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Characterization of Hydrogen Gas Flow Rate on Efficiency and Specific Fuel Consumption in a Fuel Cell-Based Electric Vehicle

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Abstract: The significant increase in carbon emissions from the transportation sector, which has risen by 108% in under five years, has intensified the need for sustainable alternative energy sources. Hydrogen energy, utilized through fuel cells in electric vehicles, presents a promising solution for achieving environmentally friendly transportation. This technology facilitates an electrochemical reaction between hydrogen and oxygen to produce electrical energy, with heat and water as the only byproducts. This research aims to characterize the effect of varying hydrogen gas flow rates on the efficiency and Specific Fuel Consumption (SFC) of a fuel cell-based electric vehicle. The study was conducted by integrating a fuel cell system into an electric car equipped with a 96 V, 50 Ah battery for energy storage. The primary investigation involved testing the system at three distinct hydrogen gas flow rates: 1 l/min, 1.5 l/min, and 2 l/min. Data on the fuel cell's power output was collected to calculate the resulting efficiency and SFC. The results demonstrate a clear and significant correlation between the hydrogen flow rate, efficiency, and SFC. It was established that a greater hydrogen gas flow rate leads to lower SFC values and consequently higher fuel cell efficiency. Specifically, at a flow rate of 1 l/min, the fuel cell's efficiency increased by 52.37% with a corresponding SFC decrease of 34.25%. Increasing the flow rate to 1.5 l/min resulted in a more substantial efficiency gain of 58.76% and an SFC reduction of 38.3%. At the highest tested flow rate of 2 l/min, the efficiency saw an increase of 59%, while the SFC value decreased by 14.17%. This data proves that the SFC value is inversely proportional to the fuel cell's efficiency. In conclusion, this research confirms that optimizing the hydrogen gas flow rate is a critical factor in maximizing the performance of fuel cell electric vehicles, reinforcing the potential of hydrogen as a viable and efficient energy source for future transportation.

Keywords: Electric Vehicle, Efficiency, Fuel Cell, Hydrogen Gas, Specific Fuel Consumption

1. Introduction

The trend of carbon gas emissions from vehicles has increased by 108% in less than 5 years [1]. Alternative energy sources have been studied, and some have the potential to be used as a power source for electric cars, with hydrogen gas being one of them. In fact, big automotive industries such as Toyota with the Mirai and BMW with the iX5 have begun to develop hydrogen energy [2,3]. Therefore, development to reduce the dependency on fuel in vehicles is necessary to decrease carbon emissions.

In principle, hydrogen energy involves a combined reaction between hydrogen and oxygen, with the final product being electrical energy [4]. Additionally, the energy formed also produces heat [5]. This process is called an electrochemical process [6]. Combining the two reactions between hydrogen and oxygen requires a device known as a fuel cell. The fuel cell has two electrodes to carry out the electrochemical process. These two electrodes, which function as an anode and a cathode, are separated by an electrolyte that carries electrically charged particles. However, the separation reaction process depends on the catalyst used on both electrodes [7]. The catalyst separates protons and electrons from the hydrogen at the anode. This results in the reaction:

$$H_2 \rightarrow 2H^+ + 2e^- \text{ (anoda)} \quad (1)$$

Electrons, protons, and oxygen from the air will combine to form water at the cathode. This results in the reaction:

$$4H^+ + O_2 + 4e^- \rightarrow 2H_2O \text{ (katoda)} \quad (2)$$

The integration of fuel cells into electric cars has become an interesting trend for many researchers in recent decades. This is aimed at testing their compatibility and performance. The Well-to-Wheel (WTW) method attempts to explain in more detail both the performance and the cost of use [8]. This method was developed and operated in China and resulted in an average WTW hydrogen energy efficiency of 6.8% and 29.2% for fuel cell vehicles [8]. It should be noted that the type of hydrogen energy used affects the operating range. For long-distance transportation cases of more than 800 km, liquid hydrogen can be used to achieve better efficiency. This research can show that fuel cells offer a better energy alternative compared to fossil fuels.

