Supersonic Ejectors in Hydrogen Refueling Stations and Fuel Cell Systems: A Review

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Abstract. Hydrogen fueling stations are becoming more widespread due to the global shift toward net zero emissions. This drives the need to improve their efficiency and reduce their energy consumption. Supersonic ejectors offer a passive alternative to traditional mechanical valves and compressors. Their integration into hydrogen fueling stations can lower compression costs and reduce refueling energy; however, the efficiency significantly drops when operating within the subcritical region resulting in an unstable system or reverse flow. Despite the advancements in ejector system analysis through numerical modeling and computational fluid dynamics (CFD), the performance limitations highlight the need for experimental validation under real-world conditions. Evaluating safety risks, adaptability to variable flow and system fluctuations is needed through an ejector system set up with instrumentation and monitoring. This review explores ejector research developments with a focus on parameters affecting efficiency such as the entrainment ratio, compression ratio, and coefficient of performance. The important role of supersonic ejectors for hydrogen recirculation in Fuel Cell systems is also discussed. Future research should focus on addressing scalability, geometry limitations, control strategies, and experimental validation to enhance ejectors' potential to be incorporated into hydrogen fueling applications and enhanced performance in Fuel Cell applications.

1 Introduction

Hydrogen is being recognized as a clean alternative to fossil fuels [1], especially in the transportation sector [2, 3]. This creates a need for more efficient hydrogen refueling stations. In traditional refueling stations, in which valves are used, significant losses can occur during the hydrogen compression stages [4]. Energy losses increase energy use and reduce efficiency. Research has shown that pressure losses in valve-based systems make hydrogen distribution less effective [4]. Therefore, alternative solutions that minimize energy losses should be explored.

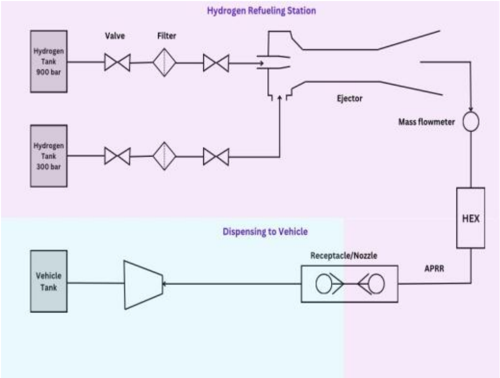

Fig. 1. Hydrogen Refueling Station Schematic using supersonic ejector

Supersonic ejectors are one possible alternative. Ejectors, unlike mechanical valves, do not have moving parts. They use high-speed gas flow to transfer or compress another gas (figure 1). Namely, when high-pressure hydrogen passes through a supersonic nozzle, it creates a low-pressure area near the nozzle exit, drawing in lower-pressure hydrogen.The gases mix and then pass through a diffuser, where pressure increases again [5]. Because ejectors lack moving parts, they require less maintenance. Another advantage of ejectors is that they reduce pressure losses and energy inefficiencies. However, ejectors have a number of drawbacks. For example, ejector performance depends on a stable pressure environment. If the hydrogen demands are low in hydrogen refueling stations, ejector performance could be negatively affected. Another challenge arises when the backpressure (pressure at the ejector exit) experiences significant variations, which further complicates the operation of ejectors [4]. Another disadvantage of ejectors is that they have limited real-time control [4], requiring a further need of monitoring and regulations. Therefore, more research is required to understand their long-term performance, safety, and integration with hydrogen stations.

Some studies have explored ejector performance in hydrogen fueling systems. Wen et al. (2020) [4] showed that ejectors can mix low-pressure hydrogen with high-pressure flow, reducing the need for high-pressure hydrogen. Rogié et al. (2020) [6] used

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simulations to optimize ejector performance and found that they can lower fueling time and energy use. Rogié et al. (2021) [7] found that ejectors in a simulated cascade system in hydrogen fueling stations were able to reduce compression energy by 6.5%, peaking at two buffer tanks. While ejector integration in hydrogen refueling stations has been studied, more research is needed to see if ejectors can fully replace valves while also improving efficiency for various operating regimes.

Additionally in automobiles, hydrogen is used in fuel cell systems to manage and increase water balance. Ejectors are utilized in these loop systems to reuse the hydrogen available due to their simple design and operation [8].

A fuel cell is a device that uses electrochemical reactions to generate electricity without the need for combustion. Specifically, the chemical energy of fuel (i.e. hydrogen) and an oxidizing agent (i.e. oxygen) is converted to electricity by the redox reaction. This process is continuous and its only byproducts are heat and water [9, 10]. Since the process generates electricity without combustion, fuel cells are a very promising alternative, supporting a widespread adoption for renewable energy.

Fuel cells have a wide range of applications in many areas, each developed with varied features. Solid oxide fuel cells (SOFCs) are used in power generation applications, where they operate at high temperatures and are efficient. In space applications, alkaline fuel cells (AFCs) are utilized due to their efficiency. However, their functionality is affected by carbon dioxide. For the transportation sector, proton exchange membrane fuel cells (PEMFCs) are used due to their quick startup time and efficiency at low operating temperatures.. In addition, other types of fuel cells are utilized in in combined heat and power systems (CHP), such as molten carbonate fuel cells (MCFCs) and phosphoric acid fuel cells (PAFCs) [9, 11].

High flexibility, efficiency, and lower pollution are the main advantages of fuel cells. Some fuel cells are capable of operating on multiple types of fuel, such as biogas and hydrogen, which makes them more flexible. Fuel cells produce fewer emissions since they operate without burning fuel, making them cleaner and friendlier to the environment, in addition to producing less noise [10]. They also have high efficiency, especially in CHPs systems. Despite these advantages, high production and infrastructure costs are a major disadvantage in fuel cell applications [11], along with durability issues, as fuel cell performance degrades with time [12]. Fuel cells, additionally, require specific operating conditions, which complicates their use. Research is ongoing to address these limitations.

This paper reviews the fundamentals of supersonic ejectors, their role in hydrogen recirculation for fuel cell systems, and their applications in hydrogen refueling stations.

