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RESEARCH ARTICLE / ARAŞTIRMA MAKALESİ

Auxiliary Air Conditioner for Vehicles Storing Liquid Hydrogen

Sıvı Hidrojenli Taşıtlar İçin Yardımcı Bir Klima Sistemi

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Abstract

Current Vehicle Air Conditioning (VAC) systems, which are operated by compressors driven by Internal Combustion Engines (ICEs) or batteries, increase the fuel consumption and emissions depending on the thermal load of the vehicle passenger cabin. Since decreasing the thermal load of the vehicle will decrease the fuel consumption and emissions, studies in this area is very important from the economic and environmental aspects. In this study, an Auxiliary Air Conditioning (AAC) system for Internal Combustion Engine Vehicles (ICEVs) or Fuel Cell Vehicles (FCVs) that store Liquid Hydrogen (LH_2) as a powering source has been proposed to make contribution to the works in this significant area. ICEVs were evaluated as Gasoline Equivalent Hydrogen Internal Combustion Engine Vehicles (GEHICEVs) and Diesel Equivalent Hydrogen Internal Combustion Engine Vehicles (DEHICEVs) considering their average fuel consumption rates according to the New European Driving Cycle (NEDC). According to the analyses, approximate hydrogen consumption values have been found that reach 0.7 g/s for GEHICEVs, 1.6 g/s for DEHICEVs, and 0.6 g/s for FCVs with maximum cooling rates of 326 W, 704 W, and 250 W, respectively.

Keywords: Liquid hydrogen, air conditioning, internal combustion engines, fuel cell vehicles.

Öz

İçten yanmalı motor veya batarya ile hareket ettirilen bir kompresör ile çalışan günümüz taşıt klimaları, taşıt yolcu kabininin ısıl yüküne bağlı olarak yakıt tüketimini ve emisyonları artırmaktadır. Kabin ısıl yükünün düşürülmesi yakıt tüketimi ve emisyonları azaltacağı için, bu alandaki çalışmalar ekonomik ve çevresel yönden çok önemlidir. Bu çalışmada, içten yanmalı motor veya yakıt hücresinde yakıt olarak sıvı hidrojen kullanan taşıtlar için yardımcı bir klima sistemi önerilmektedir. İçten yanmalı motoru olan taşıtlar, benzin (GEHICEV) ve dizele (DEHICEV) eşdeğer hidrojen yakıtlı taşıtlar olmak üzere ikiye ayrılmakta ve bu taşıtların yakıt tüketimleri Avrupa Yeni Sürüş Çevrimi'ne (NEDC) göre hesaplanmaktadır. Analizlere göre; GEHICEV, DEHICEV ve yakıt hücreli taşıtlarda (FCV) yaklaşık hidrojen tüketim değerlerinin sırasıyla 0.7-1.6-0.6 g/s olduğu ve değerlere göre yapılabilecek en yüksek soğutma değerlerinin yine sırasıyla 326-704-250 W olarak ortaya çıktığı bulunmuştur.

Anahtar Kelimeler: Sıvı hidrojen, klima, içten yanmalı motorlar, yakıt hücreli taşıtlar.

1. INTRODUCTION

Since fossil fuel sources are depleting rapidly and the enormous environmental effects of their utilization can no longer be ignored, there have been many advances in alternative fuel technology in recent years [1-3]. Being one of the alternative fuels to create clean and environment friendly future with energy-efficient and low-polluting nature, hydrogen is increasingly studied as a potential candidate to replace these fossil fuels. One of the areas that fossil fuels are being used is vehicles, which mainly benefit from internal combustion engines to convert the chemical energy of these fuels into wheel movement. Hydrogen vehicles, on the other hand, have become increasingly popular since the first hydrogen-powered fuel cell vehicle launched, and being right beside FCVs, some ICEVs with hydrogen can also be seen on the market. When hydrogen is used in a fuel cell to generate electricity or is combusted with air, the only products are water and a small amount of Nitrogen Oxides (NO_x) [4-6]. The high energy density and absence of carbon is the main advantages of the hydrogen. But, problems

