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Improving Emissions by An Auxiliary Air Conditioner in Liquid Hydrogen Powered Spark Ignition Engine Vehicles

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ABSTRACT

An Auxiliary Air Conditioner (AAC) system, which decreases the cabin air conditioning load of Liquid Hydrogen (LH_2) powered Spark Ignition Internal Combustion Engine Vehicles (SI ICEV), has been proposed in this study. Volatile Organic Compounds (VOC), Carbon Monoxide (CO), Nitrogen Oxides (NO_x), Particulate Matters (PM_{10} & $PM_{2.5}$), Sulfur Oxides (SO_x), and Carbon Dioxide (CO_2) emissions are theoretically calculated using GREET software developed by Argonne National Laboratory for decades between 2010 and 2050. The results of the study show that the proposed novel system decreases all emissions emitted from LH_2 SI ICEVs decreasing both Well-To-Pump (WTP) and Well-To-Wheel (WTW) emissions. These decreases are around 3 g/year for VOC, 20 g/year for CO, 13 g/year for NO_x, 1 g/year for both PM_{10} and $PM_{2.5}$, 1 g/year for SO_x, and 16 kg/year for CO_2.

Yardımcı Klima Kullanımı ile Sıvı Hidrojenle Çalışan Buji Ateşlemeli Motorlu Taşıtlarda Emisyonların İyileştirilmesi

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ÖZET

Bu çalışmada, sıvı hidrojen (LH_2) ile çalışan buji ateşlemeli içten yanmalı motorlu taşıtların (SI ICEV) kabin klima yükünü azaltan bir yardımcı klima (AAC) sistemi önerilmiştir. Uçucu organik bileşikler (VOC), karbon monoksit (CO), azot oksitler (NO_x), partikül maddeler (PM_{10} & $PM_{2.5}$), kükürt oksitler (SO_x) ve karbon dioksit (CO_2) emisyonları, Argonne ulusal laboratuvarı tarafından geliştirilen GREET yazılımı kullanılarak 2010 ve 2050 yılları arasındaki her on yıl için teorik olarak hesaplanmıştır. Çalışmanın sonuçları, önerilen yeni sistemin LH_2 SI ICEV'lerden yayılan tüm emisyonları azalttığını ve hem kuyudan pompaya (WTP) hem de kuyudan tekerleğe (WTW) emisyonlarını azalttığını göstermektedir. Bu azalmalar VOC için 3 g/yıl, CO için 20 g/yıl, NO_x için 13 g/yıl, PM_{10} ve $PM_{2.5}$ için 1 g/yıl, SO_x için 1 g/yıl ve CO_2 için 16 kg/yıl civarındadır.

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Introduction

Due to strict emission regulations and increasing energy demands, there has been great progress in the field of alternative fuels in recent years (Ciniviz and Köse, 2011; Tüccar et al., 2013; Akar et al., 2018). With its efficient and non-polluting nature, hydrogen is one of the first ones that come to mind of these alternative fuels. Since there is naturally no carbon content in hydrogen fuel, emissions from the combustion of hydrogen in an internal combustion engine are water vapor and some NO_x gas if the combustion temperature is too high (Baltacioglu et al., 2016; Ozcanli et al., 2017; Ozcanli et al., 2018). Another important advantage of hydrogen, apart from the absence of carbon in its content, is its high mass-energy density. But, there are some problems preventing the intensive use of hydrogen as a fuel in vehicles, such as production costs, storage challenges, embrittlement and percolation issues in the hydrogen fuel lines and hydrogen tanks (Serin and Yıldızhan, 2018). It is estimated that these problems will be eliminated in time with the help of academic studies and market requests.

