to release electrons, which are then transferred to the cathode side via an external circuit, reducing the oxidant species, usually oxygen (Albarbar & Alrweq, 2018). This process generates electrical current from the potential difference created by the reaction. Fuel cells can be utilized across various sectors, including industry, transportation, and residential applications (Smithsonian Institution, 2004).

Hydrogen fuel cells (HFCs) are particularly noteworthy in the energy economy as they are renewable when produced from water electrolysis using electricity from solar, wind, and bioenergy sources. Hydrogen is an attractive alternative because its reaction with air in a fuel cell produces water as a by-product. Therefore, hydrogen and FC technologies can significantly reduce CO₂ emissions and decrease reliance on fossil fuels (Albarbar & Alrweq, 2018).

Among HFCs, Proton-exchange membrane fuel cells (PEMFCs) have gained special attention. PEMFCs utilize a polymer electrolyte in the form of a thin, permeable sheet, which is small, light, and operates at low temperatures (about 80°C). Other electrolytes may require temperatures as high as 1,000°C.

In the early 1960s, Thomas Grubb and Leonard Niedrach, while working for General Electric, invented the first PEMFC. The initial success came in the mid-1960s when the company collaborated with the U.S. Navy's Bureau of Ships (Electronics Division) to develop a compact, portable fuel cell fuelled by hydrogen from water and lithium hydrate reactions. Despite its success, the platinum catalysts used were expensive (Smithsonian Institution, 2004). PEMFCs are applicable in portable, transportation, and stationary applications, offering quick start-up, low operating temperatures, and high efficiency. However, they face challenges such as high catalyst costs and sensitivity to fuel impurities (Albarbar & Alrweq, 2018).

The hydrogen economy holds significant potential for social and environmental benefits. Technological advancements can reduce costs and enhance economic viability, addressing sustainability's triple bottom lines. One major challenge is developing systems that are both safe and dependable (Hayes, 2021).

These challenges underscore the need for high-performance fittings that connect crucial components of high-pressure hydrogen fuel systems. Advanced fitting technology is now available to ensure gas seal integrity, tube grip strength, vibration resistance, material durability, and efficient installation— all vital for hydrogen technology

(Hayes, 2021). Moreover, fuel cell vehicle applications face demanding operating conditions that system components must withstand. Therefore, hydrogen systems for both vehicles and infrastructure must be designed and constructed to meet the highest quality standards. Tube fittings, essential for maintaining connections throughout these systems, play a crucial role and must provide leak-proof performance (Hayes, 2021). Thus, this paper explores design considerations to ensure safety and efficiency in fuel cell systems, focusing on components and materials in fuel piping, while adhering to relevant standards and regulations.

2. Methodology

This study employed a methodology based on a comprehensive review of technical literature and scientific materials from reputable sources, including manufacturers' websites, the PEMFC product manual, and competition safety rules. The literature review focused on gathering information related to the design considerations for a safe and effective piping system in self-humidifying proton exchange membrane fuel cells (PEMFCs).

Technical documentation, product manuals, guidelines, and standards provided by the valve and hose connection manufacturers were analyzed to identify suitable materials, joint designs, and sealing techniques for the fuel piping system. The PEMFC Product Manual was referenced to understand the operational requirements and specifications specific to PEMFCs. Relevant standards and regulations published by the Society of Automotive Engineers (SAE) regarding hydrogen fuel systems in vehicles were consulted to gain insights into safety considerations, testing procedures, and performance requirements.

Scientific literature was reviewed to deepen the understanding of fundamental fuel cell concepts, including operation principles, characteristics of Nafion membranes, and the advantages of self-humidifying membrane electrode assembly (MEA) fuel cells. These documents provided insights into the specific requirements and challenges associated with self-humidifying PEMFCs.

The knowledge obtained from the technical literature and scientific materials was synthesized to develop a set of design considerations encompassing material selection, joint design, and system configuration. These considerations formed the basis for proposing a fluid system solution that meets the operational requirements of the fuel cell system while ensuring safety, efficiency, and compliance with relevant standards and regulations.

