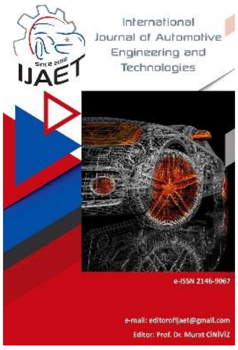
e-ISSN: 2146 - 9067

International Journal of Automotive Engineering and Technologies

journal homepage:
https://dergipark.org.tr/en/pub/ijaet



Original Research Article

An emission reduction method in liquid hydrogen powered fuel cell vehicles

Adem Ugurlu[1, *]

Kirklareli University, Technology Faculty, Department of Mechatronics Engineering, Kirklareli, Turkey.

ARTICLE INFO

Orcid Numbers
1. 0000-0002-9531-3944

Doi: 10.18245/ijaet.1035465

* Corresponding author
adem.ugurlu@klu.edu.tr

Received: Dec 11, 2021
Accepted: July 05, 2022

Published: 02 Oct 2022

Published by Editorial Board Members of IJAET

ABSTRACT

An emission reduction method has been analyzed for Liquid Hydrogen (LH_2) powered Fuel Cell Vehicles (FCVs) using GREET software in this study. In the analysis, cooling rates and Coefficient of Performance (COP) values of the proposed system have been calculated for FCVs that considered. Average reductions of the years 2010, 2020, 2030, 2040, and 2050 in emissions for the use of Auxiliary Air Condition (AAC) system in the FCVs are analyzed in g/year for Volatile Organic Compounds (VOC), Carbon Monoxide (CO), Nitrogen Oxides (NO_x), Particulate Matters (PM_{10} & $PM_{2.5}$), and Sulfur Oxides (SO_x). Average reduction in Carbon Dioxide (CO_2) emission is calculated and given in kg/year. All the emissions decrease in significant proportions due to the reduction in fuel consumption by less usage of the main AC system of the vehicles.

Keywords: Liquid hydrogen, air conditioning, fuel cell vehicles, emissions.

1. Introduction

Fossil fuel sources are rapidly depleting, and as the enormous environmental impacts of their use can no longer be ignored, many advances have been made in the area of alternative fuel technologies in recent years [1-3]. Hydrogen is increasingly being studied as a potential candidate to replace these fossil fuels. Hydrogen vehicles have become increasingly popular since the launch of the first hydrogen-powered fuel cell vehicle. When hydrogen is used to generate electricity in a fuel cell, only products are water and small amount of NO_x [4-6]. High energy density and carbon free nature are the main advantages of hydrogen. Although most hydrogen vehicles store hydrogen in gaseous form in their tanks such as the Ford Zetec 2.0 L and Toyota Mirai FCV [7-8], some examples such as the first GM FCV Electro Van (1966), GM HydroGen3, BMW Mini Hydrogen, and BMW 750hl [9-11] use liquid hydrogen as a fuel that is stored in cryogenic tanks in a vacuum environment [12-13]. Liquefaction of hydrogen is one of the best ways to store hydrogen [14], so LH_2 is a promising part of hydrogen applications [15]. The gasification of LH_2 in these applications results in waste energy which can be used for cooling purposes with some auxiliary equipment such as pressure regulator, evaporator, and air fan. This study relates to one of the areas in which this applies: AC systems in vehicles.

Farrington et al. [16] reported that the driving distance of an electric vehicle decreased by about 40% due to the use of the AC system. Therefore, reducing the energy consumption of main AC systems of vehicles will help improve the overall energy efficiency and environmentally friendly nature of vehicles [17-19]. So far, many systems and methods have been proposed to improve the energy efficiency of vehicular AC systems. For instance, Pino et al. [20] analyzed the behavior of an FCV on AC use in terms of hydrogen consumption under extreme and smooth ambient conditions and different passenger loads under standard urban and highway driving cycles. They found that the increase in hydrogen consumption to be between 3 and 12.1% when the FCV's air conditioning system was on. The nominal cooling capacity and COP of their systems are 3 kW and 3, respectively. Therefore, it can be concluded that AC systems are very important systems in vehicles [21] to develop both efficient and environmentally friendly vehicles.

In this, study, the use of LH_2 to provide both cooling for air conditioning and power for wheel movement in FCVs has been theoretically investigated. After the average AC saving values are obtained from the investigation, they are applied to the emissions from LH_2 powered FCVs gathered from GREET software for the target years of 2010, 2020, 2030, 2040, and 2050, and the reductions in emissions are calculated and presented. VOC, CO, NO_x, PM_{10}, $PM_{2.5}$, SO_x, and CO_2 emissions are included in the analysis. Since Well-To-Pump (WTP) and Well-To-Whell (WTW) emissions are almost the same in FCVs, only WTW emissions are presented in the study.