Fuel cell research was evaluated by [9] through a cost-economic analysis of fuel cells applied to transportation modes in China. The economic evaluation in 2019 showed an increase in fuel cell car purchases to 7,500 units, a 35.7% increase compared to 2018. With this increasing trend in fuel cell car purchases, it is projected that energy production from fossil fuels can be reduced from 67% in 2020 to 20% in 2050. This reduction in fossil fuel energy production could lead to an increase in hydrogen production from water electrolysis from 3% to 70%. The production cost of hydrogen from electrolysis is \$0.07 USD/kWh for 500 Nm^3/h. For comparison, the production cost of hydrogen using coal is \$84.74 USD/t for 9000 Nm^3/h. If using natural gas, the production cost is \$9.9 USD/MBtu for 9000 Nm^3/h. The production cost of water electrolysis is quite sensitive, with a sensitivity value of 68.69%, but the production cost from natural gas is more sensitive at 74.29%, whereas the cost from coal has a sensitivity of 47.51%. The results of the economic analysis show that hydrogen production for fuel cells can have a low cost.

Hydrogen can be compressed from 350 to 700 bar as a storage medium, but this depends on its application [10]. Vehicles typically used for short trips are more suitable for hydrogen tanks with 350 bar compression, whereas 700 bar compression tanks are intended for vehicles that travel long distances [11]. This, of course, plays a significant role in the cost of the transportation mode. Moreover, high compression also requires extensive maintenance and training for users. One of these dangers is the risk of explosion and fire, which can originate from leaks in the storage tank [12]. Hydrogen has auto-ignition properties, meaning a fire can start if it reaches a certain temperature point [13].

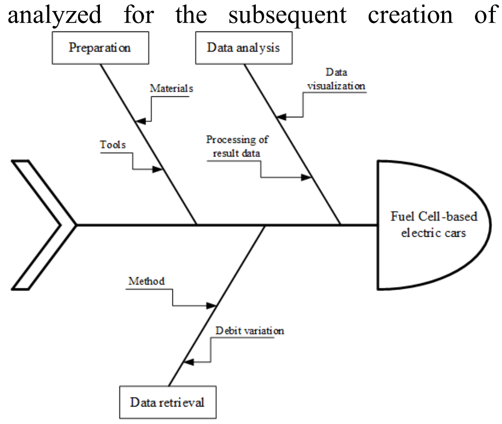
Commercially, the application of technology to reduce CO_2 also can help achieve Net-Zero CO_2 targets and reduce global warming by 1.5°C [14]. However, hydrogen also requires a higher level of handling in terms of safety, maintenance, and the prevention of dangers that may arise during its use [15].

2. Method

This research is explained through a fishbone diagram as in Figure 1.

Figure 1. *Fishbone diagram of research.*

The research can be explained through the fishbone diagram titled "Characterization of Hydrogen Gas Flow Rate On Efficiency and Specific Fuel Consumption In A Fuel Cell-Based Electric Vehicle." The workflow begins with the preparation of materials and tools, followed by data collection, methodology, and flow rate variation. Finally, the collected data is analyzed for the subsequent creation of data



visualizations with graphs.

Testing was conducted to obtain the hydrogen gas flow rate, which was then used in calculations to determine the efficiency and the specific fuel consumption value. The fuel cell was integrated into a car equipped with an electric motor as the main driver and a 96 V battery for energy storage. The DC voltage output from the fuel cell has an average of 18 V, an average power of 1000 W, and an average current of 27.8 A. The 96V battery has a DC voltage output of 96 V and a capacity of 50 Ah. After the data is collected, the fuel cell's debit can be calculated using the following formulas.

$$\dot{m}_{H_2} = \rho_{H_2} \cdot Q_{H_2} \quad (3)$$

Table 1. *Table information equation*

Symbol	Function
$\dot{m}_{H_2}$	Hydrogen mass flow (kg/s)
ρ_{H_2}	Hydrogen density (kg/m^3)
Q_{H_2}	Hydrogen flow rate (m^3/s)

Afterwards, the fuel cell's efficiency can be calculated using the following formula:

$$\eta = \frac{P_{fc}}{P_{H_2}} \times 100\% \quad (1)$$

Table 2. *Table information equation*

Symbol	Function
η	Fuel cell efficiency (%)

P_{fc}	Fuel cell power output (W)
P_{H_2}	Hydrogen power (W)

Finally, the Specific Fuel Consumption value can be calculated using the following formula:

$$SFC= \frac{\dot{m}_{H_2}}{P_{fc}} \quad (1)$$

Table 3. *Table information equation*

Symbol	Function
SFC	*Specific Fuel Consumption* (kg/kWh)
$\dot{m}_{H_2}$	Hydrogen mass flow rate (kg/s)
P_{fc}	Fuel cell power output (W)

The calculation of the flow rate, efficiency, and the Specific Fuel Consumption value is performed in stages. This helps to minimize errors in the calculation.

