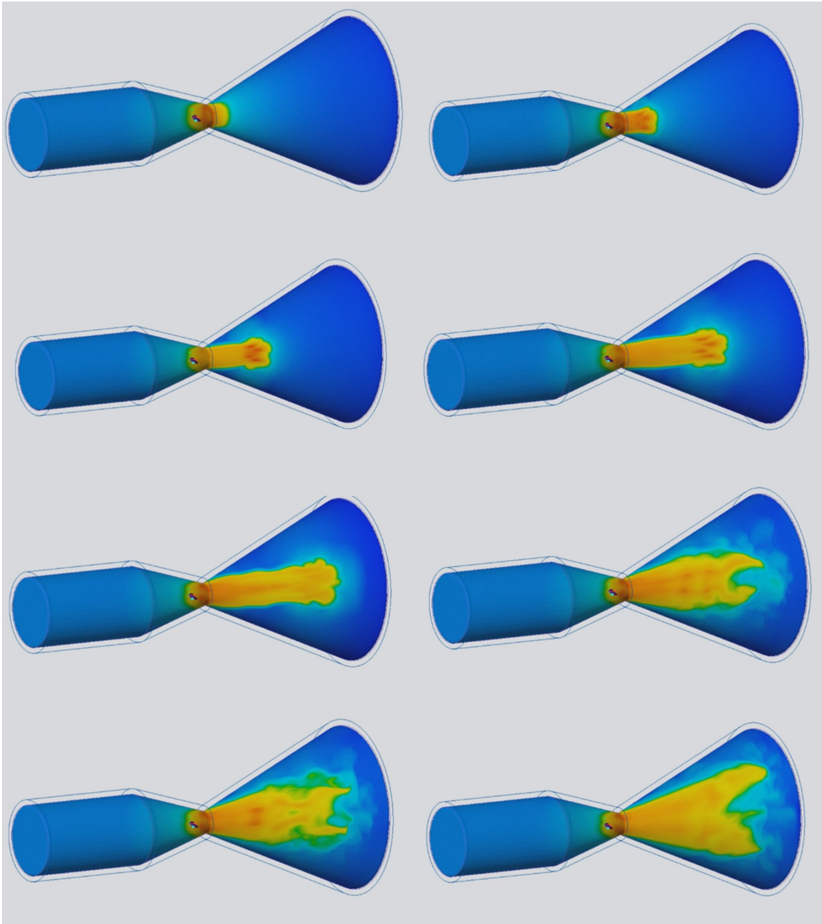

Evaluation of cooling system in an industrial fuel cell setup by effectively managing exhaust water

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DEPARTMENT OF PHYSICS

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At VOLVO PENTA
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Cover: Visualization of a nozzle sprayer with streamlines coloured in terms of velocity

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Abstract

Fuel cells are an emerging portable energy source known for their high energy density and ability to produce clean, sustainable energy. Unlike traditional combustion processes that directly burn fuels to release energy, fuel cells harness energy from the reaction between the fuel and the oxidizer while producing minimal pollutants and greenhouse gases. When it comes to the industrial scale, a more significant drawback is managing the exhaust water. One primary application is the capture and reuse of exhaust water for cooling purposes within the fuel cell system. By utilizing the waste heat generated during the electrochemical reaction, the exhaust water can serve as a cooling agent, reducing the need for external cooling systems and enhancing the overall energy efficiency of the fuel cell.

This study aims to investigate various aspects of fuel cell systems, such as quality analysis of exhaust water samples from Volvo Penta fuel cell setup, a literature survey on various applications that can be used for exhaust water, and developing 1D and 3D models for two of the identified applications. The first application is to vaporize the water using a chimney/muffler, which is most suitable for mobile applications such as trucks and marine applications. Chimney size is optimized through the Matlab Simulink model. The other application is proposed to use water as a cooling agent for a radiator setup which can be used for both stationary and mobile applications. CFD analysis is done to simulate and optimize the setup using Creo-ANSYS by considering water storage, spraying patterns, and system dynamics. Results are shown that there is a 4.8 percent increase in overall efficiency. As a summary, this report will try to clarify how to improve the industrial fuel cell setups, which can be considered a feasible alternative to substitute conventional mobility methods.

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We would like to thank Fredrick Tholander for giving us the chance to work on this project at Volvo Penta and for being an endless well of information and for always meeting us with kind and constructive help.
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Janitha Bandara and Umashankar Karthikeyan, Gothenburg, January 2024

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Introduction

1.1 Background

In an era when the world is grappling with the challenges of climate change and striving for sustainable energy solutions, fuel cells have emerged as a promising technology, offering a potential pathway to a cleaner and more efficient energy future. A fuel cell is an electrochemical device that generates electricity through a chemical reaction between hydrogen and oxygen, producing only water and heat as byproducts. This innovative technology promises to reduce greenhouse gas emissions, enhance energy security, and revolutionize various sectors, from transportation to stationary power generation. Fuel cells are innovative energy conversion devices that offer a promising alternative to traditional combustion-based power generation methods. These electrochemical devices generate electricity through a clean and efficient process, offering numerous benefits for various applications. With their ability to produce electricity without combustion, fuel cells have gained significant attention as a sustainable and environmentally friendly energy solution.

At the heart of a fuel cell lies an electrochemical reaction that converts the chemical energy stored in a fuel directly into electricity. The most common type of fuel cell is the proton exchange membrane (PEM) fuel cell, which utilizes hydrogen gas as the fuel source. In a PEM fuel cell, hydrogen is fed to the anode side of the cell, while oxygen or air is supplied to the cathode side. An electrolyte membrane, typically made of a polymer material, separates the anode and cathode compartments, allowing protons to pass through while blocking the passage of electrons. The electrochemical reaction occurs at the anode, where hydrogen molecules are split into protons and electrons. The protons travel through the electrolyte membrane to reach the cathode, while the electrons take an external pathway, creating an electrical current that can be harnessed to power devices or charge batteries. At the cathode, the protons, electrons, and oxygen combine to form water, which is the only byproduct of the reaction. This clean and efficient process distinguishes fuel cells from conventional power generation technologies that produce harmful emissions such as greenhouse gases and pollutants.

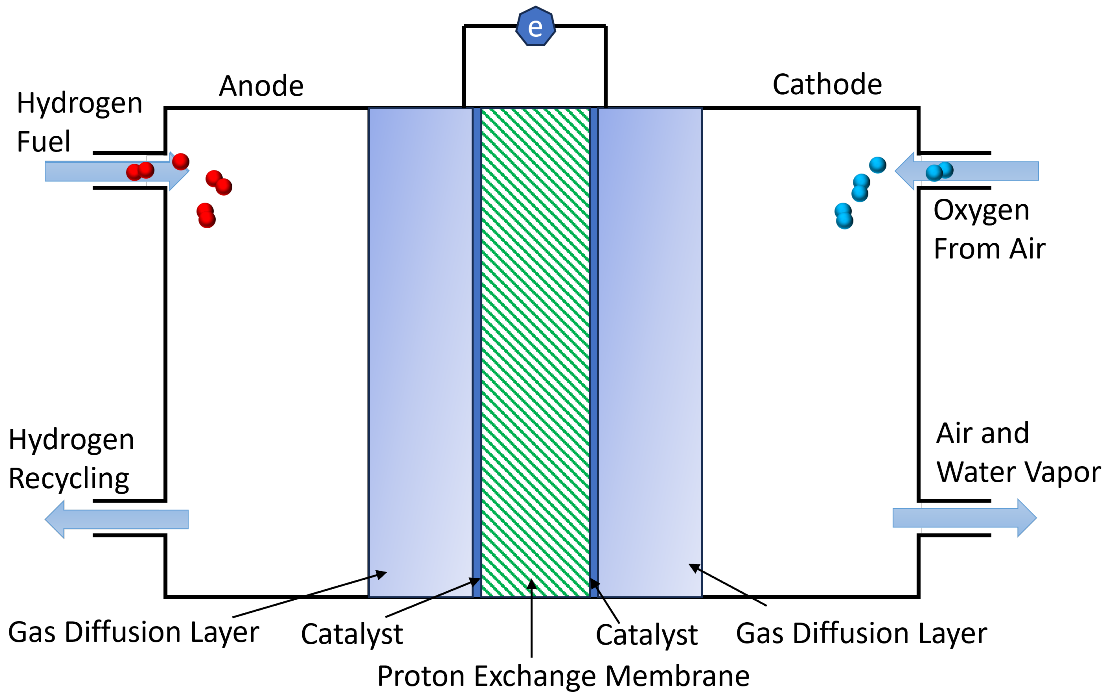

Figure 1.1: This describes a single fuel cell stack that constituting anode, cathode, gas diffusion layers, catalyst and proton exchange membrane. Along with this, hydrogen fuel source as inlet at anode and oxygen from air as inlet at cathode. Hot air and water vapor are produced as by products at cathode exhaust.

Fuel cells offer several advantages over traditional combustion engines and batteries. Firstly, they have higher energy efficiency, typically exceeding 50 percent, compared to internal combustion engines that operate at around $40 - 45$ percent efficiency. This increased efficiency translates into reduced fuel consumption and lower greenhouse gas emissions. Secondly, fuel cells produce electricity silently and without vibrations, resulting in quieter operation compared to combustion engines. Additionally, their modular design allows for scalability, enabling the use of fuel cells in various applications, from small portable devices to large-scale power generation systems. One of the most significant advantages of fuel cells is their potential for utilizing a wide range of fuels. While hydrogen is the most commonly used fuel, fuel cells can also operate on other fuels such as natural gas, methanol, ethanol, and even renewable sources like biomass or biogas. This flexibility provides opportunities for transitioning to a more sustainable energy mix while utilizing existing infrastructure.

Fuel cells have applications in various sectors, including transportation, stationary power generation, and portable electronics. In transportation, fuel cells power electric vehicles (FCEVs) by converting hydrogen fuel into electricity, offering long driving ranges and faster refueling times than battery-electric vehicles. In stationary power generation, fuel cells are used to provide reliable and clean electricity for residential, commercial, and industrial applications. They are also employed in portable electronic devices like laptops and smartphones, enabling longer battery life and faster charging times.

Despite their many advantages, there are still challenges to overcome for the widespread adoption of fuel cell technology. The high cost of materials, limited hydrogen infrastructure, and durability of fuel cell components are among the key barriers that must be addressed. Research and development efforts are focused on improving efficiency, reducing costs, and advancing fuel cell technology to make it more accessible and economically viable. Water management is a critical aspect that significantly impacts the performance and durability of PEMFCs. Efficient water management is essential to maintain proper hydration of the proton exchange membrane, prevent catalyst degradation, and optimize the overall electrochemical reactions within the fuel cell. Water management involves the delicate balance of controlling water content within the fuel cell to ensure optimal performance while avoiding flooding or drying out of the membrane and electrodes.

Water management in fuel cells presents several challenges due to the complex interplay between water transport mechanisms, electrode kinetics, and system operating conditions. Fuel cell operation involves the simultaneous transport of protons, electrons, and reactant gases and the removal of water produced as a by-product of the electrochemical reactions. The understanding and controlling these intricate processes are crucial for achieving efficient and durable fuel cell operation.

1.2 Problem statement

This thesis aims to investigate and address the critical aspects of water management in fuel cell systems, specifically focusing on water quality, quantity analysis, and water utilization by modeling cooling techniques such as spraying on radiators. The primary objective is to enhance fuel cells' performance and durability by developing efficient water management strategies and, secondly, finding the water applications. By comprehensively analyzing the existing literature and employing advanced modeling, simulation, and experimental techniques, this research aims to contribute to the body of knowledge in fuel cell water management.

Despite their immense potential, fuel cells face challenges that need to be addressed for wider adoption. One major hurdle is the cost of materials and components, particularly catalysts and membranes, which can limit their commercial viability. Durability and reliability are also important considerations, as fuel cells must withstand varying operating conditions and provide consistent performance over extended periods.

1.3 Aim

The thesis aims to investigate the following topics.

1. Calculate the theoretical water production in a fuel cell.
2. Literature survey about the chemical compounds in fuel cell exhaust water.
3. Prepare a 1D model to investigate the different factors of water production.
4. Discussion about various possibilities to re-use the wastewater.
5. Select one or two possibilities and do the 1D and 3D simulations.

2

Theory

2.1 Calculation approach for quantifying water production from a fuel cell

To understand the behavior of fuel cell systems, theoretical calculations are performed on the thermodynamics behavior of the fuel cell systems. Calculations like the requirement of hydrogen as fuel and oxygen from the air, given the appropriate conditions of fuel cell systems, with the inputs given by Volvo Penta. We performed the calculations, with the power output of the fuel cells as 300 kW (2 fuel cells, 150 kW each); the fuel cell setup is shown in section 2.6.

In PEM fuel cells, air is necessary for the reaction to take place. Also, this can dry out the membrane excessively. Therefore, it is important to know how much air needs to be introduced into the stack as a function of power delivered by the stack to adjust it to feed at the cathode. The air required to feed the system is calculated from the power generated by the stack; the power generated by each cell(P_e) is the product of average cell voltage(V_c) times the current and multiplied by the number of cells in the stack(n). Here, the power generated by the fuel cell is 300 kW (given by Volvo Penta data), and V_c=0.48 V.

From the water formation reaction, considering an entire molecule of oxygen, we obtain that the charge transport(Q) utilized in the reaction equals 4 times the Faraday's constant(F) and a number of moles of oxygen consumed(nO_2).

$$Q = 4 \cdot F \cdot nO_2 \tag{2.1}$$

$$\frac{Q}{t} = I \tag{2.2}$$

where t, given in run time mentioned by volvo penta for 8 hrs in a day (for operation).

$$\frac{nO_2}{t} = O_{2rate} \tag{2.3}$$

From Equation 2.1 and Equation 2.2, we get

$$O_{2rate} = \frac{I}{4 \cdot F} \tag{2.4}$$

For a stack of n cells, O_{2rate}, for, λ=2.

$$O_{2new} = \frac{(3.57 \cdot 10^{-7}) \cdot \lambda \cdot P_e}{4 \cdot V_c \cdot F} = 4.2\,\mathrm{kg/hr} \tag{2.5}$$

This oxygen flow rate(O_{2new}) is measured in kg/sec, For water quantity analysis,

$$Q = 2 \cdot F \cdot nH_2O \tag{2.6}$$

$$H_2O_{rate} = \frac{I}{2 \cdot F} \tag{2.7}$$

For a stack of n cells, water production rate (H_2O_{rate}) in, mol/sec

$$H_2O_{rate} = \frac{P_e}{V_c \cdot 2 \cdot F} \tag{2.8}$$

$$H_2O_{new} = (9.34 \cdot 10^{-8}) \cdot \frac{P_e}{V_c} = 220\,\text{kg/hr} \tag{2.9}$$

For the fuel requirement for 220 kg/hr of water produced, Hydrogen utilized in mol/sec

$$H_{2utl} = (1.05 \cdot 10^{-8}) \cdot \frac{P_e}{V_c} = 24\,\text{kg/hr} \tag{2.10}$$

As calculations are performed and analyzed from equations 2.9 and 2.10 for the operation of the fuel cell, the theoretical calculations state that 300 kW fuel cell, takes up 24 kg/hr of Hydrogen as fuel at the anode, and it produces around 220 kg/hr of water at cathode exhaust along with heat and by-product, which is used for heat recovery. This huge amount of water that is being generated is utilized for different applications based on water sampling and analysis.