2 Fundamentals of supersonic ejectors: design considerations and industrial applications

Ejectors differ from mechanical compressors in their ability to compress gases without the use of moving parts. To achieve compression, the proper design of the geometry is needed to regulate the flow. Factors such as geometry and operating conditions directly affect the efficiency, therefore, proper selection of those parameters is critical [13, 14]. By optimizing the geometry, the efficiency of the ejector increases, and as a result the device can operate at lower costs.

Supersonic ejector components include (Fig. 2) a convergent-divergent nozzle, suction chamber, mixing chamber, and diffuser. For hydrogen fueling applications, high-pressure hydrogen gas is the primary fluid that enters the ejector through the nozzle. The geometry of the nozzle results in an increase in the velocity and a decrease in the pressure of the gas. A supersonic jet exits the nozzle into the mixing chamber, which creates a low-pressure region that produces a suction effect that draws in the secondary fluid from the secondary inlet. After the two fluids mix, the mixture moves into the diffuser where the geometry will result in a decrease in the velocity from supersonic to subsonic. This change leads to an increase in static pressure and the compression of the fluid. In order to measure the efficiency of this process, the entrainment ratio is used which is the ratio of the mass flow rate of the secondary fluid to the mass flow rate of the primary fluid [1, 15, 16].

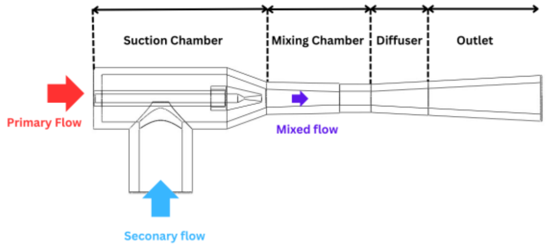

Fig. 2. Schematic of a Supersonic Ejector

The ejector's performance is measured based on several parameters. The entrainment ratio is one of the most important parameters. Specifically, the higher the entrainment ratio, the better the performance of the ejector [17]. Mathematically it is expressed as follows:

$$ER = \frac{\dot{m}_s}{\dot{m}_p} \tag{1}$$

Another key parameter is the compression ratio, which is defined as the ratio of the exit pressure to the secondary fluid's inlet pressure. It measures the ability of the ejector to increase the pressure of the secondary fluid [17]. A higher compression ratio is positively correlated with higher pressure recovery. The compression ratio is calculated as follows:

$$CR = \frac{P_{out}}{P_{Secondary\ inlet}} \quad (2)$$

To measure the overall performance of ejectors, the Coefficient of Performance (COP) is considered. The Coefficient of Performance is the ratio of the output of useful energy to the energy input [18]. The COP is directly related to the entrainment ratio. A higher COP means that the ejector utilizes less energy to compress the secondary fluid.

$$COP = \omega * \frac{h_{Secondary} + C_p\left(T_{Exit} - T_{Secondary}\right)}{h_{Primary} + C_p\left(T_{Primary} - T_{Exit}\right)} \quad (3)$$

In case of hydrogen stations, (ω) represents the entrainment ratio, $(h_{Secondary})$ and $(h_{Primary})$ refer to the enthalpy of the low pressure secondary flow and high pressure primary hydrogen, respectively. Additionally, the secondary and primary temperatures are denoted with $T_{Primary}$ and $T_{Secondary}$, while the temperature at the ejector exit corresponds to T_{Exit} [18-20].

The operating modes of the ejector include critical, subcritical, and backflow modes. If the pressure exiting the nozzle is higher than critical pressure then the ejector is operating in critical mode, in which entrainment ratio and velocity are maximum. In subcritical mode, the pressure at exit is lower than critical pressure. This results in lower entrainment ratio since the primary fluid is choked. The backflow mode occurs when the pressure at the nozzle exit is lower than the back pressure, reversing flow direction since neither the primary nor secondary fluids are chocked. This would produce an entrainment ratio equal to zero, which negatively affects the performance [6].

Ejectors are used in various applications. For example, ejectors improve the performance of refrigeration systems through enabling pressure differences. This reduces the energy consumption and further optimizes the cycle [21]. In desalination, during water purification, ejectors utilize waste heat. This leads to lower energy usage [22]. Additionally, in chemical and pharmaceutical industries, ejectors are used in low pressure operating conditions in vacuum systems [23]. They are also utilized in aerospace applications since they lack moving parts [21].

Several design considerations must be taken into account when operating the ejector (Fig. 3). Factors such as the number of fluid phases, nozzle shape, and nozzle position can significantly impact the operating conditions. First, the ejector can operate with either a single-phase flow, such as gas-gas, or a two-phase flow, such as gas-liquid. Second, the nozzle shape determines whether the ejector is supersonic - using a convergent-divergent nozzle or subsonic - using a convergent nozzle. Lastly, the nozzle position determines the type of mixing. It is either a constant pressure mixing (CPM) ejector if the nozzle is located in the suction chamber, or a constant area mixing (CAM) if the nozzle is located at the front of the mixing chamber [6].

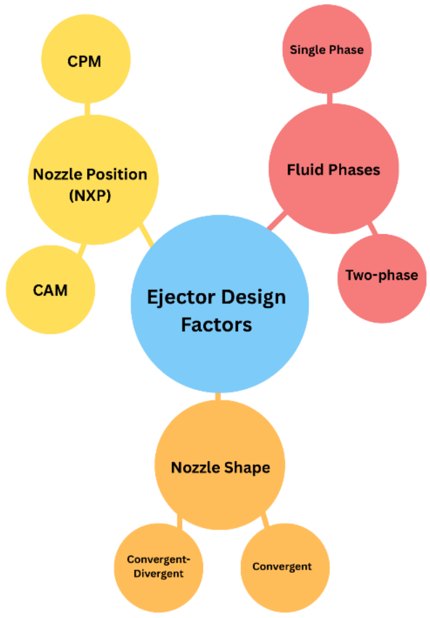

Fig. 3. Schematic of Ejector Design factors

2.1 Operational challenges faced by ejectors

One of the main concerns with ejector systems is the risk of backflow, especially when operating under high compression ratio conditions. This can cause instability in the system, potentially reducing efficiency and even posing safety risks. For example, backflow can allow contaminants to enter or even disrupt the intended direction of fluid flow, which is particularly problematic in most applications [24].