3. Material considerations

Hydrogen is a small-molecule gas that can easily escape through the tiniest of crevices and diffuse into materials designed to contain it. Thus, construction materials, including those used in piping, valves, and seals, must be carefully selected to account for their deterioration when exposed to hydrogen at the intended operating conditions. Exposure of metals to hydrogen can lead to embrittlement, cracking, and significant losses in tensile strength, ductility, and fracture toughness, potentially causing premature failure in load-carrying components (Dwivedi & Vishwakarma, 2018).

Two primary phenomena associated with materials in hydrogen use must be considered when designing a hydrogen system: 1) permeation of hydrogen through materials, resulting in an effective leak, and 2) degradation of the mechanical properties of materials, compromising structural integrity. Types of hydrogen damage on materials include:

1. Hydrogen-induced cracking (HIC): Atomic hydrogen diffuses in the material and recombines into H₂ in specific sites, developing high pressure. In ductile materials, this can cause deformation (blisters); in low-ductile materials, cracking can occur.
2. Hydrogen reaction: Hydrogen can react with metallic phases to form hydrides (e.g., Ti, Zr) or with non-metallic phases (e.g., carbides) to form methane (CH₄) or other compounds.
3. Hydrogen Embrittlement (HE) or Hydrogen Stress Cracking (HSC): This occurs when atomic hydrogen contacts a material under stress, sometimes considered a type of Stress Corrosion Cracking (SCC) (Sommerday & Gangloff, 2013).

Generally, acceptable materials include austenitic stainless steels, aluminum alloys, copper, and copper alloys. Nickel and most nickel alloys should not be used due to severe hydrogen embrittlement, though a higher concentration of chromium and nickel in stainless steel can defend against this by promoting greater ductility and corrosion resistance. The American Society for Testing and Materials (ASTM) requires a minimum of 10% nickel in 316 stainless steel formulations, but higher-quality 316 stainless with 12% minimum nickel is better suited (Devanathan, 2008). Polymeric materials like PTFE, PVDF, Teflon, or Neoprene are allowed, especially in low-pressure tubing.

Other factors affecting the hydrogen permeation rate include:

- Surface area: Larger areas increase permeation.

- Pressure: Higher pressure increases molecular count and permeation.
- Temperature: Higher temperatures increase molecular speed and permeation rate.
- Wall thickness: Thicker walls reduce permeation.

More information can be found in technical references on hydrogen compatibility of materials, summarizing scientific and institutional data from articles and reports on material selection for service with hydrogen gas. Other codes and standards for safety related to material selection include IFGC 5003.2.2.1, IFGC 704.1.2.3, and NFPA 2-10.3.1.3.

4. Fluid system solution

A properly designed hydrogen system must ensure hydrogen material compatibility and component suitability. This entails assessing materials and components alongside their management and control. Hence, system specifications should be a primary consideration for project engineers.

4.1 Design & assembly

Understanding fuel cell requirements is paramount before commencing the system's design and assembly. It's essential to identify key process variables, including temperature, pressure, and flow rate. Moreover, one should outline the necessary valves, sensors, and accessories for operational requirements. As Frost (2022) points out, several best practices ensure safety and optimize performance in fluid systems:

- ❖ Choose components based on material compatibility.
- ❖ Simplify designs wherever possible: Fewer connection points minimize potential failures. Opting for bendable tubing over piping eases direction changes.
- ❖ Steers clear of component intermixing: Using components from different manufacturers can result in inconsistent performance. Select consistent fittings and regulators from trustworthy manufacturers. Always heed manufacturer guidelines for proper assembly and disassembly of tubing and fittings.
- ❖ Design your system to handle regular operational conditions, such as vibration, high pressures, and temperatures.