Since hydrogen liquefaction is a better way of storing hydrogen (Ansarinasab et al., 2017), the liquid form of hydrogen is used in several hydrogen applications. For instance, many hydrogen-powered vehicles use gaseous hydrogen, some examples like BMW 750hl and BMW Mini Hydrogen utilize hydrogen fuel in liquid form. Gasification of LH_2 results in waste of energy, which can be possibly used in refrigeration needs at a small cost with auxiliary equipment in those applications. One of the areas where this applies is Vehicle Air Conditioning (VAC) systems. Considering the comfort functions and safety, an Air Conditioning (AC) system is one of the vital systems of vehicles. But, due to the significant power consumption of mechanical compressors in AC systems, fuel consumption increases in vehicles. And this increase can be as much as around 12-17% due to the conditions such as driver factors, environmental factors, and road factors for mid-size and subcompact cars Lambert and Jones (2006), and Khayyam (2013) report in their studies. For this reason, decreasing the energy consumption of a VAC system will maintain to improve the vehicle's overall energy efficiency. To improve the energy efficiency of VAC systems, many methods and systems have been proposed so far. Several of these methods and systems include alternative systems to the conventional vapor compression cycles (Jiang et al., 2018; Gillet et al., 2018), new designs of compressors (Yang et al., 2017; Dahlan et al., 2014) and evaporators (Zhang and Canova, 2015), alternative driving sources to the engine of the vehicle (Pang et al., 2019), and some control methods such as PID (Zhang et al., 2010; Khayyam et al., 2011a), rule based (Khayyam et al., 2009), and fuzzy (Thompson and Dexter, 2005; Calvino et al., 2004; Sousa et al., 1997; Farzaneh and Tootoonchi, 2008; Khayyam et al., 2011b).

In this study, the use of an AAC in LH_2-powered SI ICEVs has been investigated on emission basis. The proposed system provides gaseous hydrogen for both powers for the engine and cooling for air conditioning. The analyses were conducted for the vehicles with and without the AAC in GREET software. Emission reductions were calculated for different scenarios of vehicle and fuel production technologies between 2010 and 2050. VOC, CO, NO_x, PM_{10}, $PM_{2.5}$, SO_x, and CO_2 emissions were compared for an average car specified in the software.

Methodology

The proposed AAC system has two main circuits: air and hydrogen. Hydrogen circuit supplies hydrogen fuel for spark-ignition internal combustion engine of the vehicle. The air circuit maintains cooling for the cabin of the vehicle. Temperature decrease of the air is established by the latent heat of the hydrogen passing through the evaporator part of the system and reducing the cabin cooling load of the vehicle. The more hydrogen flows to power the vehicle, the more cooled-down air is supplied to cool down the vehicle cabin. Hydrogen is stored in liquid form in the cryogenic tank under pressure. Gaseous hydrogen at atmospheric pressure is required by the engine. A pressure regulator reduces the hydrogen pressure. This pressure regulation step is followed by an evaporation process. Hydrogen is evaporated in an evaporator by an air flow blown along the outer surfaces of the evaporator. To decrease the AC cooling load, the cooled-down air is directed to the vehicle passenger compartment. This cooling load highly depends on the environmental factors such as: outside temperature and humidity, number of passengers, and sun light, etc.

Analyses of the emissions from LH_2-powered SI ICEVs with and without the AAC system have been performed according to the equations from Eq. (1) to Eq. (6) as follows. Eq. (1) gives the calculation method of the average gasoline consumption (L/s) of a gasoline-powered SI ICEV. FC_g (L/100 km) is determined according to the New European Driving Cycle (NEDC) and given by the vehicle manufacturers. The vehicle takes away of 11.007 km during the NEDC cycle in 1180 s (Pacheco et al., 2013). In this study, analyses of LH_2-powered SI ICEVs have been conducted using FC_g values between 0 and 30 L/100 km as consists to vehicles on the market. Therefore, values of $\dot{v}_g$ at different conditions can be calculated, and a simple comparison between gasoline-powered SI ICEV and LH_2-powered SI ICEVs can be establish through the analysis.

$$\dot{v}_g = \frac{\frac{FC_g \times 11.007}{100}}{1180} \tag{1}$$

The average gasoline consumption is calculated as seen from Eq. (2) in mass flow rate ($\dot{m}_g$) using ρ_g, which is the average density of gasoline. ρ_g is taken as between 0.72-0.78 kg/L from the literature (Cengel and Boles, 2005).