2.2 Importance of water removal from fuel cells

2.2.1 Theoretical importance

For modeling or simulating the fuel cell system and analysis, in a Proton Exchange Membrane (PEM) fuel cell, water removal is crucial to maintain the efficiency of the electrochemical reaction. The presence of excess water can hinder the transportation of protons across the membrane, leading to reduced cell performance. Also, water accumulation at the catalyst sites can block the active sites and limit the availability of reactants, reducing the catalytic activity. Effective water removal helps to maintain optimal conditions for catalyst performance, ensuring efficient fuel oxidation and oxygen reduction reactions.

For effective ion transportation, the PEM fuel cells rely on a proton-conducting membrane. Excess water can saturate the membrane, impeding the transport of protons and reducing the ionic conductivity. By removing water, the membrane's conductivity is improved, allowing for better proton transfer and higher cell efficiency. This also prevents flooding, as too much water can flood electrodes, blocking gas diffusion pathways.These impact the thermal performance of fuel cells as cathode air dries the membrane, and hot air admits more water than cold air (dries the membrane more). Influence of stack temperature will affect the membranes performance. When the air comes in it has less water than when it comes out. It may not dry to the last membrane.

2.2.2 Practical importance

Effective water removal is crucial for managing the water content within the fuel cell. Accumulation of water can lead to flooding, which hinders reactant flow, blocks gas diffusion channels, and restricts reactant access to the catalyst. Proper water removal is necessary to prevent flooding and maintain optimal operating conditions.

For improving the system efficiency, water management plays a significant role in maximizing the overall efficiency of the fuel cell system. The removal of excess water helps maintain optimal operating temperatures, gas flow rates, and reactant concentrations, enabling efficient electrochemical reactions and minimizing energy losses. This thereby improves the life of the fuel cell as water accumulation can cause membrane degradation, catalyst poisoning, and corrosion of components within the fuel cell. Effective water removal helps to mitigate these issues, preserving the durability and extending the lifetime of the fuel cell system.

In real-time fuel cell run, water accumulation can lead to blockages and pressure build-up within the fuel cell, which can pose safety risks. Proper water removal prevents such issues, ensuring the safe and reliable operation of the fuel cell system. In summary, water removal is essential for maintaining the efficiency, performance, durability, and safety of fuel cells. Effective water management strategies, such as proper design of flow channels, membrane properties, and operating conditions, are critical to optimize water removal and enhance fuel cell performance.

2.3 Water quality and quantity analysis

In fuel cells, the presence and quality of water are crucial factors that affect the overall efficiency and durability of the system, as water is a byproduct of the electrochemical reactions. Water quantity analysis is as important as water quality analysis when assessing the characteristics of water produced by fuel cells.

2.3.1 Influential factors in the production of water

Firstly, the fuel gas temperature determines the degree of fuel utilization, i.e., the efficiency with which the fuel is consumed in the electrochemical reactions, which affects water production. This means that the fuel quality and fuel reaction temperature plays an important role in fuel utilization and lower fuel gas temperature can result in lower water production and reduced cell efficiency, while excessive fuel utilization can lead to excessive water production and flooding.

Secondly, the humidity of the inlet gases decides the hydration level of the proton-conducting membrane and affects its performance and the resulting water production. Insufficient humidity can lead to membrane dehydration, negatively impacting proton conductivity and reducing water production. On the other hand, excessively high humidity can cause membrane flooding and hinder water production. This affects the proton conductivity. In Proton Exchange Membrane (PEM) fuel cells, maintaining a certain level of humidity is essential for maintaining the proton conductivity of the membrane. The presence of water vapor in the membrane helps facilitate the transportation of protons, ensuring efficient electrochemical reactions and water production.

2.3.2 Effects on the fuel cell

Firstly the main impact is seen on changes in the level of pH of water. This increase in the current density in a fuel cell can potentially lead to changes in the pH of the water, but the specific effect will depend on the anode and cathode reactions as well as other factors within the fuel cell system.

Cell performance is impacted with respect to membrane conductivity based on working conditions like temperature regulation and catalyst activity. Water balance affects the movement of gases, such as hydrogen and oxygen, within the fuel cell. Too much water can hinder gas diffusion, restricting reactant flow and reducing the availability of reactants at the catalyst sites. Insufficient water can lead to drying and increased resistance to gas flow. Both scenarios can negatively impact the fuel cell's performance.

Proper water balance helps regulate the temperature of the fuel cell. Water acts as a coolant and aids in dissipating heat generated during operation. If there is excessive water, it can increase the cooling effect, leading to lower operating temperatures. On the other hand, insufficient water content can result in inadequate cooling and higher operating temperatures, potentially causing performance degradation or even damage to the fuel cell components.

Also, the release of fluoride ions in a fuel cell system is primarily associated with the presence of fluoride-containing compounds, such as fluoropolymers or fluoride-based electrolytes, which may be used in certain types of fuel cells. The release rate of fluoride ions can be influenced by the water balance within the fuel cell system. There are some considerations regarding the impact of water balance on fluoride release in a fuel cell, which are the hydration level of the fluoride-containing components in the fuel cell and electrolyte concentration. Higher pH levels, and increased alkalinity may enhance the solubility and release of fluoride ions. Also, temperature can also influence fluoride release from fluoride-containing components. Higher temperatures may increase the release rate, while lower temperatures might decrease it. The water balance, along with temperature regulation, can influence the overall thermal conditions within the fuel cell system, thereby affecting fluoride release.

It's important to note that the release of fluoride ions and its impact on the fuel cell system can vary depending on the specific design, materials, and operating conditions of the fuel cell. If fluoride release is a potential concern in a specific fuel cell system, it is advisable to consult the manufacturer's guidelines, recommendations, or technical documentation to understand the specific factors affecting fluoride release and to ensure proper management of water balance within the fuel cell system.

pFAS production at cathode exhaust- perFluoro-Alkyl substances (pFAS) are a class of synthetic compounds that contain fluorine atoms and are known for their persistence in the environment. These compounds have gained attention due to their potential environmental and health concerns. While pFAS are not directly related to the impact of water in fuel cell systems, their presence in the environment can have indirect implications for water quality and potentially affect fuel cell operations.

Water treatment considerations are required to purify, and condition water for fuel cell applications may need to consider the presence of pFAS compounds. These compounds can be persistent and difficult to remove through conventional water treatment methods. Specialized filtration or adsorption techniques may be required to reduce pFAS concentrations in water used for fuel cells to ensure the long-term performance and reliability of the system. As the pFAS compounds are hazardous, the environmental impact of pFAS contamination in water sources can have broader implications for ecosystems and natural water bodies. Contaminated water used in fuel cell systems can contribute to the overall environmental footprint of the technology. Constant consideration of sustainable and responsible water management practices is essential to minimize the potential environmental impact of fuel cell operations.

It's worth noting that the specific pFAS compounds, their concentrations, and their potential impact on fuel cell systems can vary depending on the region, local regulations, and the specific fuel cell technology being used. At Volvo penta, the fuel cell manufacturers from Cell-Centric understand the potential presence and behavior of pFAS compounds in water sources and are aware of the issue from water sampling, they are currently researching alternative membrane designs to eliminate the presence of the substances.

2.4 Characteristics of the fuel cell components on water production

Fuel cell sizing, like membrane thickness, area of mass, and charge transport, plays a crucial role in undermining the fuel cell performance and water qualitative production. This is important for water storage sizing and deciding for which applications it could be utilized later.

Fuel cell performance will improve if fuel cell resistance is decreased. The fuel cell resistance changes with the area and thickness of the membrane. The effective way to reduce ohmic losses is to find a lower membrane area or a thinner membrane. Also, a thinner membrane is advantageous as it keeps the anode electrode saturated through the back diffusion of water from the cathode material. At high current densities, mass transport causes a decrease in the voltage, mainly due to oxygen and hydrogen cannot diffuse through the electrode and ionize faster. Hence products cannot be moved out at the required rate. This affects the rate of transport and, hence, the water production rate.

2.5 Potential applications for produced water

Water produced from fuel cell is not entirely byproduct but a valuable source for diverse applications. By integrating water re-circulation processes, it enhance the overall efficiency of fuel cell system, creating a closed loop and macro scale sustainable energy cycle.We investigated four potential applications which can be used in industrial and agricultural processes.

1. For drinking
2. For gardening
3. Integration to a district heating network
4. Integration to industrial radiators and humidifiers

2.5.1 For drinking

Water obtained from a fuel cell can be used for drinking purposes, but it is important to ensure that the water meets certain quality standards and does not contain any harmful chemicals or impurities. The requirements for the chemical composition of water obtained from a fuel cell for drinking purposes are generally similar to those for other sources of drinking water. Here are some key considerations:

- Purity: The water should be free from contaminants and impurities, such as heavy metals, organic compounds, bacteria, viruses, and other microorganisms.
- pH Level: The pH level of the water should be within a safe range for drinking, typically between 6.5 and 8.5. This range ensures the water is not too acidic or alkaline.
- Dissolved Solids: The concentration of dissolved solids in the water, measured as total dissolved solids (TDS), should be within acceptable limits. Generally, TDS levels below 500 parts per million (ppm) are considered safe for drinking.
- Nitrates and Nitrites: The water should have low concentrations of nitrates and nitrites, as high levels of these compounds can be harmful, particularly to infants and pregnant women.
- Microbiological Contaminants: The water should be free from harmful bacteria, viruses, and other microorganisms. It should undergo proper disinfection and testing to ensure it meets microbiological safety standards.
- Taste and Odor: The water should be free from unpleasant tastes and odors, which can affect its palatability.
- Chlorine and Chlorination By-Products: The water should not contain excessive amounts of chlorine or chlorination by-products, as they can have adverse health effects. Chlorine levels should be below the recommended limits, typically less than 4 ppm.

From the table 2.1, the tolerance limit of different chemicals of water quality was reported for drinking applications based on WHO standards. To ensure that the water obtained from a fuel cell meets these requirements, appropriate water treatment and filtration methods may be necessary. It is advisable to consult water quality experts or utilize certified water purification systems to ensure the water is safe for drinking. Additionally, local regulations and guidelines for drinking water quality should be followed.

Application	Chemical Compounds	pH Level	Recommendations
Drinking	Acrylamide 0.10 μg/L Antimony 5.0 μg/L Benzene 1.0 μg/L Boron 1.0 mg/L Bromate 10 μg/L Cadmium 5.0 μg/L Chromium 50 μg/L Copper 2.0 mg/L Cyanide 50 μg/L 1,2-dichloroethane 3.0 μg/L Fluoride 1.5 mg/L Lead 10 μg/L Mercury 1.0 μg/L Nickel 20 μg/L Nitrate 50 mg/L Nitrite 0.50 mg/L Pesticides 0.10 μg/L Pesticides 0.50 μg/L	pH – 6.5 to 7 Conductivity – 500 μS/cm	Based on testing and water sampling in the setup,further treatment is needed for drinking applications

Table 2.1: This table describes the tolerance limit, pH, and conductivity of chemicals in drinking water per WHO standards and whether the collected sample is fit for drinking.

2.5.2 For gardening

When using water obtained from a fuel cell for gardening applications, the requirements for the chemical composition may be more relaxed than those for drinking water. However, it is still important to consider certain factors to ensure the water is suitable for gardening.

- pH Level: The pH level of the water should be within a range suitable for the specific plants being grown. Different plants have different pH preferences, so it is important to adjust the water pH accordingly. Generally, a slightly acidic to neutral pH range of 6.0 to 7.5 is suitable for most garden plants.

- Salinity: The water should have a low salinity level to avoid salt buildup in the soil, which can harm plants. High salts can affect water uptake and lead to plant stress. Conductivity or electrical conductivity (EC) is a common measurement of salinity. The EC of the water should be monitored and kept within acceptable limits for the plants being grown.

- Nutrient Levels: Depending on the plants' specific needs, the water obtained from the fuel cell may need to be supplemented with nutrients. This is particularly important if the water is derived from a reverse osmosis or de-ionization process, which can remove essential nutrients. Additional fertilizers or amendments may be required to ensure plants receive adequate nutrition.

- Heavy Metals and Contaminants: While not as critical as drinking water, it is still advisable to minimize the presence of heavy metals and contaminants in the water used for gardening. Excessive levels of certain heavy metals can be toxic to plants, so monitoring and keeping these levels low is beneficial.

- Microbiological Contaminants: While not as crucial for gardening water as for drinking water, avoiding using water that contains harmful bacteria or other microorganisms is generally preferable. If the water is being stored or transported in a manner that could introduce microbial growth, appropriate measures should be taken to prevent contamination.

- Water Availability: Ensure that the water supply from the fuel cell is consistent and sufficient for the plants' irrigation needs. Adequate water flow and pressure are necessary to irrigate the garden effectively.

It is worth noting that specific requirements for water composition may vary depending on the type of plants being grown, local soil conditions, and regional climate. Consulting with local gardening experts or agricultural extension services can provide more specific guidelines for using water obtained from a fuel cell in your gardening application.