Another challenge involves managing pressure fluctuations. Since ejectors are designed to work within certain pressure ranges, any significant deviation can lead to a drop in performance. Maintaining steady pressure is important to keep the system running efficiently; especially in environments where operating conditions can change rapidly [24]. To address this challenge, advanced control methods are often used to monitor and adjust the system in real time.

Material durability is also a key issue, especially in settings where corrosion or erosion is a concern. The interaction of different fluid phases within the ejector can raise unique challenges, particularly when dealing with complex mixtures or high-temperature operations. Therefore, careful design considerations, based on advanced modeling techniques, can result in adequate mixing and efficient energy transfer are essential for optimal ejector performance [24].

3 Supersonic ejectors in hydrogen recirculation in fuel cell systems

Hydrogen recirculation is crucial for increasing fuel efficiency and ensuring the long-term functionality of fuel cell systems. Recirculating unreacted hydrogen back into the system decreases fuel waste while increasing overall efficiency. Research in this field has investigated different elements of ejector design, enhancement, and integration, using both experimental and computational methods to improve system performance. This section examines the research on hydrogen recirculation ejectors, focusing on structural improvements, numerical modeling, and control systems for increasing fuel cell efficiency and reliability.

Lee et al. (2005) [25] developed a method to control the performance of a variable ejector in the hydrogen fuel cell system to optimize fuel consumption and meet the industrial demands. Both experimental and numerical studies were conducted to demonstrate the effect of the ejector throat area and the operating pressure on the entrainment of the secondary stream. For the experimental setup, they used a cone cylinder to adjust the operating conditions of the ejector, finding that the movement of the cylinder changes the cross-sectional area of the nozzle throat while keeping it constant at the ejector throat. As a result, variations in the ejector throat area ratio ranged from 11.88 to 66.69, and the operating pressure ratio varied from 1.25 to 9.0 due to the movement of the cylinder upstream the nozzle exit. Consequently, an increase in the mass flow rate of the secondary stream was achieved, leading to an enhanced performance of the ejector. For the numerical studies, k-omega turbulence model was used to determine that the recirculation ratio of the secondary stream increases when the ejector throat area ratio increases at a given operating pressure, which confirms the impact of those ratios on the entrainment ratio of the secondary stream.

Ejectors also play an important role in recovering efficiency within the proton exchange membrane fuel cell (PEMFC) systems. Here, they recover the underutilized hydrogen for recirculation in the membrane to improve the system efficiency. Nikiforow et al. (2016) [26] explored the design and validation of a hydrogen gas ejector for a 5 kW stationary proton exchange membrane fuel cell (PEMFC) system. The authors highlight the improvement of hydrogen recirculation in PEMFC systems, which is vital for maintaining fuel cell durability and efficiency. They proposed using 3D-printed ejector instead of traditional mechanical compressors. This approach is more cost-effective and simpler to implement than traditional compressors, which increase costs and reduce reliability of the system. Experimental tests were conducted using both humid hydrogen and air to validate the ejector's performance and the results were analyzed using computational fluid dynamics (CFD) with three turbulence models: RNG k-ε, SST k-ω and Realizable k-ε. Experimental results demonstrated that the custom ejector could achieve high recirculation rates across a wide range of conditions, particularly in systems with low flow resistance. In contrast, systems with higher flow resistance required higher primary pressures to maintain efficiency. The CFD simulations were most accurate when using the SST k-ω model. However, the k-ε models were more effective at predicting the point of maximum ejector efficiency. The study focuses on feasibility of customized ejector designs over commercial alternatives, proving that specific solutions can significantly enhance performance in PEMFC systems. Nikiforow et al. (2016) show that experimental validation along with CFD modeling can be considered an effective approach in enhancing ejector designs for hydrogen recirculation in fuel cell systems [26].

Additionally, adjusting parameters such as nozzle exit position (NXP) and mixing chamber dimensions allowed for improved hydrogen entrainment, reducing energy losses and enhancing overall system reliability. Adjustments to boundary conditions, including hydrogen mass fraction and pressure distribution, further contributed to more effective fuel utilization, ensuring consistent operation across varying load demands.

Feng et al. (2023) [8] investigated how to improve hydrogen recirculation ejectors in PEMFC systems by adjusting critical design parameters such as nozzle throat size, mixing chamber dimensions, and nozzle location. While Fan et al. (2022) [27] looked broadly at ejector performance, this study concentrated on real-world difficulties such as flow separation and two-phase flow, which make it difficult for fixed-geometry ejectors to remain efficient at various power levels. To address this challenge, the authors explored adjustable and multi-nozzle designs, assessing the trade-offs between efficiency, durability, and cost. They also examined advanced control systems, including hydrogen injectors and purge valves, to ensure smooth system operation under varying conditions. Ongoing research aims to refine these designs, ensuring that ejector-based recirculation systems meet the efficiency and durability demands of next-generation PEM fuel cells. At a larger scale, Zhang et al. (2024) [13] explored research trends in ejector application for hydrogen recirculation in fuel cell systems using bibliometric analysis. Research on fuel cell vehicles (FCV) using hydrogen fuel cells peaked in 2020 due to global efforts to achieve net-zero emissions.. These systems typically use a hydrogen supply system, which introduces safety concerns since hydrogen is highly flammable. To ensure sufficient energy production, excess hydrogen is often supplied, and the unused portion is typically vented into the atmosphere. To address this issue, hydrogen recirculation using mechanical pumps was introduced; however, ejectors offer a safer and more durable alternative due to their lower risk of corrosion and leakage. However, combined experimental and numerical studies have shown that ejectors are not yet fully ready for widespread application, as they require precise operating conditions. Accurate instrumentation for monitoring temperature, flow rate, and pressure is essential to ensure a reliable hydrogen supply. Integrating intelligent control systems is also considered important for eventual commercialization. In recent years CFD and various numerical models have been used to analyze ejector performance due to the lower analysis. However, the research is lacking focus on the overall system efficiency, design optimization, and long-term reliability. As a result, recent research trends are focusing on these factors on the ejector efficiency.