$$\dot{m}_g = \dot{v}_g \times \rho_g \tag{2}$$

Approximate vehicle hydrogen consumption is calculated using the equivalent heating value rate of gasoline and hydrogen ($r_{HV,h/g}$) as seen in Eq. (3) in mass flow rate ($\dot{m}_h$). Arithmetic means of lower heating values and higher heating values for both hydrogen and gasoline were calculated in this equivalent rate. Lower and higher heating values for gasoline are 44,000 kJ/kg and 47,300 kJ/kg, and they are 120,000 kJ/kg and 141,800 kJ/kg for hydrogen (Cengel and Boles, 2005). Since heating values of gasoline is lower than that of LH_2, the required amount of hydrogen mass flow rate is found approximately 0.3488 times lower than the mass flow rate of gasoline.

$$\dot{m}_h = \dot{m}_g \times r_{HV,h/g} \tag{3}$$

Eq. (4) shows how to calculate the cooling capacity of the system maintaining the liquid hydrogen to the engine at the exact amount. In this equation, $\dot{Q}_c$ presents the cooling amount (kJ/s) that the system absorbs from the air to be blown to the vehicle cabin, $\dot{m}_h$ is the approximate hydrogen mass flow rate (kg/s), and $h_{fg,h}$ is the enthalpy of vaporization (kJ/kg) of hydrogen. $h_{fg,h}$ is taken as 446 kJ/kg from the literature (Cengel and Boles, 2005). The formula gives results for the system that it works at 100% efficiency. Calculations are also maintained as if the system runs at 75%, 50%, and 25% efficiencies as well.

$$\dot{Q}_c = \dot{m}_h \times h_{fg,h} \tag{4}$$

The next part of the analysis includes COP calculation of the system as Eq. (5) shows. COP_R is the measurement of the system that is an air conditioning system in terms of performance. Peltier effect thermoelectric cooling is taken into consideration in the calculation of the COP value of the system. Thermoelectric coolers do not have compressors unlike conventional refrigerators and air conditioners. Similar to the thermoelectric coolers, the proposed system in this study includes no compressor, because they always have pressurized liquid hydrogen in their tanks. When the pressure of the liquid hydrogen becomes insufficient for the hydrogen flow, the tank is refilled with LH_2 in hydrogen fuel stations. It will be inconvenient to include the hydrogen consumption of the engine as the operating cost of the system in terms of energy consumption. The only energy the system consumes to create a cooling effect is the fan that circulates the air through the evaporator. The fan power (P_f) of the system used in the calculations is 24 W.

$$COP_R = \frac{\dot{Q}_c}{P_f} \tag{5}$$

AC savings (%) of the AAC system on vehicles at various cooling loads are calculated through Eq. (6). S_{AC} is the percent saving, $\dot{Q}_c$ is cooling capacity of the system (kW), and $\dot{L}_c$ is the cooling load of the vehicle (kW). $\dot{L}_c$ values are chosen according to the literature (Meier et al., 2018), which gives that average cooling load values for standard, compact, and subcompact automobiles are 5.12 kW, 4.15 kW, and 3.62 kW, respectively. $\dot{L}_c$ values of vehicles are continuously variable values according to the factors such as the vehicle size, number of the occupants, and weather conditions. Therefore, 1 kW, 2 kW, 3 kW, 4 kW, 5 kW, and 6 kW values were taken to determine the AC saving values for different conditions. The study of Meier et al. (2018) is also compatible with those chosen values.

$$S_{AC} = \frac{\dot{Q}_c}{\dot{L}_c} \tag{6}$$

Finally, 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 by 15%. Among the calculated average S_{AC} values, it is taken as 2.7%. The average S_{AC} of the AAC system has been chosen by assuming the system is operating at 50% efficiency and the AC load of the vehicle is 3 kW.