2.5.3 Integration to a district heating network

Water obtained from a fuel cell for district heating applications is primarily used for thermal energy transfer rather than consumption, so the requirements for chemical composition may differ from those for drinking or gardening purposes. Here are some critical considerations for the chemical composition of water used in fuel cell-based district heating systems:

- Corrosion Inhibition: The water should have appropriate corrosion inhibitors to protect the fuel cell and other system components from corrosion. Corrosion inhibitors help prevent the degradation of materials and prolong the lifespan of the equipment.
- Scaling and Deposits: The water should be treated to minimize the formation of scale and deposits that can hinder heat transfer and reduce system efficiency. Scaling occurs when certain minerals in the water precipitate and form hard deposits on heat transfer surfaces. Proper water treatment and conditioning methods, such as filtration or water softening, may be employed to control scaling and maintain system performance.
- Oxygen and Dissolved Gases: The water should be relatively free from dissolved oxygen and other gases, as they can contribute to corrosion and decrease the overall system efficiency. Appropriate de-aeration methods, such as de-gasification or de-oxygenation, may be implemented to remove dissolved gases from the water.
- pH Level: The pH level of the water should be within a range that minimizes corrosion and scaling. Typically, a slightly alkaline pH between 8.0 and 9.0 is maintained to mitigate corrosion risks in district heating systems.
- Microbiological Growth: The water should be treated to control the growth of bacteria, algae, and other microorganisms. Microbial growth can lead to fouling, bio-film formation, and system degradation. Disinfection methods or biocides may be employed to prevent microbiological issues.
- Heat Transfer Efficiency: The water should have good thermal conductivity and heat transfer properties to ensure efficient heat exchange within the district heating system. High levels of impurities, such as dissolved solids, organic compounds, or suspended particles, can impede heat transfer and reduce system efficiency. Proper water treatment and filtration methods may be employed to maintain optimal heat transfer efficiency.

  It is important to consult with system manufacturers, water treatment specialists, or experts in district heating to determine the specific chemical composition requirements for water used in fuel cell-based district heating applications. Factors such as the type of fuel cell technology, system design, and local conditions can influence the water treatment needs for optimal system performance and longevity.

2.5.4 Integration to industrial radiators and humidifiers

It's important to note that radiator cooling systems often use a mixture of water and coolant/antifreeze, which provides additional protection against freezing, boiling, and further corrosion. The coolant/antifreeze contains specific additives and chemicals designed to meet the requirements of radiator cooling systems, including providing freeze protection, heat transfer enhancement, and additional corrosion inhibition.

When using water obtained from a fuel cell for radiator cooling, it is advisable to follow the recommendations of the vehicle manufacturer or consult with automotive experts to ensure the appropriate coolant mixture and chemical composition for the specific radiator cooling system in question.

- Corrosion Protection: The water should contain corrosion inhibitors to protect the radiator and other cooling system components from corrosion. Corrosion inhibitors form a protective layer on metal surfaces, preventing corrosion and extending the lifespan of the system.

- Scaling and Deposits: The water should be treated to minimize scaling and deposits in the radiator. Scaling occurs when minerals and other impurities in the water precipitate and form deposits on heat exchange surfaces, reducing the cooling efficiency. Water conditioning methods, such as filtration or water softening, may be employed to control scaling and maintain system performance.

- pH Level: The pH level of the water should be within an appropriate range to prevent corrosion and minimize scaling. Typically, a slightly alkaline pH between 8.0 and 9.0 is recommended to mitigate corrosion risks and maintain system efficiency.

- Heat Transfer Efficiency: The water should have good thermal conductivity and heat transfer properties to ensure effective cooling. High levels of impurities, such as dissolved solids, organic compounds, or suspended particles, can hinder heat transfer and reduce cooling efficiency. Proper water treatment and filtration methods may be employed to maintain optimal heat transfer efficiency.

2.6 Volvo fuel cell container setup

The Volvo Penta fuel cell setup consists of engineered components to generate electricity through electrochemical processes. Many technology firms are integrating this technology into their industry as it offers clean and efficient energy. This technology has gained significant attention in recent years due to the scarcity and degradation of energy sources. There are several types of fuel cells, including Proton Exchange Membrane Fuel Cells (PEMFC), Alkaline Fuel Cells (AFC), Solid Oxide Fuel Cells (SOFC), and Phosphoric Acid Fuel Cells (PAFC).Designers have the flexibility to choose the fuel cell that best suits the application at hand. Volvo Penta has decided that PEMFC setup as H_2 is the most common fuel in fuel cells due to high energy content and sustainability characteristics. In this configuration, the fuel cells are at the center and each has a capacity of 150 kW.

The fuel of H_2 enters the fuel cell through the anode, an electrode where fuel oxidation occurs. In a hydrogen fuel cell, hydrogen molecules are split into protons (H^+) and electrons (e^-) at the anode. The protons enter through the electrolyte, while the electrons travel through an external circuit, creating an electric current that can be harnessed for various applications.

The cathode is located on the opposite side of the fuel cell.The cathode is where an oxidant, typically oxygen from the air, combines with electrons and protons from the anode to form water or other byproducts. This reduction reaction at the cathode completes the electrochemical process. The Volvo fuel cell setup can be illustrated in Figure 2.1. The setup can be divided into three primary components. The blue, yellow, and green parts consist of H_2 tanks, air compressors, fuel cells, and battery storage.

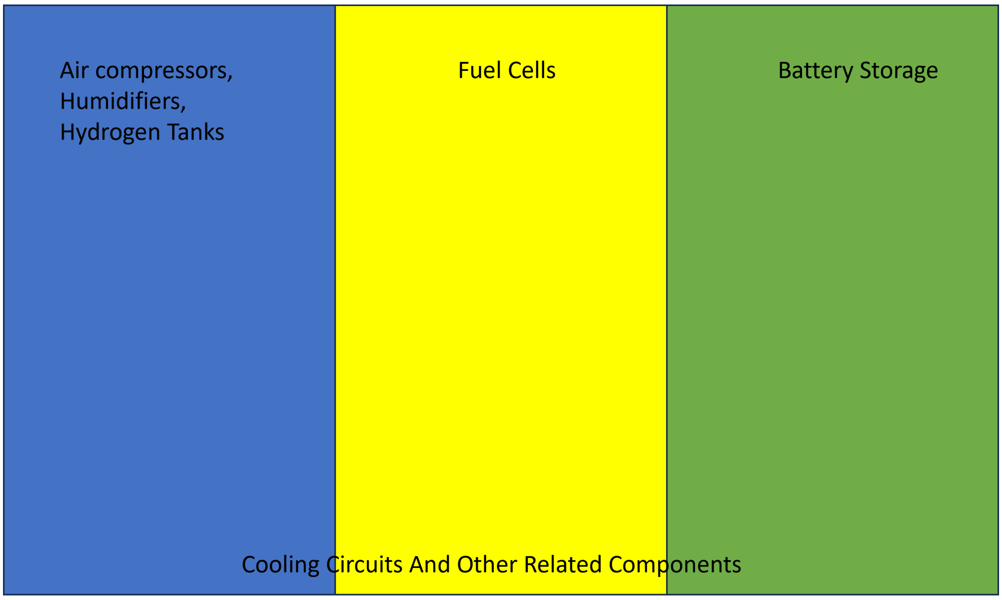

Figure 2.1: Illustration for how three major sections are combined in industrial fuel cell setup in Volvo penta

Battery pack is the important component in the setup. This consists of a series of interconnected rechargeable batteries. Depending on customer requirements, capacity, and arrangement will differ. If this is for mobile applications, the capacity will be lower and must have higher charging cycles, and for stationary applications, higher capacity can be maintained. Batteries also help with frequency regulations as well. This hybrid system of fuel cells with batteries can keep the stable power requirements in the end application. The idea is to run the fuel cells at the highest efficiency, and depending on the demand, the inverter will decide the power dissipation.

The hydrogen system also called a fuel source in this system, which consists of interconnected hydrogen tanks. Hydrogen gas is one of the cleanest fuels that can be produced through various production methods such as steam reforming of natural gas or through electrolysis. This section is subdivided into production, storage, and distribution. Those sections consist of filters, valves, and flow meters to have uninterrupted operation in the fuel cell.

The electrical harness system, also known as a cable assembly or wiring loom, is a set of wires to transmit power or signals. There are three essential parts in a harness system, which are wires, connectors, and terminals. The electrical harness system plays a vital role in the fuel cell electrical system. It interconnects all the electrical devices to facilitate safe power generation. This consists of electrical fuses and cables. Fuses and switches within the fuel cell system to ensure the proper functioning and integration. Not only on the power distribution side but even on the power generation side, electrical harness plays a significant role by interconnecting auxiliary systems such as pumps, fans, sensors, control units, and electric motors. Furthermore, this system helps data communication between different components. This allows the user to monitor and control the input and output parameters, analyze data, forecast, and diagnose errors. A controller area network (CAN) or Ethernet protocol can be used to communicate within the system. In the future, this can be developed to have a Wi-Fi system.

Radiators are known heat transfer devices which is widely used in the automotive industry. There are many types of radiators such as air to air and fluid to air. In this fuel cell setup, there are two water-to-air radiators connected to high-temperature circuits. Radiators are vital components in a system to keep the system at the desired temperature. Radiators play an essential role in the cooling system of a fuel cell setup. As fuel cells operate, they generate heat, and efficient thermal management is crucial to maintain optimal performance and prevent damage to the fuel cell components. In the beginning, to get the system to a working temperature, water will not flow through the radiators. Once it comes to working temperature, the thermostat will allow water to pass through the radiators. Radiators are vital components of the cooling system that help dissipate excess heat and maintain the desired temperature range. Radiators are connected to a coolant loop within the fuel cell system. The coolant, typically a mixture of water and antifreeze or other specialized fluids, absorbs the heat generated by the fuel cell and carries it to the radiator. The radiator fan speed is planned to vary with temperature conditions in the fluid. The radiator then facilitates heat transfer to the ambient air, cooling the coolant before it returns to the fuel cell to repeat the cycle.

By identifying the major parts of something, we can gain insight into its fundamental components and their corresponding roles. The fuel cell acts as the primary power generator, batteries enable energy storage, and the H_2 supply ensures a continuous and reliable source of fuel. Major parts of the system are summarized in Figure 2.1; However, in the latter phase of the project, hydrogen storage will move out depending on the application and fire safety guidelines. When dealing with a hydrogen project, the most challenging part will be to get the safety certification. As per the National Fire Protection Association (NFPA) guidelines, there are extra precautions must be taken as hydrogen possesses the highest flammability when mixed even in small amounts with ordinary air.

As shown in Figure 2.2, the project group has developed a schematic diagram combining all the thermal circuits in the fuel cell setup. The heating of the PEM fuel cell will affect its working performance. Therefore, it is recommended to control the temperature. When designing the thermal system for fuel cells, it is better to start with manufacturers' recommendations as they deal with efficiency and safety. It is noted that two significant cooling circuits play a vital role in maintaining optimal temperatures for critical equipment. These cooling circuits are specifically designed to dissipate heat effectively. The first circuit, known as the high-temperature circuit, operates at a temperature of 60 – 78 °C and has an impressive cooling capacity of 225 kW. It is responsible for cooling down components that generate substantial heat during operation.

On the other hand, the second circuit, referred to as the low-temperature circuit, operates at a temperature of 55 – 60 °C and has a slightly lower cooling capacity of 9 kW. The secondary circuits consist of air radiators, pumps, and thermostats to control the temperature in the desired range. This circuit is designed to handle equipment that generates less heat than the high-temperature circuit. Both circuits are crucial in ensuring critical equipment's safe and efficient operation.

There are both advantages and disadvantages of having two thermal circuits in the industrial stage. On the positive side, it is easy to operate them independently throughout the process. If there is a breakdown, the technician can easily work on the faulted part without affecting the other circuit. However, there are also some drawbacks. The repeated parts necessary for two circuits can be expensive, and additional space is required to accommodate them.

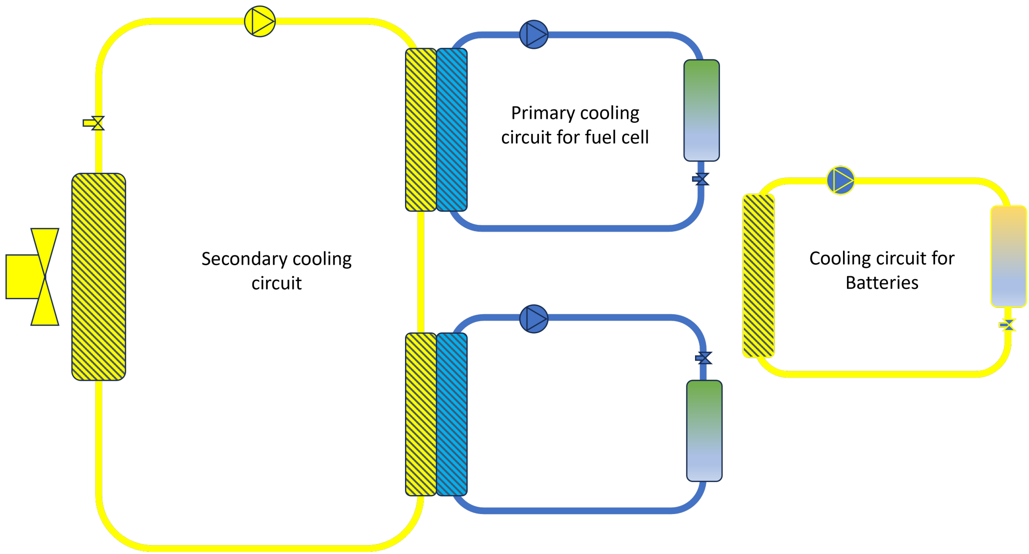

Figure 2.2: Schematic diagram of high temperature and low-temperature thermal circuits in the Volvo Penta fuel cell setup

There is another separate circuit that cools down the battery pack. These radiators employ the principle of convection, utilizing the surrounding air to extract heat from the secondary circuit, thereby maintaining the desired temperature range. Batteries are important equipment for energy storage. Keeping those at the desired temperature helps to increase the lifespan and charging capabilities. Batteries can be cooled by air or liquid, depending on the applications. However, in this setup, cooling liquid is yet to be determined. It can be either water, a refrigerant, or ethylene glycol. There was another proposal to combine all three circuits into a common circuit. However, there are some restrictions from manufacturers of fuel cells and batteries.

Generally, thermal systems are robust. However, they can also be susceptible to aging critical components, tube corrosion, and leakage. These two major cooling circuits, operating at different temperature ranges, along with the primary-secondary circuit setup and the use of plate-type heat exchangers and air-cooled radiators, form a comprehensive cooling system that ensures critical equipment remains within safe operating temperatures, enhancing performance and longevity. While the concept behind the cooling is the same as that of automobiles, the design group is still trying to test different concepts that can be embedded into fuel cell setups.