Once you grasp the fuel cell requirements, initiate:

- ❖ CAD drawings
- ❖ Piping and instrumentation design (P&ID)
- ❖ Component selection and sourcing using the S.T.A.M.P.E.D method: size, temperature, application, material, pressure, end connection, and delivery.
- ❖ Bills of Materials (BOM)

4.2 PEM fuel cell system

PEMFCs utilize a solid, polymeric membrane, typically Nafion®, for proton transport. This material, resulting from perfluorinated vinyl ether copolymerization, displays hydrophilic properties due to its attached perfluoroether side chains, which facilitate hydration and proton mobility (Liang et al, 2012). Perles (2008) stresses the importance of the membrane remaining hydrated to maintain high ion conductivity. Managing water content is a pressing challenge for commercializing low-temperature PEMFCs since decreasing water content linearly reduces conductivity (Janssen & Overvelde, 2001).

Recent decades have seen extensive research on fuel cell humidification. Broadly, humidification can be internal, encompassing physical and chemical methods, or external, involving methods like gas bubbling, direct water injection, and exhaust gas recirculation (Lu & Wang, 2004). Traditional systems pre-humidify reactant gases before introducing them to the fuel cell to prevent membrane drying. However, external humidification can complicate systems and diminish energy efficiency. Therefore, pursuing self-humidifying or low-humidity MEA can streamline and economize PEMFCs (Liang et al, 2016).

Common components for constructing a PEM fuel cell system include a heat exchanger (air, water), humidifier, air pump and blower, power system, DC/DC converter, hydrogen tank, control valves, regulator pressure, controller system, cooling, and preheating system (Ballard, 2024). As can be seen in Figure 1a, presented in the PEMFC product manual.

4.3 Self-humidifying MEA fuel cell requirements

Although PEMFCs generally require humidifiers, recent innovations have produced self-humidifying MEAs. One approach involves integrating precious metals and inorganic oxide particles into the membrane. However, this method can be complex, expensive, and potentially detrimental to membrane conductivity. This study focuses on a self-humidifying, air-cooled stack developed by Ballard Inc. This design simplifies the system and reduces costs by eliminating several components, as reflected in Figure 1 b, presented in the PEMFC product manual.

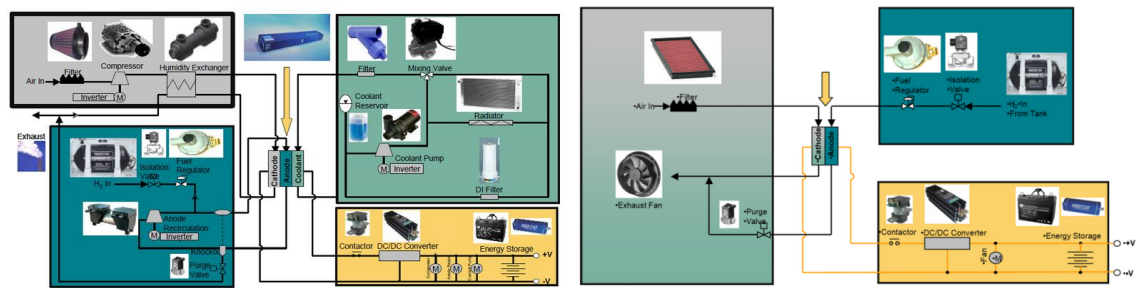


Figure 1. a) Conventional fuel cell system requirements. b) Self-humidifying fuel cell system requirements.

The piping design only considers the hydrogen stream, once the fan provides the oxidant, this factor makes the minimal requirements for FC operation easier, as can be seen in Figure 2, from the PEMFC product manual. Requires a minimum of 3 valves and 2 sensors to well manage the fuel flow and pressure into the stack. For the cathode side, a temperature sensor and a fan to cool down and provide oxygen are required (Ballard, 2024).