2. Methodology

2.1. Description of the VAAC system

As shown in Fig. 1, the proposed system consists of two main circuits: hydrogen and air. The hydrogen circuit maintains hydrogen for the vehicle's fuel cell unit, while the air circuit provides additional cooling for the vehicle cabin. Air cooling is achieved by gasification of hydrogen passing through the evaporator of the system and reduces the cooling load, which is one of the most important additional loads for today's vehicles. The energy consumption of AC systems in vehicles outweighs the loss of energy in rolling and aerodynamic resistances, or even power transmission system losses for typical vehicles [22]. As seen from the figure, when more hydrogen is supplied to power the fuel cell unit, more cooling is provided for the air to cool down the vehicle cabin. Hydrogen is stored in liquid form under pressure in the cryogenic tank. The vehicle power generator needs gaseous hydrogen at atmospheric pressure. A pressure regulating valve reduces the pressure of hydrogen. An evaporation process follows this pressure drop. The hydrogen is evaporated with the blown air through the outer surfaces of the evaporator. This cooled-down air is sent to the vehicle compartment to decrease the AC cooling load, which changes according to the environmental factors such as: sun exposure, outside temperature and humidity, number of passengers, etc.

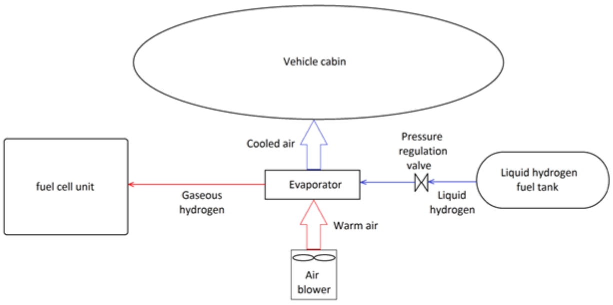


Figure 1 Layout of the AAC system for LH2 powered FCVs

2.2. FCV analysis

Fuel consumption of FCVs that are sold in the market is generally given in kg H2/100 km unit. Calculation of the average hydrogen consumption (kg/s) of an FCV is seen in Eq. (1). $\dot{m}_{h,FCV,NEDC}$ (kg/100 km), declared by the manufacturer of the FCV, is determined by the New European Driving Cycle (NEDC) standards. FCVs analyses have been conducted in this study using $\dot{m}_{h,FCV,NEDC}$ values between 0 and 6 kg/100 km to meet the fuel consumption values of FCVs in the market, such as Toyota Mirai, Honda Clarity Fuel Cell, Hyundai Nexo. Their average hydrogen consumption values are calculated using the hydrogen tank capacity and the full range with the tank. The range is in the NEDC standard. On the other hand, total range of 1 kg/100 km is also consistent with the literature [23]. Hence, $\dot{m}_{h,FCV,NEDC}$ values chosen as between 0 and 6 kg/100 km in this study are suitable for a wide variety of vehicles in a large range of driving conditions. Eq. (2) shows the calculation of the cooling capacity that the gasification of liquid hydrogen maintains. In this formula, $\dot{Q}_c$ shows the cooling amount (W) that the system gets from the air to be directed to the vehicle passenger compartment, $\dot{m}_{h,FCV}$ is the hydrogen mass flow rate (kg/s), and $h_{fg,h}$ is the enthalpy of vaporization (kJ/kg) of hydrogen. $h_{fg,h}$ is taken from the literature [24] as 402,000 J/kg. COP calculation of the AAC system is seen in Eq. (3). $COP_{R,FCV}$ is the performance measurement of the AAC system that is actually an AC system. Peltier effect thermoelectric coolers are inspired for conducting the COP calculation of the AAC system. Thermoelectric coolers have no compressors in their cooling systems unlike conventional air conditioners and refrigerators. Similarly, the AAC system proposed in this work has no compressors, because the LH_2 in the tank is pressurized. When the pressure decreases to an insufficient level for the flow, the tank is refilled with hydrogen by the driver in a fuel station. The consumed hydrogen by the fuel cell unit of the vehicle is not included in energy consumption of the AAC system. Fan power (P_f) required to circulate the air through the hydrogen evaporator is the only energy consumed by the AAC system creating cooling effect. The fan used in the calculations of the AAC system is selected as a standard one working at three positions, consuming power as 24 W, 48 W, and 72 W, respectively. These fan powers are compatible to the literature that they are widely used and suitable for the proposed AAC system [25]. As to the AC savings (%) of the AAC system, they are calculated for vehicles at various cooling loads through Eq. (4). S_{AC} is the percent saving, $\dot{Q}_c$ is cooling capacity of the system (W), and $\dot{L}_c$ is the cooling load of the vehicle (W). $\dot{L}_c$ values are selected from the literature [26], which reports that average cooling load values for subcompact, compact, and standard cars are 3,62 kW, 4,15 kW, and 5.12 kW, respectively. As $\dot{L}_c$ of vehicles constantly takes different values according to the weather conditions, size of the vehicles, and number of the occupants, the analysis are conducted for 1000 W, 2000 W, 3000 W, 4000 W, 5000 W, and 6000 W cooling load values to determine the AC savings of the AAC system at different conditions. These chosen values are also compatible with the works of Meier et al. [23], and Fayazbakhsh and Bahrami [22].