3

Methods

3.1 Fuel cell simulation model in Matlab

In the previous chapter, we discussed physical models that are included in the fuel cell model. This thesis project aims to create a model to simulate the entire system. We aim to create a virtual model by using MATLAB Simulink. Simulink is an ideal platform for model-based designing that supports engineering applications' design, simulation, and sensitivity analysis. MATLAB Simulink is a virtual tool for computer simulations. The engineering parts such as valves, batteries, humidifiers, and pumps are enabled in the library, and users can add those into the model pace by drag and drop system. Then, the components can be interconnected with lines. The mathematical functions related to the element are embedded to block itself. There are a few advantages to using model-based developments with MATLAB Simulink.

- Cost: engineers can work on all the possibilities since it facilitates a virtual prototype to vary the parameters. Thus, reduces rework effort on actual prototypes.
- Schedule: Rather than producing more real prototypes, this allows the conveying of the multiple tests parallel, which leads to a shorter time for the research and development phase in the project.
- Performance: Optimizing the product is beneficial for customers and manufacturers. This virtual environment allows us to do rigorous calculations, which leads to the finest product.

By replicating a fuel cell's physical setup, we created a virtual model. However, a default model is available in the MATLAB software. The parameters of each component were changed to match with a physical model. We even added a few simscape blocks to represent the cathodes, anodes, valves, and humidifiers. To understand the behaviors of the fuel cell, three methods are available to vary the electrical load. However, during the prototype phase, each load scenario will be tested and investigated separately to get the certifications.

- Step load: Step load is defined as the amount of load that will be placed at one time. This load will be there throughout the process, irrespective of the demand. However, multiple load sets can be archived by giving a certain load at several intervals. These intervals can be defined according to demand, capacity, and variety of fuels, including hydrogen and natural gas.
- Ramp load: Ramp load can be defined as a load supplied with a time gradient. The final load is being changed throughout the period. However, this mode has some limitations due to restrictions from fuel sources.

- Dynamic load: Dynamic load changing mode is the most commonly available in engineering applications. Depending on the situation, fuel cells are sensitive to degrading or upgrading the load. However, the system has been designed to overtake the fluctuations.

After recreating the same conditions used in the MATLAB model, we performed a simulation and analysis of the behavior of different components. This helped us to understand their individual contributions and enabled us to study the overall performance of the fuel cell system. With this information, we were able to explore different scenarios, evaluate the impact of design modifications, and gain insights into the system's efficiency, durability, and overall functionality.

Through our efforts in recreating the fuel cell setup in the MATLAB model, we aimed to enhance our understanding of fuel cell technology, optimize its performance, and lay the foundation for further research, development, and improvement in this field.

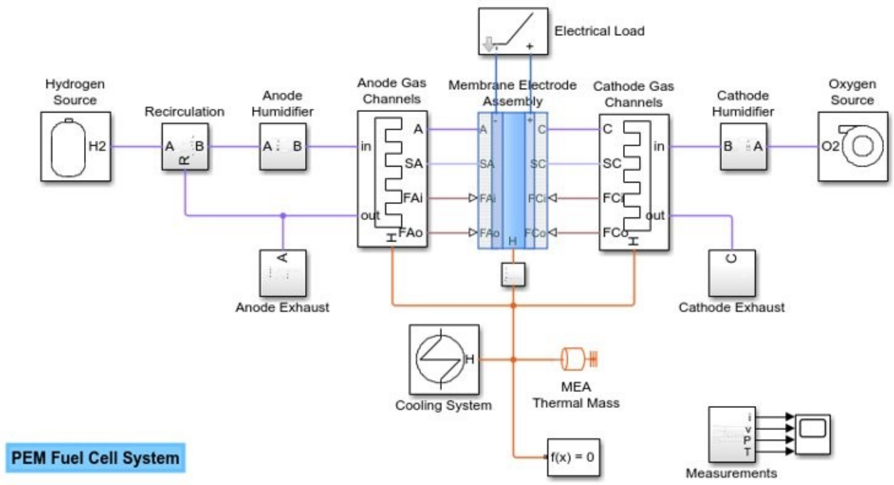

Figure 3.1: Matlab simulink setup showing the essential components of a PEM fuel cell

With the help of Simscape, we have the flexibility to tailor a comprehensive model of a PEMFC. This model can be customized to include not only the fuel cell stack but also various balance-of-plant components crucial to its operation. These components encompass air compressors, humidifiers, hydrogen recirculation paths, cooling systems, and water management systems.

By utilizing first-principles-based modeling techniques, Simscape empowers engineers to develop an accurate and detailed representation of a PEM fuel cell, both at the component and system levels. This approach considers the intricate electrochemical processes that occur within the fuel cell, ensuring a more realistic simulation. The level of detail achieved through Simscape enables the simulation and study of functionalities such as current, voltage, and power monitoring. This capability is valuable for understanding the performance characteristics of the fuel cell and allows for precise control and optimization. Additionally, Simscape facilitates the modeling of thermal management aspects, enabling engineers to analyze and optimize heat transfer and cooling strategies within the fuel cell system.

In this thesis, the main objective is to investigate the critical aspects of water management in fuel cells. Understanding water management in a fuel cell is crucial as it affects the performance, efficiency, and overall functionality of the cells. By conducting a thorough examination of the cathode exhaust, researchers can uncover valuable information related to water management strategies, such as humidity control, condensation prevention, and adequate water removal. This knowledge contributes to developing enhanced fuel cell designs, optimized operating conditions, and improved overall performance.

To gain deeper insights into the complexities of water management and its influence on fuel cell operation, an in-depth investigation of the cathode exhaust is necessary. According to the literature survey and lab tests, it is found that water in the cathode exhaust is not in a fully liquefied phase. Therefore, a series of interconnected applications is needed to collect water. We identified four major parts that should be included in the process. These mechanisms, dynamics, and interactions are involved in removing and controlling water vapor from the fuel cell system.

1. Modified cathode exhaust
2. Pressure relief valve
3. Water condenser
4. Water storage

3.1.1 Development of cathode exhaust block

After referring to several technical papers, we discovered that water present in the cathode exhaust may be in a different liquid phase. To facilitate the liquefaction of water, four essential components are required.

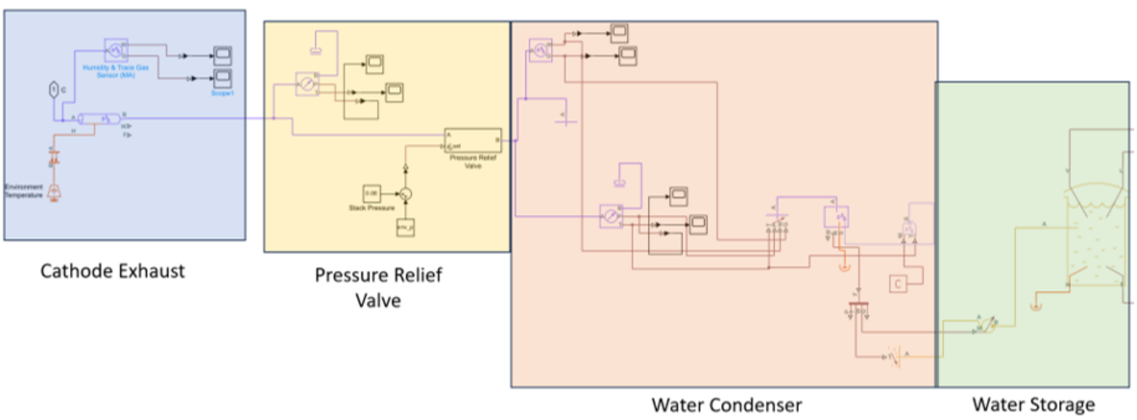

Figure 3.2: Extended cathode exhaust block for the water condensation from fuel cell setup

3.1.1.1 Modified cathode exhaust

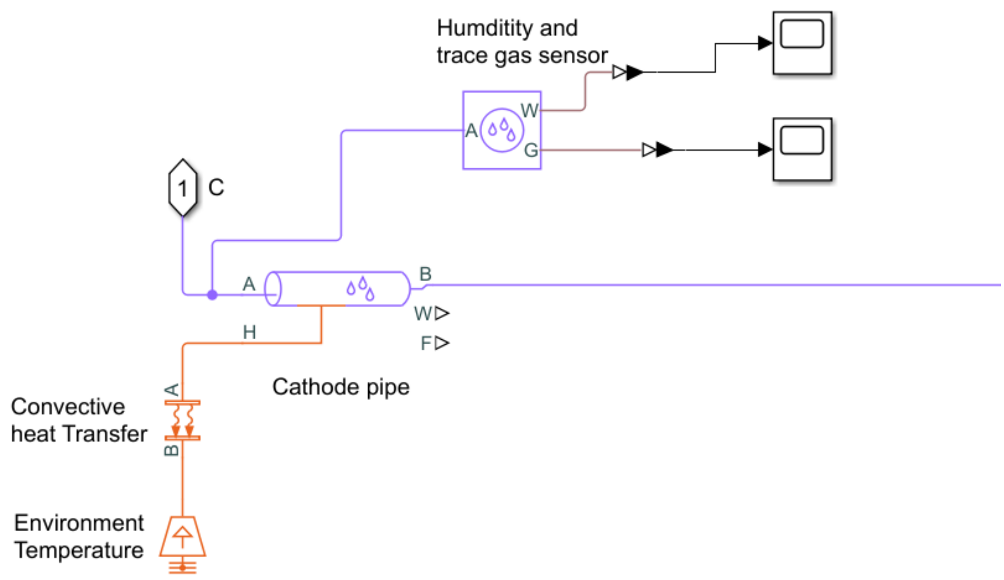

Figure 3.3: Modified cathode exhaust with having insulated layer and sensors

The cathode exhaust, a critical component of the fuel cell system, is encompassed by several elements. These elements include the cathode pipe, humidity, trace gas sensor, and a heat transfer element that facilitates the exchange of thermal energy between the pipe and the surrounding environment. As per Figure 3.3, to replicate the cathode exhaust in the MATLAB model, we have to include the cathode pipe, Humidity, and trace gas sensor, convective heat transfer block, temperature reference block, and pipe connections. Water humidity just after the humidity sensor monitors the cathode operation.

As per the theory, unused hydrogen should not be found in the cathode exhaust. However, we can measure this using a trace gas sensor. This information provides valuable insights to monitor and control the fuel cell performance. In the virtual model, monitoring the excessed hydrogen does not make any sense, but it will be useful in the actual model. The humidity and trace gas sensor is a vital component integrated into the cathode exhaust system. Its purpose is to monitor and analyze the humidity levels and trace gas concentrations present within the exhaust gases. This information provides valuable insights into the state and composition of the cathode exhaust, enabling better control and optimization of the fuel cell's performance.

Convective heat transfer can occur in the wall of the pipe, which is represented by the orange color blocks. This ensures the temperature will remain in the desired range in the block. In the sensitivity analysis, we can vary the environment temperature and investigate the results. Since the final product shall have the rigidity to take care of the obstacles irrespective of the environmental temperature and humidity. The heat transfer element acts as a medium for exchanging thermal energy between the cathode pipe and the surrounding environment. It facilitates the dissipation of excess heat generated within the fuel cell system, ensuring the temperature remains within the desired operating range. This heat transfer mechanism aids in maintaining optimal conditions for the efficient functioning of the fuel cell and contributes to overall system stability.

3.1.1.2 Pressure relief valve

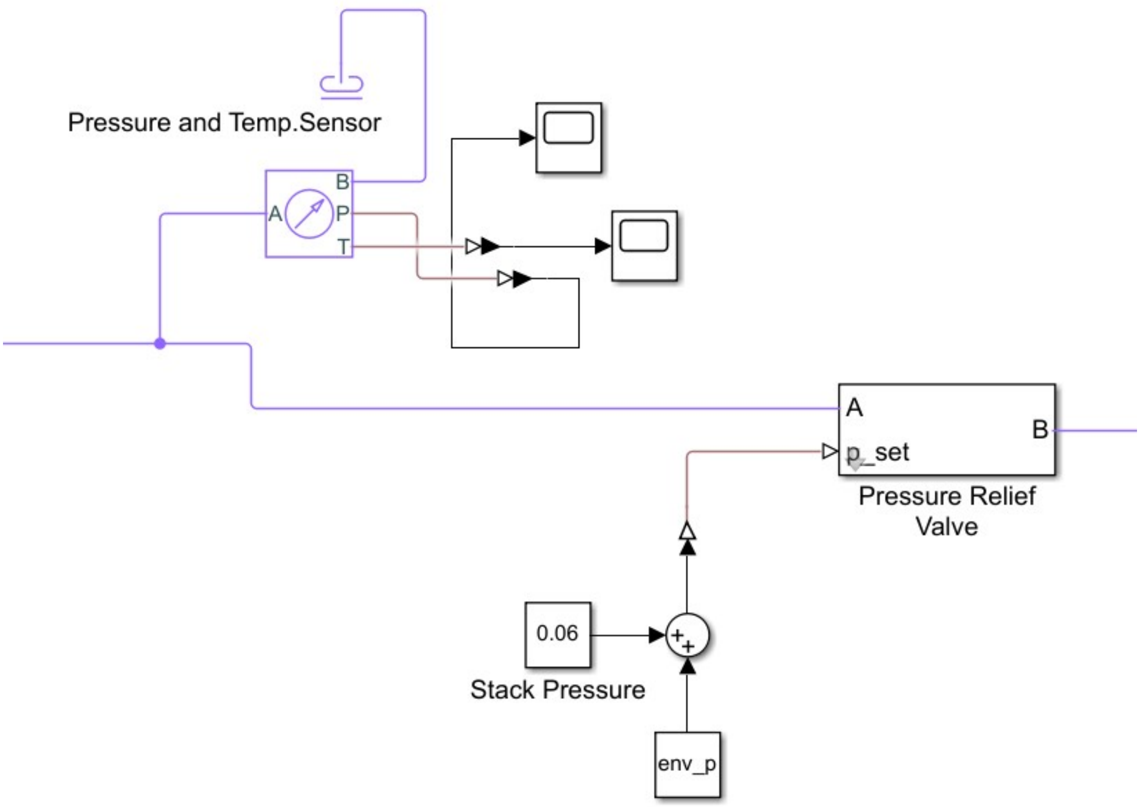

Figure 3.4: Modified pressure relief valve to reduce the incoming pressure from cathode exhaust

We noticed that the outlet pressure is higher than the atmospheric pressure of the cathode exhaust. To collect the water and keep the system within a safe environment, it is recommended to reduce the pressure to atmospheric level. The pressure relief valve is represented by a set of Simulink variables. Pressure and temperature can be monitored before and after the valve so that the user can be aware the valve is functioning according to the limits. In this model, irrespective of upstream pressure, downstream pressure is always set to be at 1 bar. The pressure relief valve plays a critical role in the fuel cell system by ensuring the appropriate pressure levels are maintained and regulated between the fuel cell stack and the surrounding atmosphere. This valve can act as a safety valve to the system. When designing an engineered system, safety will be the highest priority; hence, these types of valves are recommended to consist of three main parts: valve elements, a spring-loaded poppet valve, a diaphragm sensing element, and a reference force element. Generally, the valve is in the closed position until the upstream pressure exceeds the set point value. Further, this valve can also be a separator between the fuel cell system and water-collecting devices. When in maintenance, the operator can work on either side without shutting down the entire plant. The pressure relief valve acts as a safeguard, preventing any potential overpressure situations that could compromise the integrity and performance of the fuel cell system.