Xu et al. (2024) [28] analyzed the performance of ejectors for hydrogen supply in proton exchange membrane fuel cells (PEMFCs) using a semi-empirical simulation model. The study utilized a fuzzy logic controller (FLC) instead of the conventional proportional-integral-derivative (PID) to regulate the hydrogen supply. The goal was to predict the entrainment ratio and as a result, predict the performance. The results showed better hydrogen supply regulation using the FLC compared to PID controllers, which is important for the fuel cell system since it maintains pressure levels. These results are yet to be validated experimentally; however, they show the potential of ejectors to be applied in hydrogen fueling stations.

Further, Antetomaso et al. (2024) [29] developed ejector designs for an anodic recirculation system (ARS) to increase the efficiency of the hydrogen consumption by recirculating the anodic gas in the exhaust stream of the Proton Exchange Membrane Fuel Cells (PEMFC). In this application, ejectors were used to provide a specific amount of reactant to the system. The study verified the 3D model of the ejector for a 5000 W PEMFC and proposed three additional geometries for 3000 W, 1000 W, and 300 W stacks. Varying primary pressure conditions were used to evaluate the performance of the four ejector designs. However, full model validation was limited due to insufficient data for the smaller geometries. Initially, the primary flow remained stable despite increase in the back pressure, which appeared to be a positive result, as it indicated that the desired amount of reactant was being supplied from the tank. However, a reverse flow in the secondary inlet boundary occurred when the back pressure exceeded 1.55 bar due to the pressure difference. This caused a failure in the ejector's performance in supplying the required reactant to the stack, prompting the activation of the valve to increase the primary pressure. Therefore, to avoid such failures, more efficient control strategies need to be developed. In terms of the scalability of the design, traditional 3D printing was recommended in this paper to fabricate ejectors for better geometric customization, as 3D printing might be limited to power output range from 1000 W to 3000 W despite its cost effectiveness and high efficiency.

4 Hydrogen refueling station using supersonic ejectors

Hydrogen refueling stations are essential for recharging fuel cell vehicles (FCVs) and other hydrogen-powered technologies. These stations have the infrastructure to store, compress, and, in some cases, produce hydrogen fuel. Additionally, they are designed to safely manage excess hydrogen, minimizing risks associated with storage and dispensing.

4.1 Key components

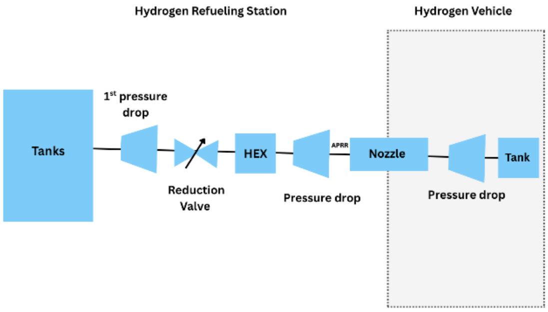

Fig. 4. Hydrogen Refueling Schematic According to SAE Standards [30]

Hydrogen stations consist of multiple components (fig. 4), including high-pressure storage tanks, compressors, cooling systems, nozzles, valves, and pressure control systems. Compressors are used to increase hydrogen pressure from its initial low-pressure state to levels suitable for high-pressure vehicle tanks. High-pressure storage is necessary to provide sufficient driving range for vehicles [30].

4.2 Hydrogen storage

At hydrogen refueling stations, hydrogen can be produced locally or offsite. On-site or locally produced hydrogen is made through several processes such as steam methane reforming, in which the hydrogen is extracted from fossil fuels [31]. Another known method is by separating hydrogen and oxygen from water through electricity, which is called electrolysis [31]. Hydrogen produced offsite is transported by either pipelines, cryogenic liquid trucks, and other methods. At the refueling station, hydrogen is stored at high pressures within tanks or at lower pressures but inside cryogenic tanks.

Once delivered, hydrogen is stored either as a compressed gas or as a cryogenic liquid. In gas form, it is stored inside highly pressurized tanks, specifically at pressures around 350 bar to 900 bar. Liquid hydrogen is stored in cryogenic tanks at temperatures as low as −253°C [30]. Liquid hydrogen must be compressed before dispensing, using ionic, reciprocating, or diaphragm compressors.

4.3 Hydrogen dispensing to vehicles

Before hydrogen is dispensed to vehicles, it needs to be cooled down to -40°C, which is achieved by using refrigeration systems and heat exchangers. This aims to mitigate the heat buildup during hydrogen compression stages [30]. Each type of vehicle requires different dispensing pressures, which is usually 700 bar for cars and 350 bar for trucks or buses. Hydrogen refueling stations follow SAE standards for nozzle and receptacle to ensure flow control and pressures are handled safely.

4.4 Challenges and limitations

Despite their potential, hydrogen stations face several limitations and challenges. Hydrogen flammability presents a safety hazard due to its high combustion energy [32]. Supply chain vulnerabilities can lead to intermittent availability [30], High construction costs, ranging from $910K to $4.6M [33], make infrastructure development a financial challenge. In contrast, electric vehicles (EVs) can be charged at home or in public spaces, making them more convenient and affordable compared to hydrogen-fueled vehicles.

4.5 Safety and monitoring

Since hydrogen is highly flammable, hydrogen stations are required to adhere to high standards and safety measures. Several sensors are used in hydrogen stations to monitor temperatures and leaks. The presence of any hydrogen leak will trigger safety protocols [34]. Additionally, hydrogen stations are equipped with pressure control systems to maintain an average ramp rate, in which pressure rise is kept consistent in the vehicle tank. In addition, the average ramp rate controls the mass flow rate and adjusts it based on the volume of the tank [30]. These systems ensure that the hydrogen fueling stations are safe for use.