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such as cost of production, storage issues, hydrogen embrittlement, and percolation through the tank and the fuel line are the main drawbacks of the hydrogen usage in vehicles [7]. Though most hydrogen vehicles store hydrogen in gaseous form in their tanks like Ford Zetec 2.0 L [8, 9] and Toyota Mirai FCV, some examples like first GM FCV Electro Van (1966), GM HydroGen3, BMW Mini Hydrogen and BMW 750hl [10-12] use liquid hydrogen as a fuel, which is stored in vacuumed cryogenic tanks [13, 14]. Liquefaction of hydrogen is one of the best ways to store hydrogen [15], thus LH_2 constitutes a promising part of hydrogen applications [16]. LH_2 is presently used for some other areas such as space applications and the semiconductor industry. Gasification of LH_2 in those applications results in waste energy that can be used for refrigeration purposes with auxiliary equipments at small costs. This study deals with one of the areas where this applies: VAC systems.

Considering the safety and comfort functions, an AC system is one of the essential subsystems of vehicles. But, fuel consumption of vehicles increases due to the mechanical compressor of the AC system that uses a significant power. This increase can reach to the values of 12-17% according to indeterminate conditions such as road factors, environmental factors and driver factors for subcompact to mid-size cars [17-18]. In a study, it is maintained that air conditioning usage can increase the vehicle fuel consumption by 20% on average [19]. Farrington et al. [20] reported that the driving range of an electric vehicle decreases by nearly 40% due to the use of AC system. Welstand et al. [21] investigated the effects of AC system on vehicle exhaust emissions and fuel consumption variations, and they found out a high correlation among them. For these reasons, reducing the energy consumption of the VAC systems will help to improve overall energy efficiency and environment friendly state of vehicles [22-24]. Many systems and methods have been proposed to improve energy efficiency of VAC systems so far. A few of these systems and methods include: alternative systems to the conventional vapor compression cycles [25-31], new designs of compressors [32-34], and evaporators [35], alternative driving sources to the engine of the vehicle [36], additional functionalities like calculating skin temperatures of the vehicle passengers by an infrared sensor [37] and some control methods such as PID [38, 39], rule based [40], and fuzzy [41-45]. Linder and Kulenovic [46] proposed a prototype of a hydrogen open sorption system to decrease the cooling load of air-conditioning systems. They experimentally investigated the system on a laboratory circumstances using metal hydrides. They derived the energy source of the system from a compressed hydrogen storage tank, which is used in hydrogen powered vehicles. Not wasting the compression of hydrogen and using it for additional cooling purpose, the proposed system could increase the overall energy efficiency of hydrogen powered vehicles. In their system, supply pressure of the hydrogen was 53 bar and they reach a cooling power of about 900 W. Pino et al. [47] analyzed the behavior of an FCV on AC usage in terms of hydrogen consumption under standard urban and highway driving cycles at extreme and smooth ambient conditions and different passenger loads. They found the increase of hydrogen consumption as varying value of between 3-12.1% when the air conditioning system of the FCV is on. The nominal capacity and COP of their system were 3 kW and 3, respectively. They also found out that the most effective parameters of the hydrogen consumption increment are: number of passengers and weather conditions. Thus, it can be concluded that the VAC systems are crucial systems [48] in vehicles to develop both efficient and environmental friendly vehicles, having internal combustion engines, fuel cells, or batteries. On the other hand, there are limited studies on cryogenic fluids (including hydrogen, helium, nitrogen, oxygen, and air) and their usage to generate cooling by researchers. For instance, Liquid Natural Gas (LNG) was used to provide cooling during its gasification process in an open Rankine power cycle in some studies [49-54]. Deng et al. [50] reports that providing only cooling or only power is not an efficient way to wholly extract the stored energy of the LNG. Therefore, it requires a combined system to provide both cooling and powering ability of LNG at a maximum degree. In some other studies [55, 56], Liquid Nitrogen (LN_2) was investigated as a cryogenic fluid to provide cooling in refrigerators. Dakhil [57] used LN_2 by spraying it in a cooling space to generate cooling in a refrigerator system. LN_2 was also evaporated using the ambient temperature and low heat source and then expanded to generate power in an open Rankine cycle in some studies [58-62]. The reported literature indicates that there is a need to investigate combined cooling and power systems to extract more energy from cryogenic fluids, and to see the feasibility of using these systems to meet economical and environmental concerns.