$$\dot{m}_{h,FCV} = \frac{\frac{\dot{m}_{h,FCV,NEDC} \times 11{,}007}{100}}{1180} \tag{1}$$

$$\dot{Q}_{c,FCV} = \dot{m}_{h,FCV} \times h_{fg,h} \tag{2}$$

$$COP_{R,FCV} = \frac{\dot{Q}_{c,FCV}}{P_f} \tag{3}$$

$$S_{AC} = \frac{\dot{Q}_c}{\dot{L}_c} \tag{4}$$

2.3. Emission analysis

GREET software is used to determine VOC, CO, NO_x, PM_{10}, $PM_{2.5}$, SO_x, and CO_2 emissions for 2005, 2015, 2025, 2035, and 2045 model years LH_2 powered FCVs in 2010, 2020, 2030, 2040, and 2050 years, respectively. In the calculation of the reductions in emissions when the AAC system is used in LH_2 powered FCVs, average values are used. It is assumed that the AAC system operates at 50% efficiency and cooling load of the vehicle is 3 kW, which are average values in the analysis. FCVs with hydrogen consumptions of between 0-6 kg/100 km were considered in the analysis. This consumption range is suitable for FCVs encountered in the market. It is also compatible for the vehicles examined in literature, which are mainly automobiles. Although some academic and commercial circles started to build fuel cell heavy vehicle prototypes, which have probably large hydrogen consumption values, they are not included in the FCV analysis. In the near future, it is estimated that fuel cell systems will be used for vehicles of any size; however, they are only used in some automobiles in small numbers nowadays. After the S_{AC} is determined for a variety of fuel consumptions, AAC efficiencies, and AC loads, reductions in the emissions are calculated and presented for years and vehicle technologies using an average value of S_{AC} together with the real values of emissions found out by running GREET software. At this stage, it was assumed that when the main AC system is turned on, it increases emissions 15%, and this increase is already embedded in the emissions that GREET gives.

3. Results and Discussion

According to the analysis, cooling capacity of the AAC system in FCVs rises to the highest value of 250 W depending on the hydrogen consumption. As to the COP of the system, it negatively varies by the increase of the fan power, which have the highest values of 10.4, 5.2, and 3.5, respectively for 24 W, 48 W, and 72 W fan powers. Saving from the main AC of the FCVs using the AAC system can reach to the values of about 25%, 12%, 8%, 6%, 5%, and 4%, respectively for the AC loads of 1 kW, 2kW, 3kW, 4 kW, 5 kW, and 6 kW. In the emissions analysis, S_{AC} value is taken as 2.1%, which is the S_{AC} value of the AAC system that is assumed operating at 50% efficiency and the AC load of the vehicle is 3 kW so as to model real operating conditions, which require different fuel consumption rates. This is an average value, which can be lower or higher in real conditions depending on factors such as driver, road, climate, traffic, etc.

Table 1 shows WTW and WTW_{AAC} emissions of LH_2 powered FCVs by years. With the use of the AAC system, WTW_{AAC} emissions get lower than WTW as seen in the table, due to the decrease in the AC load of the vehicle cabin, less air conditioning requirement, and therefore reduced fuel consumption. Although the decreases in all the WTW emissions are seen as insufficient, since they are given in g/km, when large numbers of FCVs make long kilometers with this system is thought, the emission reductions will be seen as significant. On the other hand, all the emissions decrease by year is seen from the table. This decrease is due to the technological developments which are embedded in GREET software as scenarios. Since the emissions from FCVs decrease by years, the reductions in the emissions from FCVs that use the AAC system decrease at the same time by years.

Reductions in emissions from FCVs with and without the AAC system by years are shown in Fig. 2. In the calculation of the emissions, it is assumed that the vehicles make 15000 km / year. According to the scenarios in GREET software, all emissions emitted from FCVs decrease together with technological developments by years. Reductions decrease by years due to the levels of emissions decrease by years. These reductions are clearly seen especially in NO_x and SO_x emissions by years. Average reductions in emissions can be briefly given as 0.82 g/year in VOC, 2.12 g/year in CO, 3.87 g/year in NO_x, 0.58 g/year in PM_{10}, 0.36 g/year in $PM_{2.5}$, 5.48 g/year in SO_x.