4.6 Applications of ejectors in hydrogen fueling stations

A promising method for improving energy efficiency at hydrogen refueling stations is the use of ejectors to replace traditional expansion or reduction valves. Rothuizen et al. (2013) [30] introduced a dynamic simulation model to improve the performance of hydrogen fueling stations, in which they studied station design following SAE TIR J2601 standards. Dymola Software was used in simulating two hydrogen station designs, with a different configuration. To investigate mass flow rates, cooling needs, and pressure losses, Rothuizen et al. (2013) [30] used discrete components. It was found that multiple pressure tanks (cascades) reduced cooling energy demand by up to 12%, along with power usage by 17%. Additionally, refuelling duration was reduced by 5%, and the amount required to store the highly pressurized hydrogen gas was lowered by 20%. However, further investigation is required to account for real-world dynamics and effects from internal components such as pressure tubing. This is necessary to fully validate the practical benefits of ejector integration in hydrogen refueling infrastructure. Reddi et al. (2014) [35] further studied the compression and storage in hydrogen fueling stations. Similar to Rothuizen et al. (2013), they used J2601 refueling protocols, in addition to U.S. fuel economy regulations They developed a simulation model called H2SCOPE, which evaluates operational methods and station designs by incorporating mass, momentum, and energy conservation equations. Their results demonstrated that both costs and compression demands could be reduced by initially filling vehicle tanks using a tube trailer and lowering the tube trailer pressure cutoff. Increasing the return pressure of the tube trailer from 1.5 MPa to 5 MPa also reduced compression requirements, although it raised hydrogen delivery costs. Additionally, using a buffer tank was shown to decrease both hydrogen storage compression needs and refueling costs. Gökçek & Kale (2018) [36] studied the integration of renewable energy systems in hydrogen refueling stations. The study analyzed two configurations of hybrid power systems which included a wind-photovoltaic-battery system and a wind-battery system. An economic and technical assessment was performed using the Hybrid Optimization of Multiple Energy Resources (HOMER) software to evaluate the ability of those systems to meet the demand of 125 kg/day. The levelized cost of hydrogen (LCOH) was used as an indicator for the most cost-effective solution. Their findings showed that the wind-photovoltaic-battery system was the optimal configuration, with an an LCOH of $8.92/kg, compared to $11.08/kg for the wind-battery system. The results highlighted the potential of powering hydrogen fueling stations with renewable energy courses as a sustainable solution towards clean energy.

Bhogilla & Niyas (2019) [37] proposed an alternative to traditional mechanical compressors by investigating metal hydride-based thermally driven hydrogen compressors (MHHC). Since hydrogen compression in fueling stations makes up 31% of the total costs, using MHHC in place of traditional mechanical compressors is an economical alternative. This study investigates two-stage MHHC using metal hydride alloys to allow for efficient hydrogen absorption and desorption. The reaction kinetics, energy, and momentum equations were analyzed by developing a numerical model using the finite volume method which was verified by experimental data. The effects of supply pressure (SP) and heat source temperature (HST) on the performance of the system were studied. The results showed a maximum compression ratio of 26 and work output of 39 kJ/kg with an HST of 150°C and SP of 10–20 bar which can reach 365 of hydrogen storage pressure. This study highlighted the importance of optimizing MHHC performance to improve its potential to be incorporated into hydrogen fueling systems.

Wen et al. (2020) [4] developed a computational fluid dynamics (CFD) model, which analyzes hydrogen flow within an ejector by replacing the reduction valve in hydrogen fueling stations. Using SST k-ω turbulence model, the study analyzed the mass flow rate of 0.06 kg/s, in addition to the primary and suction chamber pressures of 450 bar and 300 bar, respectively. The results showed that the highly pressurized hydrogen created a suction effect, which pulled in lower-pressure hydrogen in. The entrainment ratio was stable under critical conditions (back pressures from 100 to 250 bar). However, the entrainment ratio decreased in sub-critical mode, leading to reverse flow when back pressure exceeded 250 bar. At a primary nozzle pressure of 900 bar, the ejector achieved a peak entrainment ratio of 0.75, allowing 10% of the fuel used in a 7 kg refueling process to come from low-pressure hydrogen.

Rogié et al. (2020) [6] expanded on this by simulating similar operating conditions to Wen et al. (2020) using a 2D axisymmetric CFD model. This study also applied SST k-ω turbulence model, and followed Society of Automobile Engineers (SAE) standards. However, Rogié et al. (2020) studied ejector performance at higher nozzle primary pressures. Specifically, their results in critical conditions aligned with (Wen et al., 2020), with an entrainment ratio of 0.68 at 450 bar. At 900 bar, it was observed that the critical condition could be maintained at back pressures between 360 and 480 bar, resulting with an entrainment ratio of 0.75. Furthermore, it was found that using the ejector from the beginning of fueling reduced the amount of fuel drawn from the low-pressure tank compared to reduction valves. When the ejector was used only at higher back pressures, it increased low-pressure fuel by 12% and shortened fueling time by 6%, showing that ejectors are able to reduce fueling time with less high pressure gas. Building on previous work, Rogié et al. (2021) explored how ejectors can improve energy efficiency in hydrogen fueling stations by integrating a 1D ejector model into a dynamic station simulation. Unlike previous work, which focused on isolated ejectors performance, this study examined real-world interactions. Rogié et al. (2021) [7] studied the difference between direct fueling and hybrid fueling. Direct fueling, which involves using high-pressure tanks and hybrid fueling (starting with low-pressure tanks) were compared. Hybrid fueling was found to be more efficient. However, direct fueling is faster than hybrid fueling due to the ejector flow limits. Replacing reduction/expansion valves with ejectors was found to reduce energy consumption by 6.5%. Peak performance was observed with two tanks, while adding more buffer tanks reduced performance. Additionally, even though it was not fully explored by Rogié et al. (2021), it was recommended that optimizing the throat area of the ejector would improve fueling efficiency and speed. This paper further confirmed the ability of the ejector to be integrated in hydrogen refueling stations.

The development of hydrogen fuel cell cars is heavily reliant on the optimization of hydrogen refueling stations (HRS). High-energy consumption during refueling process, particularly in the cooling and pressure reduction stages, impacts station efficiency. Recent research has proposed the use of turbo-expanders as an innovative alternative. By converting the thermal energy generated in the reduction valve into useful work, turbo-expanders effectively enhance overall system efficiency. Chen et al. (2022) [38] presented a detailed thermodynamic model showing that integrating a turbo-expander could reduce precooling energy consumption by 52.6% during refueling, which is a significant performance gain.