Maintaining and regulating the pressure effectively allows the system to operate optimally and ensures the water collecting tank remains at the desired atmospheric pressure, which is crucial for its proper functionality. One specific requirement within the fuel cell system is the operation of the water collecting tank at atmospheric pressure. To meet this requirement, it becomes necessary to reduce the pressure within the system. This is where the pressure relief valve comes into play. It is designed to alleviate any excess pressure that may build up in the fuel cell stack, ensuring that the pressure is maintained within the desired range.

3.1.1.3 Water condenser

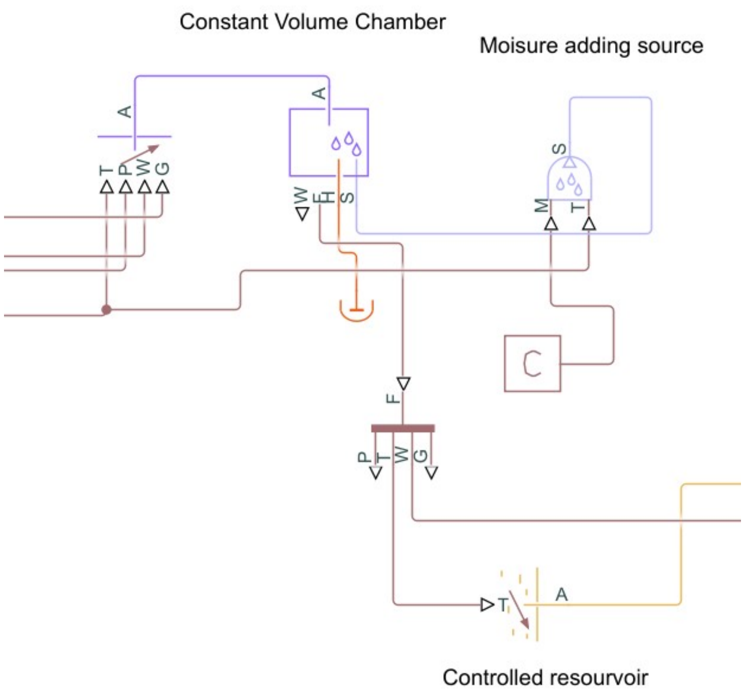

Figure 3.5: Water condenser consists of constant volume chamber and moisture adding source

We noticed there is a requirement for a water condenser as the water in the cathode exhaust is not in the liquid phase. The function of this condenser is to change the phase in the water by removing the latent heat. In the MATLAB workspace, a condenser can be represented by a set of blocks such as a constant volume chamber, moisture-adding source, and controlled reservoir. A water condenser serves a crucial function in the fuel cell system by transforming water vapor emanating from the cathode exhaust into its liquid state. The condenser is composed of several key components, including a volume chamber, a moisture-adding source, and a controlled reservoir. Within the condenser, the water phase within the volume chamber is carefully monitored to ensure optimal operation. The monitoring process enables precise control over the condensation process. Based on the water phase conditions, water droplets are added accordingly to facilitate the conversion of vapor into liquid. Operating at room temperature, typically set at 20 °C, the moisture-adding source plays a vital role in introducing the necessary water content into the condenser. It ensures a controlled supply of moisture, contributing to the condensation process.As the water vapor condenses and transforms into liquid form, the liquefied water is directed and collected in a controlled reservoir. This reservoir ensures that the condensed water is appropriately stored and managed within the fuel cell system. A constant volume chamber is where the phase change happens by allowing the mixing of the water with moisture. The temperature, humidity level, and pressure can be controlled externally. The moisture will be produced in the moisture-adding source. This consists of a water collector and a set of pressurized nozzles. In this setup, we considered the water at 20°C. However, effacing can be increased by adding warm water to the setup as more exergy is available. After condensing the water is stored at the controlled reservoir. Although this is shown as a separate part in the virtual model, in the actual case, this can be a part embedded in the constant volume chamber.

3.1.1.4 Water storage

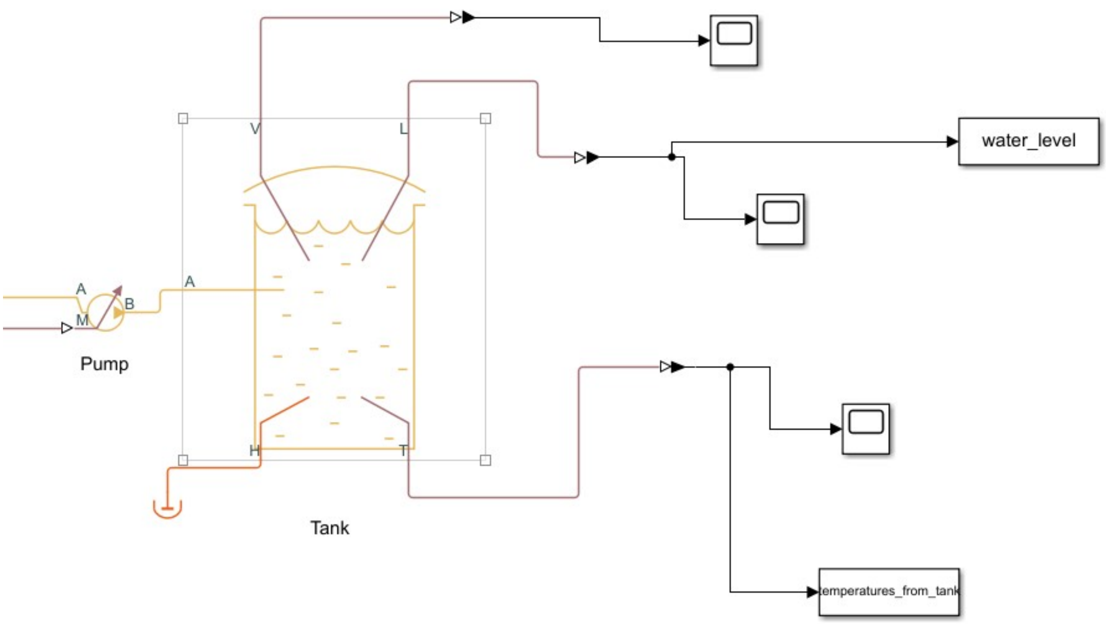

Figure 3.6: Water storage with insulated layer to keep the temperature in constant level

After the condensation is processed, water will flow to the water collector, which is an insulated tank. Depending on fuel cell applications, size and arrangement can be defined. At the end of the condenser, we assumed that vaporized water is fully transformed into liquid water even though, in actual scenarios, it may differ due to practical issues. At this point, the liquid water is pressurized utilizing a pump, which imparts the necessary force to propel the water forward. The pressurization facilitates the efficient movement and transfer of the water to a designated collecting tank. To keep the water temperature at a steady level, the collecting tank is wrapped with insulation. The insulation acts as a barrier between the surroundings and collected water. Maintaining the water at a higher temperature allows the water to be used for another purpose in the latter stage. By maintaining a stable temperature within the tank, the insulation helps preserve the desired thermal conditions of the water, which can be crucial for subsequent stages or applications within the fuel cell system.

Also, the water is pressurized through a pump to manage and control the water flow between the condensing chamber and the collection tank. Water pumps are defined as impulse turbine that works using a spinning propeller to convert potential energy from pressure into kinetic energy. It helps to change the pressure or flow rate of the fluid. There are a few types of pumps available, such as centrifugal, axial flow, and diaphragm pumps. However, we decided to go with a centrifugal pump for this application.

3.2 Simulations for stored water(1D and 3D)

In Chapter 2, we discussed potential applications for stored water from fuel cell applications. There are many possibilities, such as drinking, gardening, connecting to the district heating network, and also using it as a cooling source. Due to the time constraints of the thesis period, we have narrowed our focus to two specific scenarios that can be used in mobile and stationary applications.

1. Chimney/muffler design
2. Water sprayer to heat exchanger

3.2.1 Chimney/muffler design

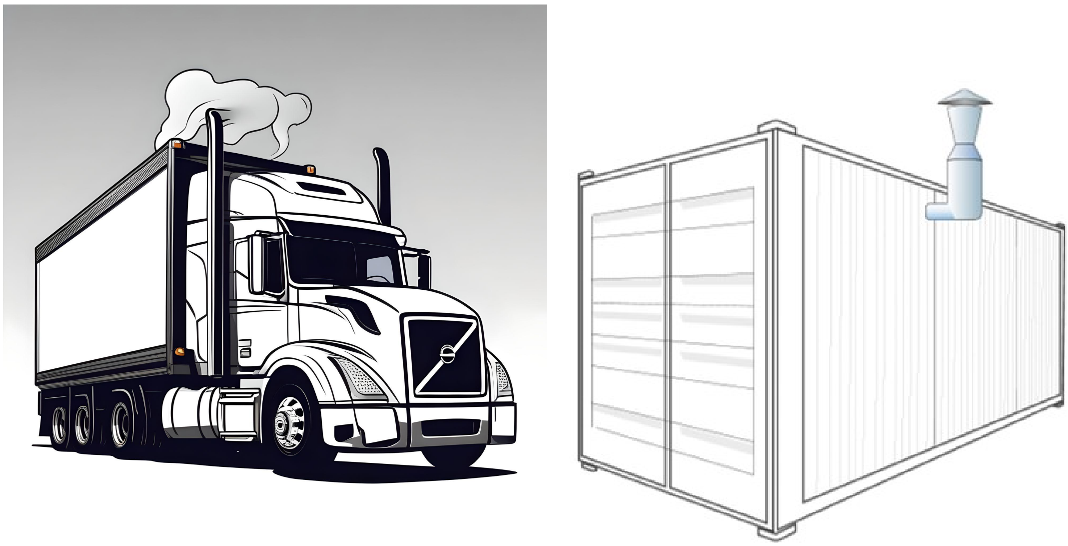

Figure 3.7: Chimneys design for mobile and stationary applications

When deciding applications that are suitable for this fuel cell setup, a few key aspects are considered. Simplicity and maintenance are the key factors when it comes to designing parts for mobile applications; hence, the idea of a chimney or muffler popped up. The purpose of the chimney is to facilitate the evaporation of the stored water by elevating its temperature to the point of boiling. Generally, mufflers are used in the exhaust system to guide and filter the exhaust from the internal combustion engine. It also acts as a soundproofing device to reduce the noise from the engine. This carefully designed mechanism harnesses the heat energy within the system to induce the vaporization process. As the water is heated, it transitions from its liquid state to a gaseous form, creating water vapor. This evaporation method holds applicability across a wide range of scenarios, encompassing both mobile and stationary applications. Whether in mobile fuel cell systems or stationary power generation setups, the chimney-based evaporation technique proves to be versatile and adaptable.

In mobile applications, such as fuel cell-powered vehicles or portable energy systems, the chimney-based evaporation method offers an efficient means of utilizing stored water. By evaporating the water, it generates steam or water vapor, which can be employed in various ways to drive specific functions within the mobile system. This could include steam-assisted processes, power generation, or other necessary functionalities.

Similarly, in stationary applications, such as residential or industrial power generation, the chimney-based evaporation method proves valuable. By raising the temperature of the stored water to its boiling point, the chimney facilitates the production of water vapor, which can be utilized for steam-based power generation or other thermal applications. The versatility of this method lies in its ability to transform stored water into a useful gaseous form; the proposed chimney design consists of a few engineering components such as a heater, vertical stack, and insulated body. A simple water heater with a coil can be used for this system. The heater is an element that converts electricity energy to thermal energy by conduction heat transfer. It can be either a single, double, or triple rolled design to maximize the contact area. Recommended materials are stainless steel or copper. As per Figure 3.7, a vertical stack can be designed. It shall be robust, having less pressure drop and maintenance design.

As the water temperature in the collecting tank is 80 °C, the heat shall be supplied to get the water to 100 °C and then for the vaporization process. There are two heating processes that can be observed in this process, which are sensible heat and latent heat. Sensible heat is defined as when the object is heated up; its temperature also rises as the heat is added. Between 80 °C and 100 °C, sensible heat is added to the system. Latent heat can be written as a hidden energy required for a phase change of a fluid.