Results and Discussion

For a gasoline consumption range of 0-30 L/100 km, gasoline-powered SI ICEVs have the highest hydrogen consumption of about 0.0007 kg/s. And this amount of hydrogen can supply 326 W cooling power to the cabin. The COP of this process will be 13.6. The amounts of cooling powers seem to be only enough at very low AC loads with humid weather and fewer occupants. When the AC load increases over the amounts of cooling capacities of the vehicles with this proposed system, it can only be used in the assistance of the main AC unit of the vehicle. The main air conditioner should operate at the rate which the air conditioning load exceeds the cooling capacity of the proposed system. According to the variations of AC savings in percent, on the other hand, the AAC system can decrease the AC load of the vehicle cabin up to the value of about 33% in 1 kW AC load with 100% efficiency operation of the system. This value is directly connected to the fuel consumption of the vehicle. When the fuel consumption decreases, the AAC system can assist the main AC system of the vehicle at a lower percentage. Averagely, if the AAC system operates at 50% efficiency, it can assist the main AC of the vehicle at 2.7% with a COP of 3.4. The average S_{AC} value of 2.7% will be used in the emissions calculations to find reductions when the AAC system is used in LH_2-powered SI ICEVs.

Table 1 shows VOC, CO, NO_x, PM_{10}, $PM_{2.5}$, SO_x, and CO_2 emissions from 2005, 2015, 2025, 2035, and 2045 model years LH_2-powered SI ICEVs with and without the AAC system in the years 2010, 2020, 2030, 2040, and 2050 according to GREET software and calculations are performed by using specified equations above. The AAC system reduces the AC load of the vehicles, thus decreasing fuel consumption, hence WTP emissions of the vehicles, which are given in g/km, decrease as well as

WTW emissions of the vehicles, which are operational emissions added to WTP emissions. As seen from Table 1, all the emissions decrease by year, thanks to the enhancements in both vehicle technologies and fuel production processes according to the scenarios in GREET. The decline in emissions is particularly evident between 2010 and 2020. Emissions between 2040 and 2050 remain almost the same. But, the proposed AAC system slightly decreases all emissions of SI ICEVs powered by LH_2 fuel due to the reduction in fuel consumptions of the vehicles. If we give the WTW emissions in the year 2010 as examples, these decreases are 3×10^{-4} g/km in VOC emissions, 21×10^{-4} g/km in CO emissions, 20×10^{-4} g/km in NO_x emissions, 3×10^{-4} g/km in PM_{10} emissions, 2×10^{-4} g/km in $PM_{2.5}$ emissions, 23×10^{-4} g/km in SO_x emissions, and 1.7 g/km in CO_2 emissions.