Hydrogen fueling stations require precise pressure regulation, cooling, and safety mechanisms to ensure efficient operation. One key aspect is managing buffer volume to prevent pressure pulsations in booster compressors, piping, and hydrogen vehicle storage systems. Genovese et al. (2023) [39] found that most hydrogen losses occur during dynamic operations rather than standby. Effective maintenance, can prevent unnecessary hydrogen venting. Safety valves play a vital role in preventing rupture, with vented mass flow influenced by pressure, ambient conditions, and Mach number. Another critical component of hydrogen fueling stations is the cooling system, which maintains hydrogen at -40°C and 700 bars for storage and dispensing. This process typically involves a vapor-compression refrigeration system, where a refrigerant absorbs heat from hydrogen and transfers it to the surroundings. The efficiency of this system can be assessed using the coefficient of performance (COP), providing a correlation that links COP to external temperature.

Hydrogen refueling procedures follow three main control strategies: controlling the pressure ramp rate, imposing the mass flow rate, or combining both for efficiency and safety. Advanced technologies, including submerged cryopumps and metal hydride storage, are being studied to improve hydrogen refueling efficiency and economic viability for both light- and heavy-duty vehicles [39].

While research on replacing reduction valves with ejectors in hydrogen fueling stations looks promising, further study is required. It remains uncertain whether ejectors can consistently deliver energy savings and reduce hydrogen losses under varying real-world conditions.

5 Experimental and numerical Results

Tables 1 and 2 summarize the main experimental and numerical methods and results of using supersonic ejector in Fuel Cell Systems and Hydrogen Fueling Stations, respectively.

Table 1. Supersonic ejector in Fuel Cell Systems

NO.	Author	Methods	Findings
1	(Lee et al., 2005) [25]	Cone cylinder for the experimental set up and k-omega turbulence model for the numerical study	Secondary mass flow rate increased when the throat area ratio ranged from 11.88 to 66.69
2	(Nikiforow et al., 2016) [26]	Experimental testing and CFD using turbulence models (RNG k-ε, SST k-ω, and Realizable k-ε).	Enhanced ejector designs for hydrogen recirculation in fuel cell systems
3	(Feng et al., 2023) [8]	CFD simulations and experimental analysis were used to evaluate ejector performance under wide load conditions.	Entrainment ratio improved with specific throat and mixing diameters across 10–80 kW power range, while multi-nozzle and adjustable ejectors enhanced adaptability under varying loads
4	(A. Fan et al., 2022) [27]	Specific nozzle and CFD with k-epsilon turbulence model for the simulation.	The hydrogen ejection coefficient doubled from 0.75 to 1.55 across all conditions.
5	(Zhang et al., 2024) [13]	Bibliometric analysis on fuel cell research trends	Ejectors offer a safer alternative to pumps for hydrogen recirculation but require efficiency improvements
6	(Z. Xu et al., 2024) [28]	FLC used to regulate hydrogen supply in place of traditional PID controller	Anode pressure fluctuations reduced by 5% during step changes and 2% in dynamic operations
7	(Antetomaso et al., 2024) [29]	3D CFD model for an ejector was used on 5000 W PEMFC	Primary flow was stable indicating a positive result, but a reverse flow occurred when the back pressure exceeded 1.55 bar causing a failure in the system.

Table 2. Supersonic Ejector in Hydrogen Fueling Stations

NO.	Author	Methods	Findings
1	(E. Rothuizen et al., 2013) [30]	Dymola Software to simulate two hydrogen station designs	Cooling demand was reduced by 12%, power usage by 17%, refueling duration was reduced by 5%, and storage pressure was lowered by 20%.
2	(Reddi et al., 2014) [35]	H2SCOPE simulation model to assess designs and working parameters	Lower trailer pressure from (1.5 MPa – 5 MPa) reduced costs, while increasing return pressure at 5 MPa lowered compression demands in a cascade system.
3	(Gökçek & Kale, 2018) [36]	Simulation using HOMER software	Low LCOH=$8.92/kg using wind photovoltaic battery indicates renewable energy can improve hydrogen fueling stations

4	(Bhogilla & Niyas, 2019) [37]	Finite volume method and experimental set up	MMHC can reduce hydrogen compression costs, reaching CR= 26 and work output of 39 kJ/kg.
5	(Wen et al., 2020) [4]	Ejector replaced reduction valve, CFD model, SST k-ω turbulence model	CR= 1, ER= 0.75, back pressure = 360 to 480 bar. Low pressure hydrogen increased by 10% in a 7 kg refueling process
6	(Rogié et al., 2020) [6]	Ejector replaced reduction valve, 1D CFD model, SST k-ω turbulence model	CR=1, primary pressure = (2 to 7 bar), constant secondary and exit pressure of 1.25 bar. Lower pressure fuel usage increased by 12% and fueling time was reduced by 6%
7	(Rogié et al., 2021) [7]	Ejector replaced reduction valve, 2-Daxisymmetric CFD model, SST k-ω turbulence model	Cascade system pressure ranging from 300 to 900 bar. Energy consumption reduced by 6.5%.
8	(J. Chen et al., 2022) [44]	Simulation-based study integrating a turbo-expander in a hydrogen refueling station to analyze isentropic expansion effects.	Reduced precooling energy demand by 52.6%, improved COP, lowered compressor load, and enhanced energy recovery without compromising hydrogen quality.
9	(Genovese et al., 2020) [37]	Integrated modeling of buffer-volume control, safety-valve venting, high-pressure leakage, and vapor-compression cooling COP	Dynamic losses dominate; manual-valve closure saves ~0.5 kg; improved leakage prediction; COP enables cooling optimization.

6 Conclusion

In summary, ejectors are passive devices, which require less maintenance and preserve energy consumption. Their integration into hydrogen refueling stations has demonstrated potential for reducing both fueling time and energy use, making them a compelling alternative to conventional reduction/expansion valves. In hydrogen fuel-cell recirculation systems, ejectors have shown effectiveness in improving hydrogen utilization. However, their applications face challenges. In fuel cell systems, ejectors are sensitive to backpressure, two-phase flow, and specific operating conditions. In refueling stations, their performance may decline under low-demand conditions or with pressure fluctuations.