3.2.1.1 Matlab simulation setup for chimney/Muffler

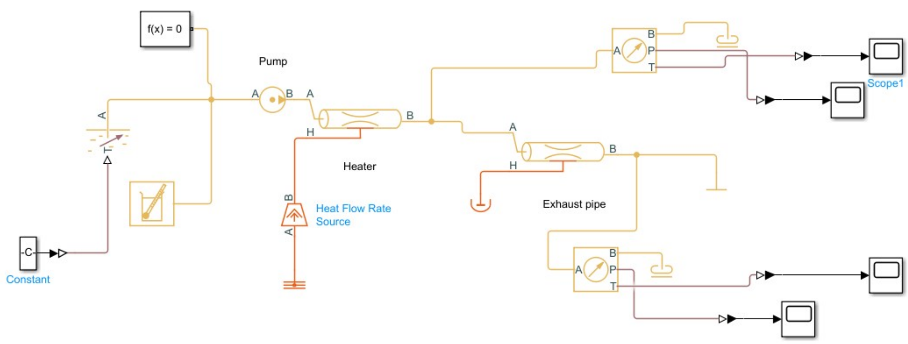

Figure 3.8: Simulation setup for a chimney to vaporize the condensed water

Next objective in this muffler/chimney setup is to design a 1D and 3D models to investigate aspects. It allows us to see a comprehensive representation of the complete system and its functions. The model has a few sub-modules that represent exact physical components, such as a heater, pump, insulation, and pipes. As an input, data from the previous model, the temperature, and pressure of the collection data are considered. The heater is adjusted depending on the incoming temperature of the water, while the pump will adjust with incoming water pressure. The fixed insulation layer is used to maintain the thermal barrier outdoors. When the vapor is produced, it will flow through the duct to the top. The top of the chimney has a special conical shape to prevent dust and sand. As per Figure 3.8, the yellow color path indicates the water and vapor path before and after the heater. The orange color section indicates the insulation layer. Pressure and temperature are measured along the path by adding an oscilloscope. However, the cross area of the chimney was subjected to change due to the sizing of other components in the fuel cell setup.

In addition to the pump, a heater is integrated into the chimney assembly. This heater serves a crucial role in raising the temperature of the fluids passing through the chimney. By applying heat energy, the heater elevates the fluid temperature to the desired levels required for specific processes or reactions within the system. Modern-day chimney systems come with excellent safety systems that trigger an alarm to shut down the operation. These type of safety systems helps to prevent any dangerous situations for humans and components. Recommended safety systems for chimney systems shall include safety valves, low water level controls, and flame safeguard systems.

3.2.2 Water sprayer to the heat exchanger/Radiator

Radiators consist of four major parts, which are radiator core tubes, inlet/outlet pipes, cooling fins, and plastic header tanks. Radiator core tubes provide a path to remove the heat from the heated fluid. Usually, they are made up of brass, copper, or aluminum, depending on the design. With time, wear and clogs happen inside the tubes because of particles in the fluid. Therefore, it is recommended to have a filtering system. The inlet/outlet pipes are commonly used and manufactured from composite plastics. The material should be durable and has the capability to be resistant to heat. Cooling fins provide the extra surface area to the fluid to have a better thermal exchange between surroundings.

Radiators also play a vital role in power generation. Thermal power plants and nuclear power plants utilize radiators to remove heat from steam turbines and other machinery involved in electricity generation processes. These radiators are designed to handle substantial amounts of heat and aid in maintaining efficient operation and safety within power plants.

Industrial radiators have higher market potential all over the world. Industrial radiators can be seen in their applications in the oil and gas industry, power and energy industry, food production, chemical, marine, and pharmaceutical industries. There are various types of radiators, such as skid-mounted radiators, belt-driven radiators, vertical remote radiators, and horizontal remote radiators. In the high precision industries, copper fin radiators have numerous desirable characteristics such as high thermal conductivity, corrosion resistance, higher melting point, and ease of production. In the Volvo Penta fuel cell setup, there are three main skid-mounted radiators. Two of them are used for the fuel cells, while the other is used for the batteries.

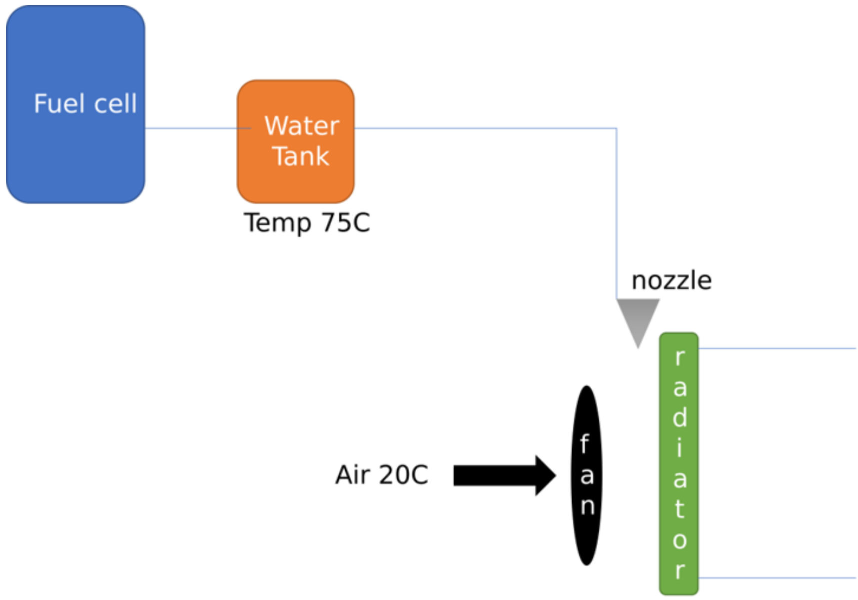

Figure 3.9: Connection diagram for sprayer/radiator with fuel cell and condensed water tank

Water spraying is a technique employed in radiators to optimize cooling efficiency and improve the performance of heat exchange systems. By introducing a fine mist or spray of water onto the radiator's surface, this method enhances heat transfer capabilities and ensures effective temperature regulation. In this comprehensive overview, we will explore the benefits, applications, and considerations associated with water spraying in radiators.

Improving the efficiency of industrial radiators is a huge task for design engineers as it affects the overall efficiency of the system. There is a considerable amount of research ongoing on this topic. There are many ways to improve the efficiency of a radiator system, such as using high thermal conductivity materials, improving the quality of primary liquid, and introducing the sprayer network. One of the objectives of this project is to check water spraying to radiators. By applying a fine mist of water onto the radiator's heat exchange surface, the water droplets act as a medium for heat absorption. As the heated air passes through the radiator, the water droplets evaporate, absorbing heat energy from the air and promoting efficient heat transfer. This evaporative cooling process significantly improves the radiator efficiency, leading to a low operating temperature in the system being cooled. Since water for the mist is from a byproduct of the fuel cell, this can be considered as a sustainable method of water reusing.

A schematic diagram for the nozzle radiator setup is shown in Figure 3.9. The collected water is pressurized by a pump, and it is injected onto the radiator surface.

A typical radiator system consists of an aluminum fin body, top and bottom water inlets and outlets, and an air blower. Air temperature is assumed to be constant at 20 °C, and the RPM of the blower fan will also be at a constant speed. One of the key advantages of water spraying in radiators is its versatility across various industries and applications. It finds extensive use in automotive cooling systems, where the high-temperature conditions of engines necessitate efficient cooling mechanisms. Water spraying helps to maximize the cooling efficiency of radiators in vehicles, thereby preventing engine overheating and ensuring optimal performance.

3.2.2.1 Parameters for design of sprayers

When in the literature survey, we found that various parameters will affect the design of sprayers. Among those, the overall heat transfer coefficient, local film thickness, and weber number are more dominant parameters. The overall heat transfer coefficient, normally donated as U-value, is a measure of the overall flux of heat transfer of two or more surfaces. It can be calculated as a parallel or series method. Each material or liquid has its own thermal conductivity. By combining the materials together, we can get a unique heat transfer coefficient. There are ways to calculate the U value for different fluids, regimes, and various thermohydraulic conditions. It can be estimated by dividing the fluid thermal conductivity by a length scale. The overall heat transfer coefficient takes into account the individual resistances to heat transfer, including conduction, convection, and radiation. These resistances are associated with different modes of heat transfer and are determined by various factors such as material properties, surface area, fluid flow characteristics, and temperature gradients. As a conclusion of this thesis, the comprehensive comparison will be done related to with and without having sprayers in the radiators.

Weber number is another characteristic number used in fluid dynamics applications.it is a dimensionless number that describes the ratio between inertial forces and stabilizing forces for liquids. It also provides the behavior of fluid flows involving the formation of splashing, droplets, and jet break up. In the radiator setup, a 1.5 mm thickness of water layer shall be formed all the time. To form it, the corresponding velocity is calculated using the Weber number. When the Weber number is less than 1, surface tension force dominates creating smooth and cohesive flow. When it is higher than 1, initial forces become more prominent, creating more instability and atomization in the flow. High Weber numbers are commonly used in sprayers, liquid jets, and mist systems when atomization is needed in the fluid impact on solid surfaces.

The local film thickness is also an important fluid hydrodynamic parameter in the sprayer-radiator system. It refers to the thickness of the liquid film that forms on the surface of the radiator surface. It also combines to determine the spray characteristics such as spray pattern, droplet size distribution, and spray coverage. Spray manufacturers and researchers always study to optimize the local film thickness to achieve desired spray characteristics and behaviors. This is crucial in applications such as coating process, agricultural sprayers and fuel injections. Local film thickness may vary with the flow regimes such as functions of Reynold and Kapitza numbers. The flow can be mapped into five different zones such as laminar, sinas-shaped waves, wavy laminar, transition laminar, and turbulent. These five steps describe how the flow transfers from laminar to turbulent.

3.2.2.2 Simulation setup for analysis

In the context of the CFD simulations, a general setup has been established. To simulate the sprayer system, the setup has been established as per Figure 3.10 with a few assumptions. The simulation will be done with Creo live simulation. It is assumed that the inlet air temperature is fixed at 20 °C. Velocity at the inlet velocity is fixed at 5 m/s and it is assumed that it will not vary with the time. Further, as this is a customized setup, the hot water inlet to the radiator is at 90 °C. The water flow rate is at 5 L/s, ensuring that constant water flow is flown through the radiator. To replicate the real-world conditions, all the nozzles are pressurized in to 10 bar. However, as per figure 3.10, even though it is shown as a single nozzle, it represents a set of nozzles. The temperature in the nozzle is set at 46 °C, which is equal to the temperature at the fuel cell water collecting tank. These parameters are essential in accurately simulating the behavior and performance of the system under investigation.

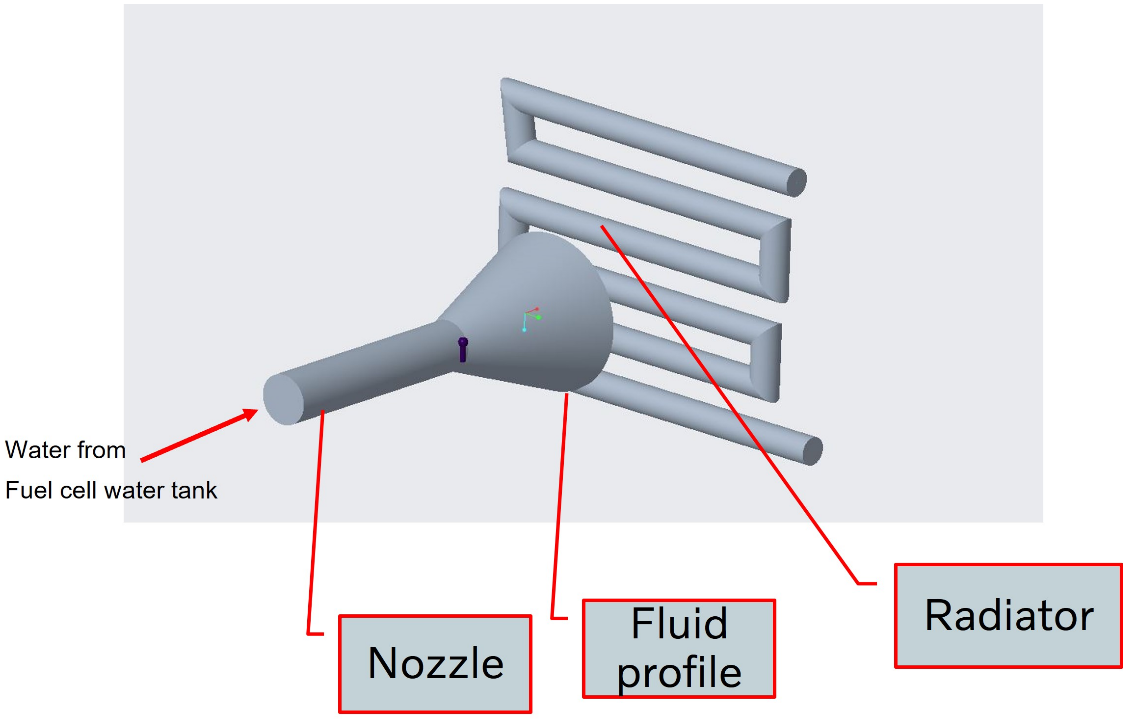

Figure 3.10: Computational fluid dynamics setup for small portion from nozzle and radiator setup

We have also made a few additional assumptions. It is assumed that no flooding occurs during the operation of the system. Additionally, it is assumed that no drifting occurs during the nozzle operation. However, it is essential to note that these factors can be visible in actual scenarios.

While these assumptions allow for simplification and easier analysis in the context of the simulations, it is essential to acknowledge that real-world conditions may differ. Flooding, for example, refers to a situation where an excess amount of liquid accumulates in a specific part of the system, leading to operational issues. Similarly, drifting can occur when the spray from the nozzle deviates from its intended trajectory, impacting the spray pattern and coverage. In practical applications, the occurrence of flooding and drifting should be considered and accounted for, as they can affect the performance and efficiency of the system. Engineers and researchers need to be aware of these possibilities and implement appropriate measures to mitigate or manage such issues if they arise. While our assumptions provide a baseline for the simulations, it is crucial to validate the results and analyze the system's behavior under realistic conditions, taking into account the potential occurrence of flooding and drifting. This helps ensure that the simulation outcomes align with the actual performance and behavior of the system in practical applications.