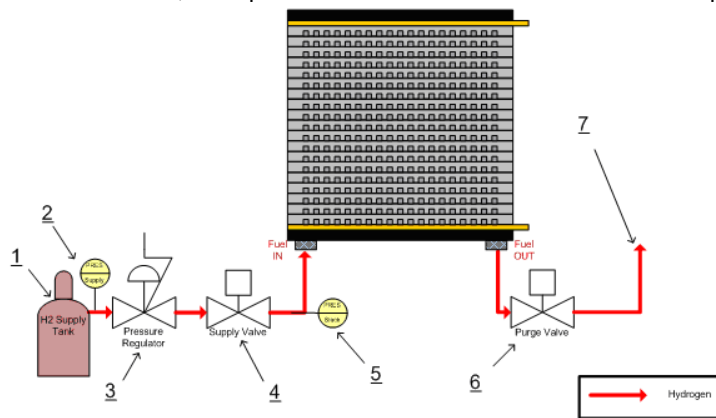


Figure 2. Minimal requirements for FC operation.

4.4 System Configuration Overview

The foundation of a robust piping system lies in the precise selection and arrangement of its components. From the SAE Brasil safety rule, Figure 3 delineates the basic components required, although additional elements can be incorporated subject to the evaluation of competition authorities concerning safety. Essential system components include:

- ❖ **Hydrogen Storage and Delivery:** Hydrogen storage tank, filling plug with an optional safety valve, main cutoff valve, and metal braided flexible hose form the core of hydrogen supply to the fuel cell stack, ensuring a secure and controllable hydrogen flow.
- ❖ **Pressure Regulation and Monitoring:** Components like the pressure regulation valve, relief valve, and pressure transducer are pivotal in maintaining desired pressure levels, thereby preventing overpressure and fuel cell starvation.
- ❖ **Fuel Cell Stack Connection:** The system employs flexible hoses at fuel cell inlet and outlet ports to avert vibration and load transfer, safeguarding the fuel cell stack and facilitating easy maintenance.
- ❖ **Hydrogen Flow Control:** The purge valve, acting as the primary control element, is remotely managed by the control system to modulate hydrogen flow through the fuel cell stack, also preventing outside air contamination during system downtime.
- ❖ **Cooling and Exhaust Management:** The incorporation of a cooling fan and closed catch tank ensures effective temperature control and collection of liquid water generated during operation.
- ❖ **Electrical Connection and Control:** Components like contractor, battery, control system, and electric motor are crucial for the conversion of electrical power to mechanical power and managing the entire electrical system of the vehicle.

- ❖ Monitoring and Additional Components: A monitoring system is integrated for real-time observation and emergency shutdown, alongside other components like a rotameter, needle valve, and various connections ensuring precise gas flow control and compatibility with the fuel cell supply line.