Table 1. Emissions of LH_2-powered SI ICEVs with and without the AAC system

Year	**Vehicle**	**Emission**	**VOC [g/km]**	**CO [g/km]**	**NO_x [g/km]**	**PM_{10} [g/km]**	**$PM_{2.5}$ [g/km]**	**SO_x [g/km]**	**CO_2 [g/km]**
2010	SI ICEV - LH_2 (2005)	WTP	0.0485	0.1281	0.3541	0.0683	0.0428	0.5707	416.2
		WTW	0.0768	0.5173	0.4829	0.0686	0.0431	0.5707	415.5
		WTP_{AAC}	0.0483	0.1276	0.3527	0.0680	0.0426	0.5684	414.5
		WTW_{AAC}	0.0765	0.5152	0.4809	0.0683	0.0429	0.5684	413.8
2020	SI ICEV - LH_2 (2015)	WTP	0.0348	0.0871	0.1236	0.0137	0.0079	0.1556	295.5
		WTW	0.0494	0.4062	0.1923	0.0140	0.0082	0.1556	295.0
		WTP_{AAC}	0.0347	0.0868	0.1231	0.0136	0.0079	0.1550	294.3
		WTW_{AAC}	0.0492	0.4046	0.1915	0.0139	0.0082	0.1550	293.8
2030	SI ICEV - LH_2 (2025)	WTP	0.0269	0.0683	0.0933	0.0104	0.0060	0.1168	228.1
		WTW	0.0361	0.2329	0.1370	0.0106	0.0062	0.1168	227.9
		WTP_{AAC}	0.0268	0.0680	0.0930	0.0103	0.0060	0.1163	227.2
		WTW_{AAC}	0.0360	0.2320	0.1364	0.0106	0.0062	0.1163	227.0
2040	SI ICEV - LH_2 (2035)	WTP	0.0238	0.0609	0.0816	0.0089	0.0053	0.0983	200.5
		WTW	0.0330	0.2255	0.1252	0.0091	0.0055	0.0983	200.2
		WTP_{AAC}	0.0237	0.0607	0.0812	0.0089	0.0052	0.0979	199.7
		WTW_{AAC}	0.0329	0.2246	0.1247	0.0091	0.0054	0.0979	199.4
2050	SI ICEV - LH_2 (2045)	WTP	0.0238	0.0614	0.0816	0.0087	0.0052	0.0944	199.1
		WTW	0.0330	0.2260	0.1253	0.0089	0.0054	0.0944	198.8
		WTP_{AAC}	0.0237	0.0612	0.0813	0.0086	0.0052	0.0940	198.3
		WTW_{AAC}	0.0329	0.2251	0.1248	0.0088	0.0054	0.0940	198.0

Fig. 1 shows the reductions of WTW VOC, CO, NO_x, PM_{10}, $PM_{2.5}$, and SO_x emissions when the proposed AAC system is used in LH_2-powered vehicles for the decades between 2010 and 2050. The values are calculated for vehicles traveling 15000 km/year. Almost all types of emissions are characterized by a high drop between 2010 and 2020 as clearly seen from the figure. This reduction is particularly noticeable in NO_x, PMs, and SO_x emissions. This can be interpreted that a significant improvement in fuel production and vehicle operation technologies was made between 2010 and 2020. The reductions of emissions decrease, again, for all emission types due to the decrease in emission levels over the years. Average reduction values for the emissions are 2.8 g/year for VOC, 19.5 g/year for CO, 12.9 g/year for NO_x, 1.4 g/year for PM_{10}, 0.8 g/year for $PM_{2.5}$, and 12.6 g/year for SO_x.