3. Results and Discussion

The hydrogen gas flow rate can affect the level of efficiency and the specific fuel consumption (SFC) value. A higher specific fuel consumption (SFC) value is influenced by the power output of the fuel cell. The influence of power output on the change in SFC can be seen in Figure 2. At flow rates of 1 l/min, 1.5 l/min, and 2 l/min, there was a decrease in SFC of 34.2%, 38.31%, and 14.17%, respectively. The average values were 0.087 kg/kWh, 0.085 kg/kWh, and 0.0717 kg/kWh. In general, the fuel cell's SFC value is related to the power output, representing the fuel consumption of the hydrogen vehicle. The higher the power output from the fuel cell, the lower the SFC value will be.

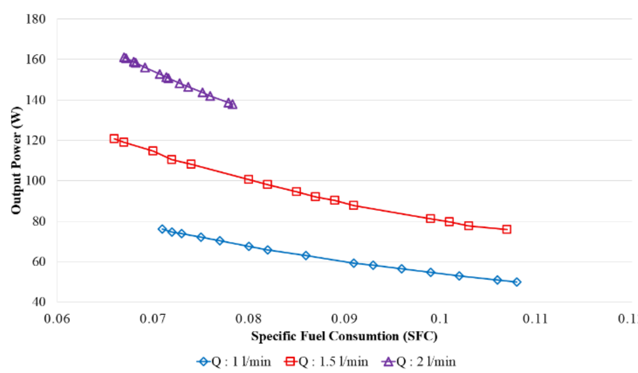


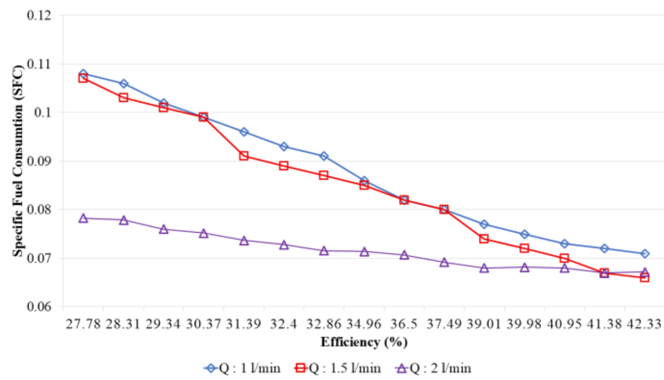
Figure 2. *Characteristics of output power versus Specific Fuel Consumption (SFC) of fuel cell*

The efficiency of the fuel cell is also influenced by the specific fuel consumption (SFC) value. This is shown in Figure 3, where at a flow rate of 1 l/min, the highest SFC value is 0.108, while the efficiency at the same flow rate is 27.78%. For the highest efficiency at the 1 l/min flow rate, the value is 42.3%, while the SFC value is 0.071. This clearly shows an inverse relationship between efficiency and the SFC value. At flow rates of 1 l/min, 1.5 l/min, and 2 l/min, a decrease in the SFC value occurred, which corresponds to an increase in efficiency of 52.3%, 58.76%, and 16.41%, respectively. The average efficiencies are 35%, 35.79%, and 41.94%. Meanwhile, the SFC experienced a decrease of 34.25%, 38.3%, and 14.17%. Its average values were 0.087 kg/kWh, 0.085 kg/kWh, and 0.0717 kg/kWh, respectively. This data proves that the SFC value is inversely proportional to the fuel cell's efficiency. The greater the hydrogen gas flow rate used in the fuel cell, the lower the SFC value and the higher the fuel cell's efficiency. The fuel cell can increase efficiency by lowering the SFC value that results from the hydrogen gas flow rate.

Figure 3. *Characteristics of Specific Fuel Consumption (SFC) of fuel cell versus fuel cell efficiency*

4. Conclusion

Hydrogen energy has good potential for its application in electric vehicles. This potential makes it a solution for environmentally friendly transportation modes in the future.



However, it still faces several challenges, such as the high cost of fuel cells, the uneven distribution of hydrogen gas, and a lack of clear public knowledge regarding the dangers of hydrogen gas. The fuel cell's efficiency has been proven to increase the charging of electric cars by 52.37% at a flow rate of 1 l/min, 58.76% at 1.5 l/min, and 59% at 2 l/min. As for the SFC value, it experienced a decrease of 34.25% at a flow rate of 1 l/min, 38.3% at 1.5 l/min, and 14.17% at 2 l/min. This proves that the fuel cell has a high level of efficiency and a low SFC value resulting from the hydrogen gas flow rate.

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