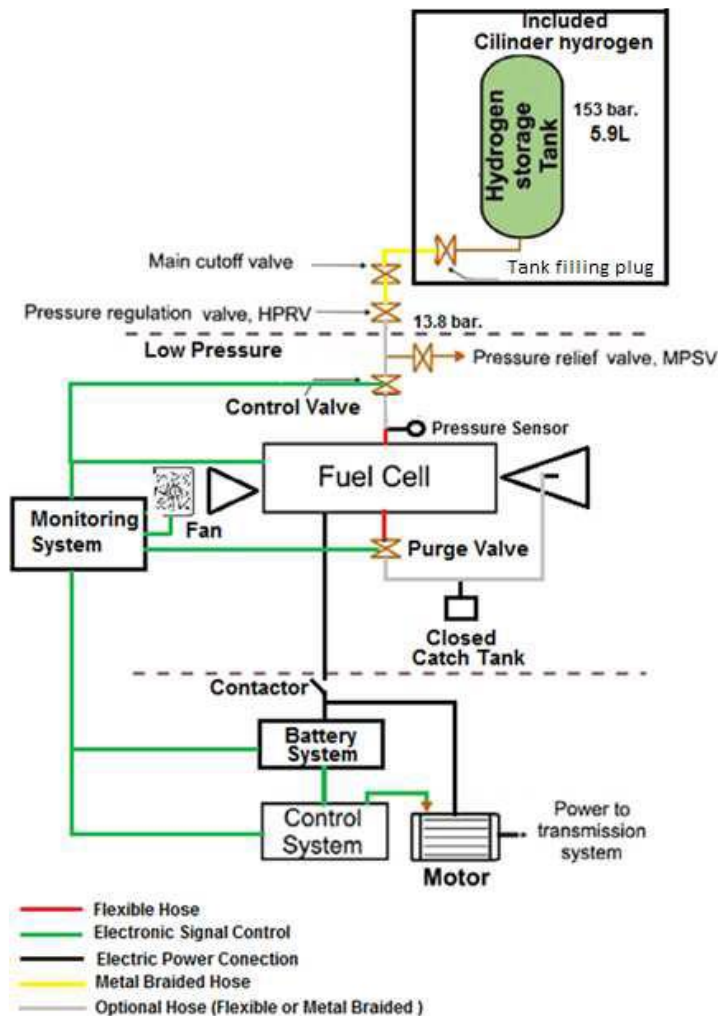


Figure 3 – Integrated Hybrid powertrain scheme.

5. Valves and Hose end connections

The choice of high-performance valves is cardinal for regulating hydrogen flow, with a focus on meeting pressure, safety, and maintenance demands, alongside withstanding stress and vibration. Four primary types of valves—ball valves, needle valves, pressure regulators, and pressure relief valves—are discussed, each with its unique advantages and considerations in hydrogen applications. Manufacturer's websites provides insights into the specifications and functionalities of these valves. Moreover, the selection of hose end connections and tubing fittings, as discussed in the provided link, is crucial and depends on several factors including ease of installation, inventory simplification, and cost. The lifetime cost consideration is emphasized, hinting at the importance of quality over upfront savings. The highlighted design considerations serve as a guideline for engineers to evaluate and construct a fluid system that not only meets the operational requirements but also adheres to safety standards, ensuring reliable and efficient performance of the Self-humidifying PEMFC.

A designer should holistically assess fluid systems when picking end connections and components. Hose end connections and tubing fittings' design should consider installation ease, inventory streamlining, and cost-effectiveness, balancing initial savings with potential long-term maintenance expenses. Figure 4 shows the piping and Instrumentation Diagram proposed for the PEMFC system.

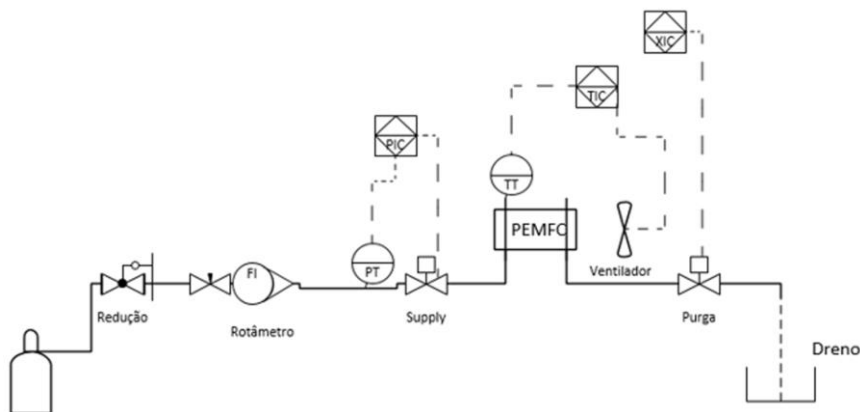


Figure 4: Piping and Instrumentation Diagram of the PEMFC system.

6. Conclusions

This study underscores the practical importance of designing robust fuel systems and conducting comprehensive research on hydrogen-compatible materials, which are crucial for developing a cost-effective and safe hydrogen-based future. Ensuring safety requires a deep understanding of the properties of both the hydrogen fuel and the materials used in the system's construction. Additionally, the operational requirements of fuel cell stacks must be carefully considered to ensure system efficiency. It is important to note that this study primarily relied on a literature review approach and did not conduct empirical experiments. Future research should focus on optimizing the supply stream, including the correct specification of valves, connections, and instruments, to achieve a well-integrated and reliable hydrogen infrastructure.

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