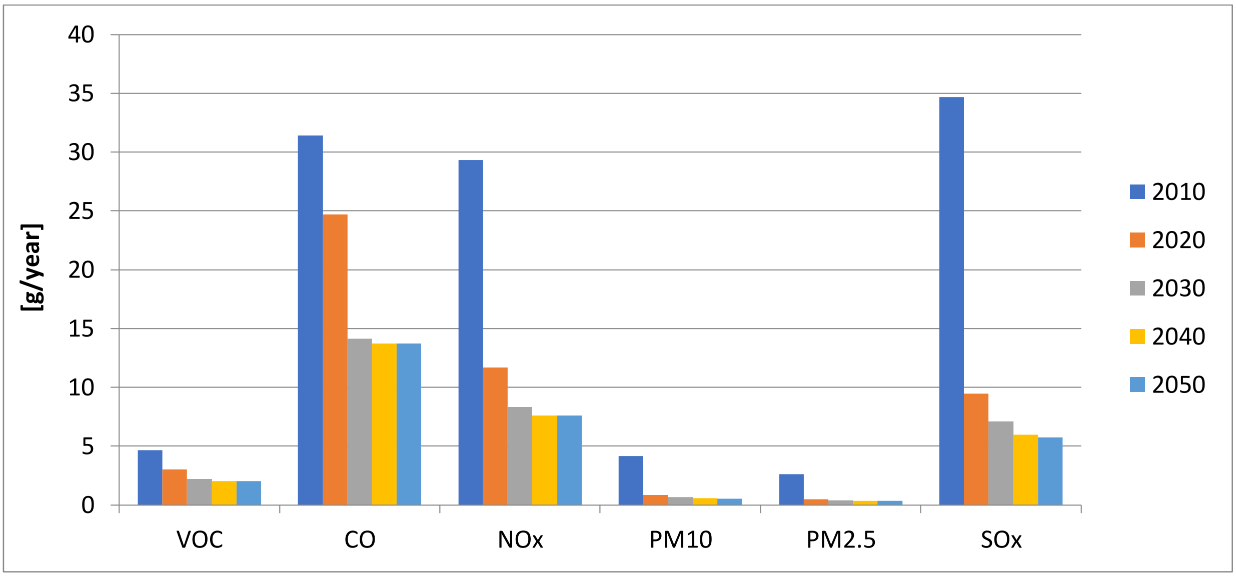

Figure 1. Reductions of emissions by years in LH_2-powered SI ICEVs with AAC

Reductions in CO_2 emissions of LH_2-powered SI ICEVs with AAC system over the years are shown in Fig. 2. Differently from the previous emission types, the reductions in CO_2 emission are given in kg/year as seen from the figure. It is assumed in the calculation that the vehicles take 15000 km/year. Using the proposed AAC system, CO_2 emissions of LH_2-powered SI ICEVs can be reduced over 16 kg/year averagely for the years between 2010 and 2050. This reduction is at the levels of 25.2 kg/year in 2010, and it decreases in every decade until 2050.

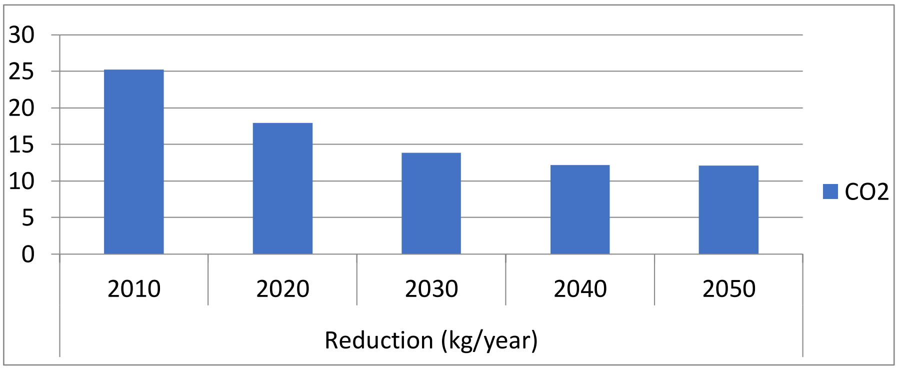

Figure 2. Reductions of CO_2 emissions by years in LH_2-powered SI ICEVs with AAC

Conclusion

In this study, an AAC system was proposed for LH_2-powered SI ICEVs, and an emission analysis was performed for the vehicles with and without the proposed system. GREET software was used in the analysis. VOC, CO, NO_x, PM_{10}, $PM_{2.5}$, SO_x, and CO_2 emissions are included for the target years of decades between 2010 and 2050 in the analysis. Both WTP and WTW values were calculated for the emissions. Therefore, it can be concluded from the study that:

- All emissions decrease due to the developments in vehicle technologies and fuel production processes from the year 2010 to 2050.

- The highest decrease in emission is between the years 2010 and 2020.

- The AAC system reduces all the emissions due to the decrease in the fuel consumption of the engine.

- The decrease in VOC, CO, NO_x, PM_{10}, $PM_{2.5}$, and SO_x emissions emitted from LH_2-powered SI ICEVs taking 15000 km/year using the AAC system is 8.3 g/year on average, which is a very low value. Average reduction in CO_2 emission, however, is over 16 kg/year.

It can be understood from the study that the proposed AAC system can be an auxiliary air conditioning system to the main air conditioning system of LH_2-powered SI ICEVs. They have acceptable cooling capacity values and COP rates. The widespread utilization of this system in LH_2-powered vehicles can lead to a further reduction in fuel consumption, emissions, and overall costs.

Competing Interests

The author declares that there is no competing interest in this study.

Authors Contributions

The author is the only writer of this study.

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