4

Results

4.1 Matlab simulation for water accumulating

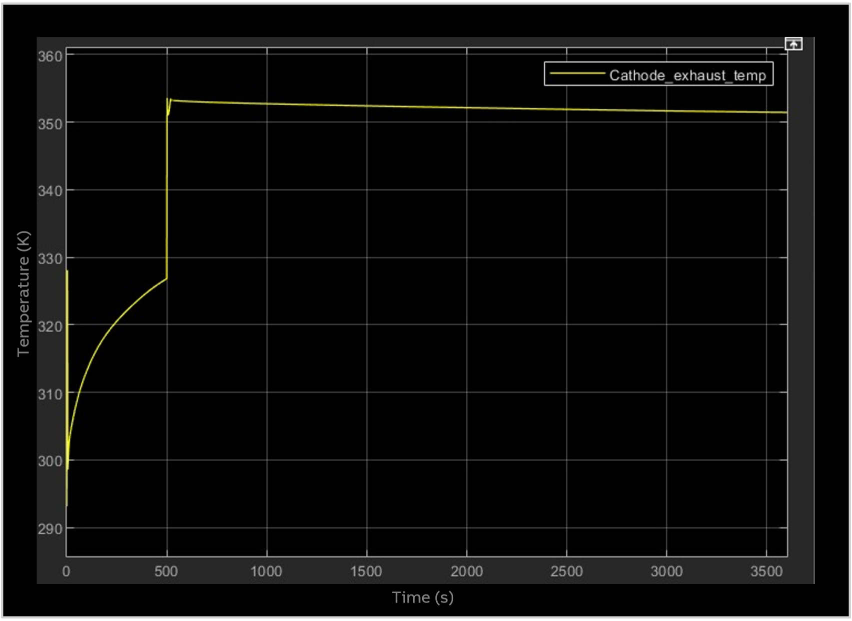

Figure 4.1: Simulated cathode exhaust temperature from the startup to one hour

Figure 4.1 shows a graph of the temperature changes observed in the cathode exhaust. The graph shows the temperature progression starting from an initial value of 293 K, corresponding to the room temperature. As the system operates, the temperature gradually increases, reaching a peak of 325 K. It is seen that temperature is stable at 325 K for the rest.

However, we identified that a considerable change occurs when a step load is introduced as an electrical load. This sudden increase in power demand leads to a rapid rise in temperature within the cathode exhaust, resulting in a sharp spike to 353 K. This sudden temperature surge is a direct consequence of the increased electrical load and its impact on the system's thermal dynamics and electrical load fluctuations. After this surge, the temperature stabilizes, and a steady-state condition is reached. The temperature settles at 353 K, indicating a balanced state in which the heat generated and dissipated within the cathode exhaust is in equilibrium. This stable temperature level is sustained if the system operates under similar load conditions.

The information shown in Figure 4.1 sheds light on the dynamic behavior of the temperature within the cathode exhaust, indicating the impact of varying load conditions on the thermal characteristics of the system. When it comes to mobile applications, this fluctuation can affect vehicle dynamics as well. Understanding these temperature variations is crucial for assessing the fuel cell system's performance, efficiency, and overall thermal management.

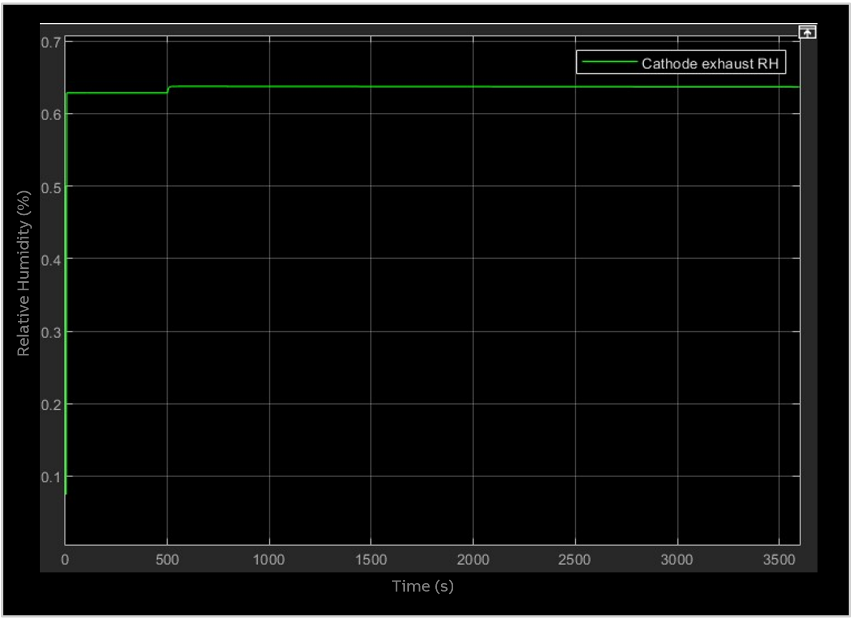

Figure 4.2: Simulated cathode exhaust relative humidity from the startup to one hour

Upon analysis of the temperature of the cathode exhaust, it is evident that there is a minor fluctuation in the range of 63 – 64 percent. This observation is significant as it suggests that the liquid present within the exhaust is not entirely in a liquid state. Instead, it shows the presence of a mixed phase, where the liquid may be partially evaporated or exist in a vapor form.The variation in temperature within this narrow range indicates that the liquid phase is undergoing a transition or experiencing changes in its physical state. It is possible that some of the liquid is evaporating, resulting in a partial vapor phase. This can occur due to heat transfer, flow conditions, or the specific composition of the liquid.

The presence of a non-fully liquid phase within the cathode exhaust has implications for the overall performance and operation of the system. It suggests the need for careful consideration of the vapor-liquid equilibrium and the liquid phase dynamics within the exhaust. Understanding these phenomena is crucial for accurately modeling, analyzing, and optimizing the fuel cell system.

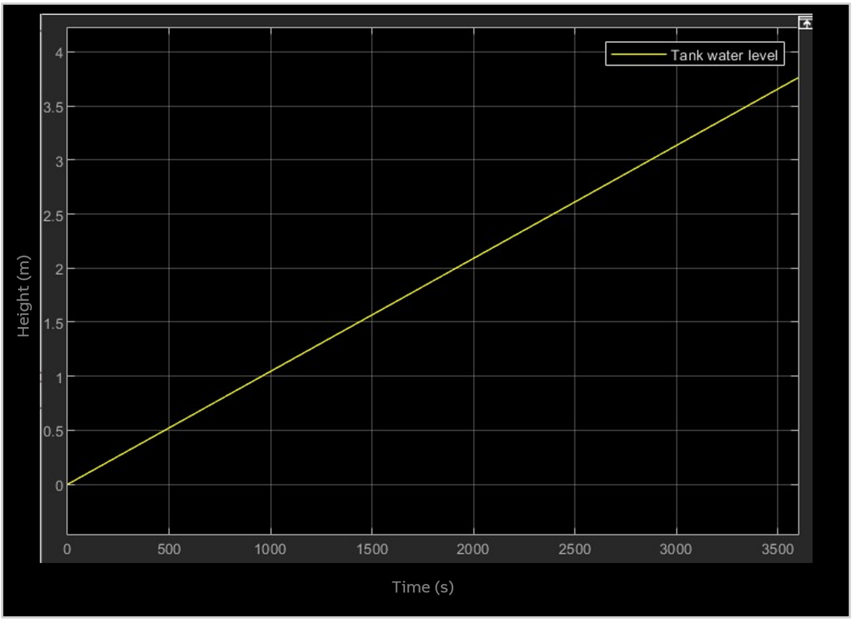

Figure 4.3: Water tank level based on 75 kW fuel cell

The graph demonstrates that after one hour of operation with a 75 kW fuel cell, approximately 3.75 kg of water has been collected and stored in the tank. This data provides a baseline for estimating the water accumulation rate with the power output of the fuel cell. Due to limitations, this model was developed to illustrate a 75 kW fuel cell. The water level is shown with respect to 1 kg of hydrogen. By extrapolating this data, we can estimate a 300 kW fuel cell, which accounts for 24 kg/hr of hydrogen utilized as fuel (theoretical calculation obtained from section 2). Generally, 1 kg of hydrogen would generate approximately 9 kg of water. However, in this model, we obtained a value of 3.75 kg for the liquid phase. We can assume that the rest will be in the vapor phase. Assuming a proportional relationship between power output and water accumulation, it can be inferred that the accumulated water would be around 90 kg/hr after one hour of operation (as liquid water). The remaining is evaporated as water vapor based on condensation duty for 24 kg/hr of hydrogen as fuel.

However, it is essential to note that these estimates are based on extrapolation and should be treated as approximations. The actual water accumulation in a 300 kW fuel cell may vary depending on various factors, including system design, operating conditions, and water management strategies. Theoretical calculations in Chapter 2 show that an ideal water accumulation rate for one hour of operation would be 220 kg. This value serves as a reference point for assessing the effectiveness of the water accumulation process in the fuel cell system. Any deviation from this theoretical value could indicate inefficiencies or system performance variations.

4.2 Chimney design

We conducted a 1D simulation to optimize the chimney and its related components. As shown in figure 3.8, the chimney model has a few sub-models representing exact physical components such as a heater, pump, insulation, and pipes. The chimney-based evaporation method offers an efficient means of utilizing stored water. By evaporating the water, it generates steam or water vapor, which can be employed in various ways to drive specific functions within the mobile system.

4.2.1 Matlab simulation for chimney

As per Figure 4.4, we aimed to investigate the performance characteristics of a heater with a power rating of 2.3 kW. To achieve this, a simulation was conducted to emulate the behavior of the heater under study. The simulation commenced with an initial temperature of 353 K, representing the system's stored temperature. Subsequently, the heater's temperature progressively rose, ultimately reaching a final value of 373 K. This experiment enabled us to analyze the heater's dynamic response and thermal behavior throughout the specified temperature range. Adding more insulated layers into the piping system can further optimize this system.

However, this system has some practical limitations, such as considerable space and periodic maintenance. Limescale and sediment buildup are also drawbacks of this system. This can depend on the chemical composition presented in the water.

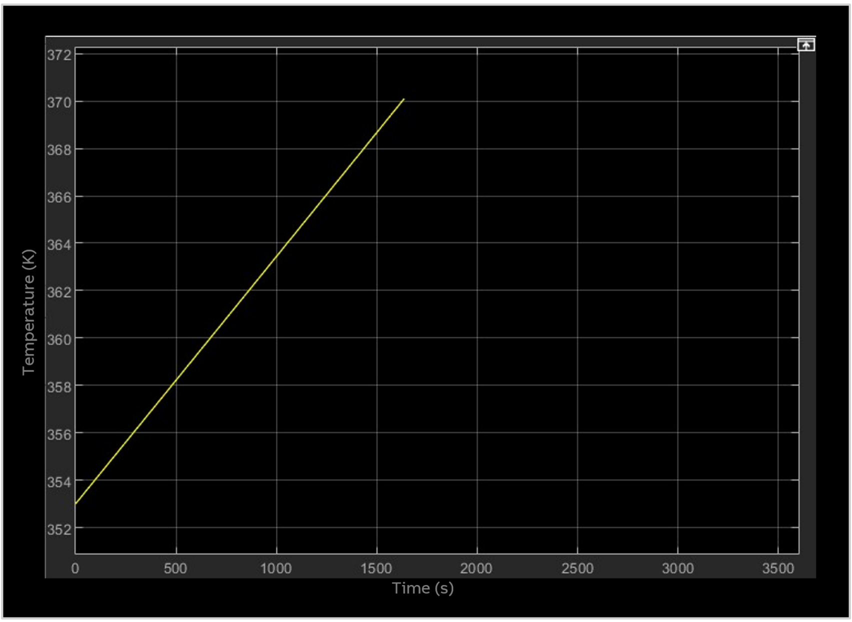

Figure 4.4: Simulated chimney temperature from startup to one hour of operation

4.3 Water sprayer

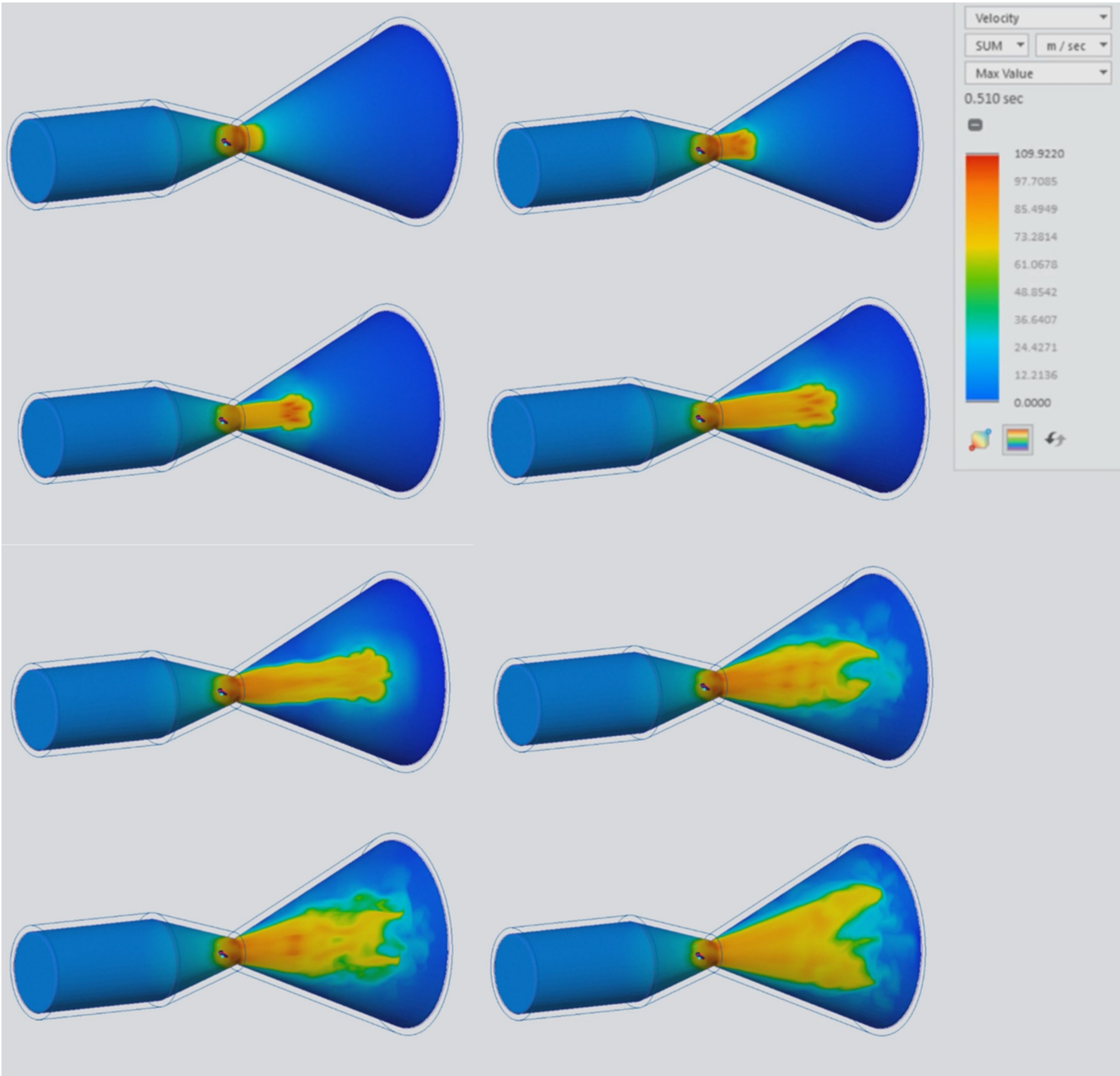

Figure 4.5: Velocity variation across the nozzle with the constant temperature of inlet

The purpose of this analysis is to check the velocity profile of the sprayer concisely and accurately. The velocity profile refers to the distribution of velocities within the sprayer system and provides valuable insights into the fluid's behavior. In this study, particular attention is given to the parameters such as the inlet pressure, outlet pressure, initial velocity, and average velocity of the sprayer. To commence, the inlet pressure is rigorously set at 10 bar, ensuring a consistent and controlled fluid flow into the sprayer. This pressure condition governs the entry point of the fluid and plays a critical role in determining the subsequent velocity characteristics within the system. Maintaining a fixed and substantial pressure at the inlet makes it feasible to regulate the velocity of the fluid as it traverses through the sprayer.