Fig. 3 shows CO_2 emission reductions in FCVs with and without the AAC system by years. CO_2 emissions are differently given in kg/year unit for a standard vehicle that takes 15000 km per year so as to see the changes easily by years. When using the AAC system in LH_2 powered FCVs, reductions in CO_2 emissions by years are calculated as 11.24 kg/year in 2010, 8.11 kg/year in 2020, 6.06 kg/year in 2030, 4.79 kg/year in 2040, and 4.75 kg/year in 2050 according to the analysis. As FCVs are considered as vehicles of the future, the reductions in emissions by years, which are seen as decreasing in Fig. 3, will be actually increased in total due to the increase in the number of vehicles depending on the years.

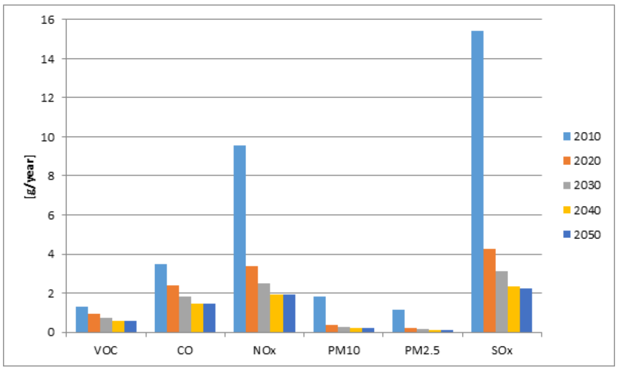


Figure 2 Reductions of emissions by years

Table 1 WTW and WTWAAC emissions of LH2 powered FCVs by years

	2010		2020		2030		2040		2050	
	FCV - LH_2 (2005)		FCV - LH_2 (2015)		FCV - LH_2 (2025)		FCV - LH_2 (2035)		FCV - LH_2 (2045)	
	WTW [g/km]	WTW_{AAC} [g/km]	WTW [g/km]	WTW_{AAC} [g/km]	WTW [g/km]	WTW_{AAC} [g/km]	WTW [g/km]	WTW_{AAC} [g/km]	WTW [g/km]	WTW_{AAC} [g/km]
VOC	0.0277	0.0276	0.0202	0.0201	0.0151	0.0151	0.0120	0.0120	0.0120	0.0120
CO	0.0732	0.0730	0.0506	0.0504	0.0384	0.0383	0.0308	0.0307	0.0310	0.0309
NO_x	0.2024	0.2018	0.0718	0.0715	0.0525	0.0523	0.0412	0.0411	0.0412	0.0411
PM_{10}	0.0390	0.0389	0.0079	0.0079	0.0058	0.0058	0.0045	0.0045	0.0044	0.0044
$PM_{2.5}$	0.0244	0.0244	0.0046	0.0046	0.0034	0.0034	0.0027	0.0027	0.0026	0.0026
SO_x	0.3261	0.3251	0.0903	0.0901	0.0656	0.0654	0.0496	0.0495	0.0477	0.0475
CO_2	237.8	237.1	171.6	171.1	128.2	127.8	101.3	101.0	100.6	100.3

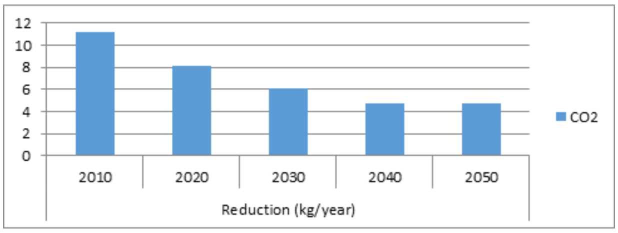


Figure 3. CO_2 reductions by years

4. Conclusion

An emission analysis is conducted using GREET software for LH_2 powered FCVs by years in this study. VOC, CO, NO_x, PM_{10}, $PM_{2.5}$, SO_x, and CO_2 emissions are investigated for the vehicles with and without the proposed AAC system. The highest reductions in emissions are seen between the years 2010 and 2020. This situation is more visible especially for NO_x and SO_x but applies to all emission types. Decreases in emissions continue in 2030, 2040 and 2050, also. Emission reductions have a great value especially for CO_2, which is of great importance in terms of being a greenhouse gas.

The results of the analysis show that the system can supply an adequate cooling to assist the main AC system of the vehicle with very little initial and operating costs. Therefore, all the emissions emitted from the vehicle decrease depending on the reduction in fuel consumption by less usage of the main AC system. Even though, this decrease will be lower over the years due to the fuel consumption reductions in vehicles by year, considering that FCVs will be used frequently in the future, the overall emissions savings will reach very high amounts using this AAC system.

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