Additional research is needed to address the limitations of ejectors, especially in hydrogen refueling stations, to investigate their feasibility and effectiveness. While ejectors have the potential to improve hydrogen infrastructure, their adoption will rely on enhancing their stability, efficiency, and most importantly their adaptability to real dynamic conditions.

References

1. A. Ajanovic, A. Glatt, and R. Haas, “Prospects and impediments for hydrogen fuel cell buses,” *Energy*, vol. 235, p. 121340, Nov. 2021, doi: 10.1016/j.energy.2021.121340.
2. Y. Manoharan *et al.*, “Hydrogen Fuel Cell Vehicles; Current Status and Future Prospect,” *Applied Sciences*, vol. 9, no. 11, p. 2296, Jun. 2019, doi: 10.3390/app9112296.
3. G. Trencher, “Strategies to accelerate the production and diffusion of fuel cell electric vehicles: Experiences from California,” *Energy Reports*, vol. 6, pp. 2503–2519, Nov. 2020, doi: 10.1016/j.egyr.2020.09.008.
4. C. Wen, B. Rogie, M. R. Kærn, and E. Rothuizen, “A first study of the potential of integrating an ejector in hydrogen fuelling stations for fuelling high pressure hydrogen vehicles,” *Applied Energy*, vol. 260, p. 113958, Feb. 2020, doi: 10.1016/j.apenergy.2019.113958.
5. H. Charton, C. Perret, and H. T. Phan, “Analysis of Supersonic Flows inside a Steam Ejector with Liquid–Vapor Phase Change Using CFD Simulations,” *Thermo*, vol. 4, no. 1, pp. 1–15, Jan. 2024, doi: 10.3390/thermo4010001.

6. B. Rogié, M. Ryhl Kærn, C. Wen, and E. Rothuizen, “Numerical optimization of a novel gas-gas ejector for fuelling of hydrogen vehicles,” *International Journal of Hydrogen Energy*, vol. 45, no. 41, pp. 21905–21919, Aug. 2020, doi: 10.1016/j.ijhydene.2020.05.169.
7. B. Rogié, C. Wen, M. R. Kærn, and E. Rothuizen, “Optimisation of the fuelling of hydrogen vehicles using cascade systems and ejectors,” *International Journal of Hydrogen Energy*, vol. 46, no. 14, pp. 9567–9579, Feb. 2021, doi: 10.1016/j.ijhydene.2020.12.098.
8. J. Feng, J. Han, Z. Pang, and X. Peng, “Designing Hydrogen Recirculation Ejectors for Proton Exchange Membrane Fuel Cell Systems,” *Energies*, vol. 16, no. 3, p. 1201, Jan. 2023, doi: 10.3390/en16031201.
9. N. A. A. Qasem and G. A. Q. Abdulrahman, “A Recent Comprehensive Review of Fuel Cells: History, Types, and Applications,” *International Journal of Energy Research*, vol. 2024, no. 1, p. 7271748, Jan. 2024, doi: 10.1155/2024/7271748.
10. L. Fan, Z. Tu, and S. H. Chan, “Recent development of hydrogen and fuel cell technologies: A review,” *Energy Reports*, vol. 7, pp. 8421–8446, Nov. 2021, doi: 10.1016/j.egyr.2021.08.003.
11. N. Sammes, R. Bove, and K. Stahl, “Phosphoric acid fuel cells: Fundamentals and applications,” *Current Opinion in Solid State and Materials Science*, vol. 8, no. 5, pp. 372–378, Oct. 2004, doi: 10.1016/j.cossms.2005.01.001.
12. V. Patil *et al.*, “Degradation mechanisms in PEM fuel cells: A brief review,” *Materials Today: Proceedings*, p. S221478532301670X, Apr. 2023, doi: 10.1016/j.matpr.2023.03.603.
13. C. Zhang *et al.*, “The experiment and the control of hydrogen circulation of fuel cell based on of fuel ejector: A review,” *International Journal of Hydrogen Energy*, vol. 50, pp. 1415–1431, Jan. 2024, doi: 10.1016/j.ijhydene.2023.10.307.
14. B. El Zohbi, N. Bukharin, H. H. Assoum, K. Abed-Meraim, A. Sakout, and M. El Hassan, “Investigation of the effects of the jet nozzle geometry and location on the performance of supersonic fluid ejectors,” *Energy Reports*, vol. 8, pp. 228–233, Jun. 2022, doi: 10.1016/j.egyr.2022.01.029.
15. M. El Hassan, “Numerical Investigation of the Flow Dynamics Inside Supersonic Fluid Ejector,” *Arab J Sci Eng*, vol. 45, no. 2, pp. 909–919, Feb. 2020, doi: 10.1007/s13369-019-04179-w.
16. N. Bukharin and M. El Hassan, “Numerical and Experimental Investigation of Supersonic Binary Fluid Ejector Performance,” *Fluids*, vol. 8, no. 7, p. 197, Jun. 2023, doi: 10.3390/fluids8070197.
17. B. M. Tashtoush, M. A. Al-Nimr, and M. A. Khasawneh, “A comprehensive review of ejector design, performance, and applications,” *Applied Energy*, vol. 240, pp. 138–172, Apr. 2019, doi: 10.1016/j.apenergy.2019.01.185.
18. M. El Hassan and N. Bukharin, “Numerical investigation of the flow dynamics inside single fluid and binary fluid ejectors,” *J. Phys.: Conf. Ser.*, vol. 1276, no. 1, p. 012012, Aug. 2019, doi: 10.1088/1742-6596/1276/1/012012.
19. M. El Hassan, H. H. Assoum, N. Bukharin, K. Abed-Meraim, and A. Sakout, “Investigation of thermo-physical fluid properties effect on binary fluid ejector performance,” *Energy Reports*, vol. 6, pp. 287–292, Feb. 2020, doi: 10.1016/j.egyr.2019.11.076.
20. M. El Hassan, “System COP of Ejector-Based Ground-Source Heat Pumps,” *Energies*, vol. 15, no. 22, p. 8509, Nov. 2022, doi: 10.3390/en15228509.
21. H. Chen, C. Cai, J. Luo, and H. Zhang, “Quasi One-Dimensional characteristic analysis of ejector nozzle for turbofan propulsion system,” *Applied Thermal Engineering*, vol. 239, p. 122112, Feb. 2024, doi: 10.1016/j.applthermaleng.2023.122112.
22. E. S. Ali, H. Muhammad Asfahan, M. Sultan, and A. A. Askalany, “A novel ejectors integration with two-stages adsorption desalination: Away to scavenge the ambient energy,” *Sustainable Energy Technologies and Assessments*, vol. 48, p. 101658, Dec. 2021, doi: 10.1016/j.seta.2021.101658.
23. Q. Han *et al.*, “Working condition expansion and performance optimization of two-stage ejector based on optimal switching strategy,” *Energy*, vol. 282, p. 128376, Nov. 2023, doi: 10.1016/j.energy.2023.128376.
24. R. Koirala, Q. L. Ve, B. Zhu, K. Inthavong, and A. Date, “A Review on Process and Practices in Operation and Design Modification of Ejectors,” *Fluids*, vol. 6, no. 11, p. 409, Nov. 2021, doi: 10.3390/fluids6110409.
25. J.-H. Lee, A. Sameen, V. Sanal Kumar, H.-D. Kim, C. Bo-Gyu, and K.-H. Kim, “Studies on Ejector Systems for Hydrogen Fuel Cell,” in *41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, Tucson, Arizona: American Institute of Aeronautics and Astronautics, Jul. 2005. doi: 10.2514/6.2005-3590.
26. K. Nikiforow, P. Koski, H. Karimäki, J. Ihonen, and V. Alopaeus, “Designing a hydrogen gas ejector for 5 kW stationary PEMFC system – CFD-modeling and experimental validation,” *International Journal of Hydrogen Energy*, vol. 41, no. 33, pp. 14952–14970, Sep. 2016, doi: 10.1016/j.ijhydene.2016.06.122.
27. A. Fan, D. Fan, W. Xiao, and C. Ye, “Simulation and optimization design of hydrogen ejector in