Conversely, at the sprayer outlet, the pressure is set to match the atmospheric pressure. This adjustment allows for a smooth transition from the pressurized environment within the sprayer to the ambient atmospheric conditions outside. Calibrating the pressure at the outlet ensures the fluid is released into the surrounding environment without any forceful disturbances, thereby promoting a controlled dispersion.

Regarding the initial velocity, the fluid emanating from the sprayer commences with a velocity of 100 m/s. This denotes the speed at which the fluid particles are propelled upon release. The direction of this velocity is not explicitly stated, and thus, it may vary depending on the specific context of the sprayer system. The average velocity of the sprayer is reported to be 40 m/s. This value encapsulates the overall behavior of the fluid particles during the spraying process, representing the mean speed of the particles as they disperse.

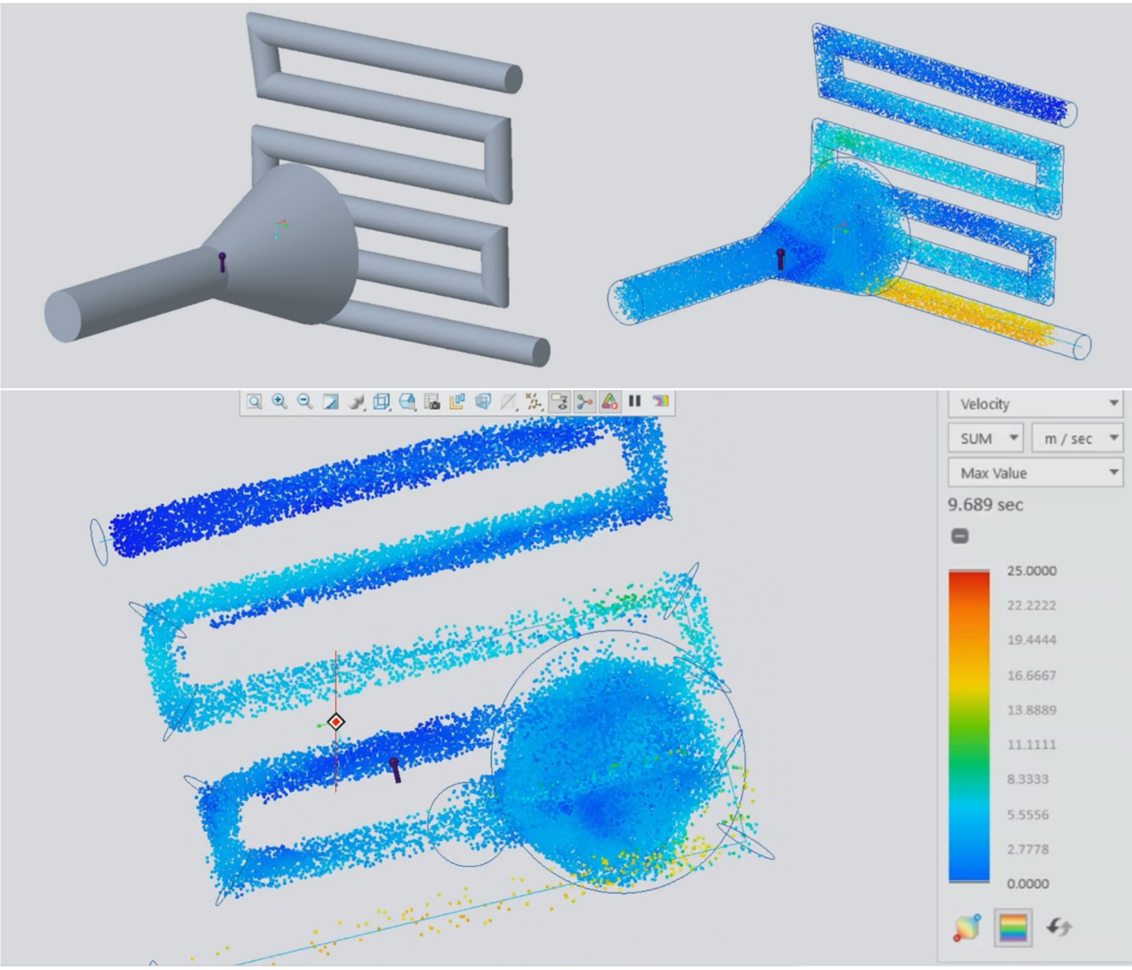

Figure 4.6: Velocity variation across the small portion of a nozzle and radiator

from this figure, we can see the velocity distributions over the setup. Slow velocity can be expected compared to the nozzle to achieve better heat conduction. A deliberate selection of a relatively lower velocity compared to the nozzle velocity is conducive to enhancing the efficacy of heat conduction. This deliberate manipulation of velocity aids in optimizing the system's performance in terms of thermal conductivity. Moreover, it is plausible that the system can attain further refinements by meticulous adjustment and fine-tuning of the velocity gradients, thereby ensuring enhanced efficiency and effectiveness.

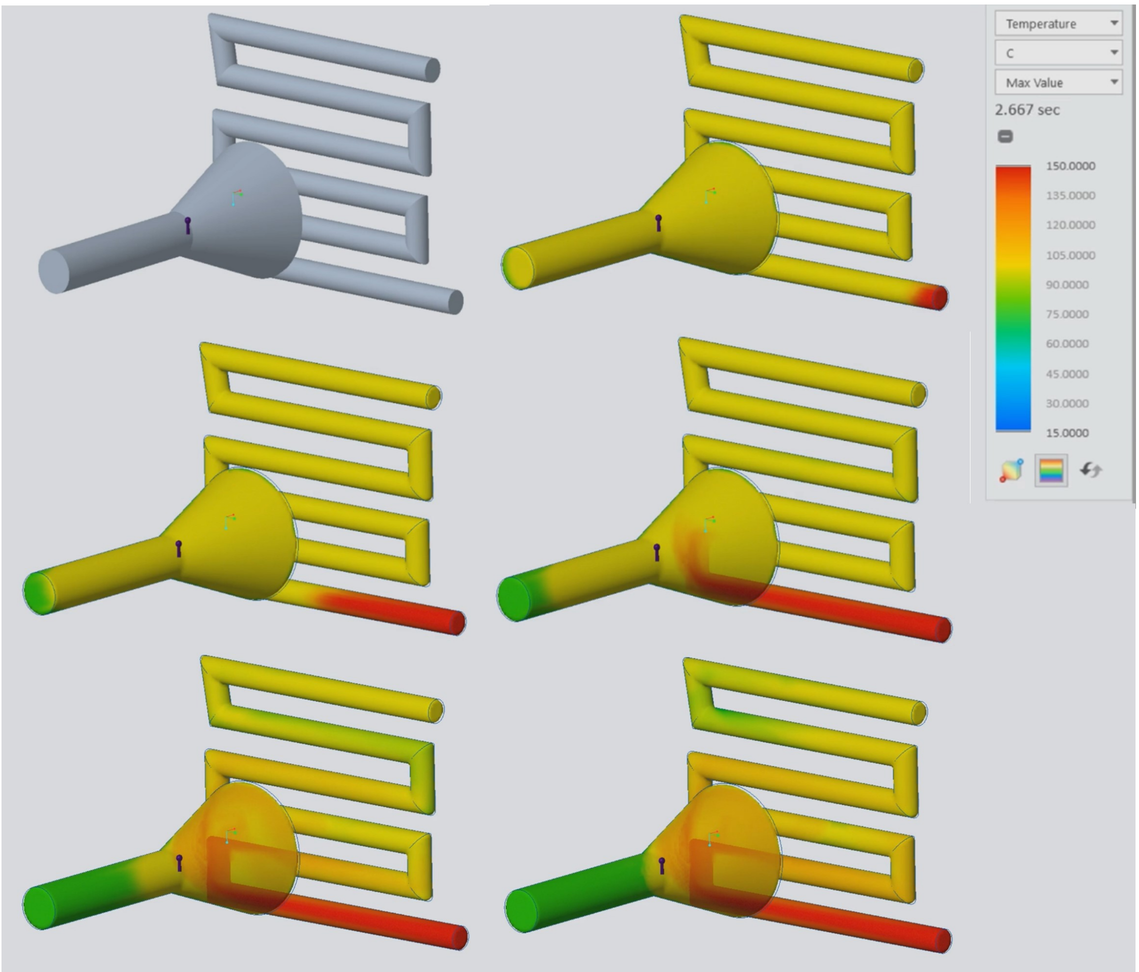

Figure 4.7: Temperature variation across the small portion of a nozzle and radiator

As per figure 4.7, it is shown that the temperature of the nozzle is around 75 °C. It is important to note that the temperature of the nozzle is dependent on several factors, including the specific application and the type of fuel cell system being used. However, for the purpose of this discussion, let's assume that the temperature mentioned is suitable for a particular fuel cell system. The equal temperature of the nozzle and the storage tank suggests a thermal equilibrium between these components. The fuel cell system could achieve this through appropriate insulation or temperature regulation mechanisms. Maintaining a consistent temperature within the system is important for efficient operation and to avoid any potential issues caused by temperature variations. The chosen operating temperature for the nozzle and the storage tank in this scenario may be based on factors such as the type of fuel cell system being used, the specific fuel being utilized, and the desired performance characteristics. To ensure efficient and safe operation, it is important to ensure that the chosen temperature is within the recommended operating range for the particular fuel cell technology.

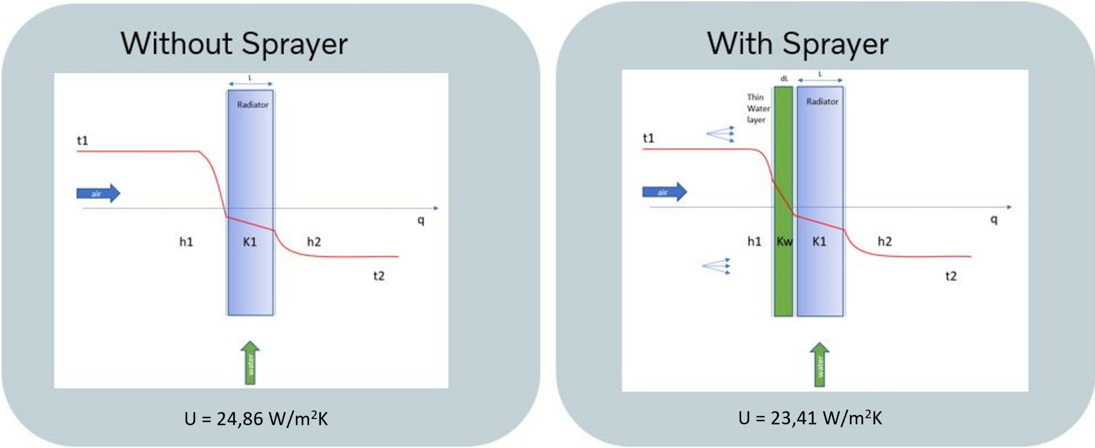

Figure 4.8: U value calculation for with and without water sprayer

By comparing the radiator surfaces with and without sprayers, it is evident that the system exhibits an overall improvement. The improvement is indicated by a reduction in U values and thermal resistance, ultimately leading to an increase in energy efficiency by approximately 4.8 percent. When introducing sprayers to the radiator surfaces, it suggests a mechanism that facilitates cooling or enhances heat transfer. The sprayers could improve heat dissipation by promoting better airflow or facilitating evaporation. This improved cooling mechanism reduces U values, meaning that the radiator surfaces are more effective in transferring heat away from the system. By reducing U values, the thermal resistance of the system is also reduced. Thermal resistance represents the opposition to heat flow through a material or assembly. It is the reciprocal of the U value. A lower thermal resistance indicates that heat can more easily flow through the system, resulting in improved heat transfer efficiency.

5

Conclusion and Recommendations

The study shows that a considerably high amount of water is produced during fuel cell operations. Therefore, proper water management is needed prior to the operation. Furthermore, we discussed various possibilities for the utilization of wastewater, such as drinking, gardening, and connecting it to the district heating network. However, all the chemical limitations mentioned are subject to a literature survey. Hence, it is essential to verify the outcomes by cross-checking them with actual results.

As part of future work, it is recommended to cross-check the chemical tolerant limits for different applications with actual test results. It is essential to ensure that the levels of per- and poly-FluoroAlkyl Substances (pFAS) are maintained within acceptable limits. In Volvo Penta, research is done and analyzed with different membranes to eliminate the presence of pFAS. It is important to verify the accuracy of information by comparing it with real-world outcomes. This recommendation is made in response to concerns regarding the negative impacts of pFAS on human health and the environment.

Introducing a chimney is an economical approach. It can be activated once the collecting tank is full. The advantages of this system include easy installation, maintenance-free operation, and suitability for both mobile and stationary applications. However, it should be noted that this system does not offer any energy recovery.

The study also shows that introducing sprayers to the radiator surfaces results in an overall improvement in the system. This improvement is evidenced by a reduction in U values and thermal resistance, leading to an increase in energy efficiency by approximately 4.8 percent. The effectiveness of the sprayers in enhancing cooling and reducing U values may depend on various factors and the system's specific design and operating conditions. This system is most suitable for stationary applications. However, there are certain drawbacks to consider. Periodic maintenance is required, and it may also require more space due to the presence of critical components, especially in dusty and winter conditions.

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