proton exchange membrane fuel cell system," *J. Phys.: Conf. Ser.*, vol. 2360, no. 1, p. 012035, Nov. 2022, doi: 10.1088/1742-6596/2360/1/012035.

28. Z. Xu, B. Liu, Y. Tong, Z. Dong, and Y. Feng, "Modeling and Control of Ejector-Based Hydrogen Circulation System for Proton Exchange Membrane Fuel Cell Systems," *Energies*, vol. 17, no. 11, p. 2460, May 2024, doi: 10.3390/en17112460.
29. C. Antetomaso, A. Irimescu, S. S. Merola, B. M. Vaglieco, S. Di Micco, and E. Jannelli, "Ejector design for PEM fuel cells and assessment of its scalability," *International Journal of Hydrogen Energy*, vol. 95, pp. 1235–1241, Dec. 2024, doi: 10.1016/j.ijhydene.2024.07.433.
30. Rothuizen, Erasmus Damgaard, "Hydrogen Fuelling Stations: A Thermodynamic Analysis of Fuelling Hydrogen Vehicles for Personal Transportation.," PhD, University of Denmark. Department of Mechanical Engineering, 2013. [Online]. Available: https://backend.orbit.dtu.dk/ws/files/108702334/Hydrogen_Fuelling_Stations.pdf
31. J. Alazemi and J. Andrews, "Automotive hydrogen fuelling stations: An international review," *Renewable and Sustainable Energy Reviews*, vol. 48, pp. 483–499, Aug. 2015, doi: 10.1016/j.rser.2015.03.085.
32. V. P. Utgikar and T. Thiesen, "Safety of compressed hydrogen fuel tanks: Leakage from stationary vehicles," *Technology in Society*, vol. 27, no. 3, pp. 315–320, Aug. 2005, doi: 10.1016/j.techsoc.2005.04.005.
33. J. Kurtz, S. Sprik, and T. H. Bradley, "Review of transportation hydrogen infrastructure performance and reliability," *International Journal of Hydrogen Energy*, vol. 44, no. 23, pp. 12010–12023, May 2019, doi: 10.1016/j.ijhydene.2019.03.027.
34. M. Genovese, D. Blekhman, M. Dray, and P. Fragiacomo, "Hydrogen losses in fueling station operation," *Journal of Cleaner Production*, vol. 248, p. 119266, Mar. 2020, doi: 10.1016/j.jclepro.2019.119266.
35. K. Reddi, A. Elgowainy, and E. Sutherland, "Hydrogen refueling station compression and storage optimization with tube-trailer deliveries," *International Journal of Hydrogen Energy*, vol. 39, no. 33, pp. 19169–19181, Nov. 2014, doi: 10.1016/j.ijhydene.2014.09.099.
36. M. Gökçek and C. Kale, "Optimal design of a Hydrogen Refuelling Station (HRFS) powered by Hybrid Power System," *Energy Conversion and Management*, vol. 161, pp. 215–224, Apr. 2018, doi: 10.1016/j.enconman.2018.02.007.
37. S. S. Bhogilla and H. Niyas, "Design of a hydrogen compressor for hydrogen fueling stations," *International Journal of Hydrogen Energy*, vol. 44, no. 55, pp. 29329–29337, Nov. 2019, doi: 10.1016/j.ijhydene.2019.02.171.
38. J. Chen *et al.*, "Dynamic simulation of the potential of integrating a turbo-expander in a hydrogen refueling station," *Applied Thermal Engineering*, vol. 202, p. 117889, Feb. 2022, doi: 10.1016/j.applthermaleng.2021.117889.
39. M. Genovese, V. Cigolotti, E. Jannelli, and P. Fragiacomo, "Hydrogen Refueling Process: Theory, Modeling, and In-Force Applications," *Energies*, vol. 16, no. 6, p. 2890, Mar. 2023, doi: 10.3390/en16062890.