In the present paper, the use of LH_2 to provide both cooling for air conditioning and power for wheel movement in vehicles has been theoretically investigated, where several thermodynamic equations and calculations apply in terms of the consumption, cooling, COP, and AC saving. The analyses were conducted for vehicles in two groups: GEHICEV and DEHICEV as ICEVs and FCVs, mainly depending on their fuel consumption and latent heat of evaporating hydrogen. Parking analysis was also performed for vehicles. Proposing an auxiliary air conditioner, it is aimed at the study that LH_2 can be feasibly used in ICEVs and FCVs as the main power source together with the supplementary refrigerant at the same time. Therefore, fuel economy and environmental friendly operation will be improved in LH_2 powered vehicles.

2. LIQUID HYDROGEN AS A FUEL FOR VEHICLES

2.1. Liquid Hydrogen

Having an element number of one, hydrogen is located at the top left of the periodic table. It is abundant in nature as in many natural compounds. It is lighter than air when present in gaseous form. It rises and dissipates without toxic effects if released to the air. Hydrogen is currently used for commercial purposes in petroleum refining, glass purification, semiconductor manufacturing, aerospace applications, fertilizer production, welding, annealing and heat-treating metals, pharmaceuticals, hydrogenation of unsaturated fatty acids in vegetable oil, food production, electric generation, and in the petrochemical industry to reformulate fuels. Electrolysis of water (H_2O) and steam reformation of natural gas (CH_4) are the main typically separation methods of hydrogen from other elements to form pure hydrogen. With hydrogen, we can produce power without harmful air emissions in burners or fuel cells. Hydrogen can be stored physically in gaseous form like conventional fuels, such as propane and natural gas or liquid form in cryogenic tanks [63]. Since the energy density by weight of hydrogen is too large to be compared with the energy density by volume, which are 120 MJ/kg and 10.05 MJ/m^3, respectively, liquefaction of hydrogen is one of the best ways to store hydrogen [64-67]. Table 1 shows this and some other prominent properties of hydrogen. Some remarking properties of hydrogen are its low heating value by volume but high heating value by mass, high heat of vaporization, ultralow boiling point, extra-large flammability limits in air, zero carbon rate, and high octane number. It is important that these properties must be taken into account in the design of hydrogen fuel systems in ICEVs or FCVs.

Table 1. Properties of hydrogen/liquid hydrogen [68-70]

Property	**H_2/LH_2**
Molecular weight (kg/kmol)	2.016
Lower heating value (MJ/m^3)	10.05
Lower heating value (MJ/kg)	120
Higher heating value (MJ/kg)	142
Heat of vaporization (kJ/kg at 1atm)	446
Liquid density (kg/m^3 at 283 K)	71
Boiling point (K at 1 atm)	20.27
Freezing point (K)	14.40
Specific heat (kJ/kg K)	9.69
Diffusion velocity in air (m/s)	≤2.00
Flammability limits in air (% by volume)	4.0-75.0
Buoyant velocity in air (m/s)	1.2-9
Minimum ignition energy in air (mJ)	0.02
Burning velocity in air (cm/s)	265-325
Flame temperature in air (K)	2318
Thermal energy radiated to surroundings (%)	17-25
C/H ratio	0
Octane number	130

In the past years, the demand of liquid hydrogen has constantly increased in some prominent areas. For instance, as an alternative to kerosene, liquid hydrogen is used for rocket propulsion systems in space applications [71] and for unmanned aeronautic vehicles [72]. Another area is the semiconductor industry [73]. There is no need for liquid hydrogen in this area, but a minimum 99.999 mol.% extremely high purities are required, and this is achieved by a temperature close to liquid hydrogen temperature in pre-purification at ambient conditions and fine purifications at cryogenic conditions. There are also some studies on LH_2 as an alternative fuel for air transportation [68, 74-76]. Another area that liquid hydrogen is used is clean energy vehicles such as hydrogen cars, hydrogen buses, and hydrogen forklifts [77]. Although some brands like GM/Opel have introduced the feasibility of LH_2 as a fuel in vehicles since 1960s [10], a rather excessive increase in demand are not encountered in this area, however, due to the reduction policies in carbon free vehicle emissions, a probable increasing demand can be expected in the near future. Liquid hydrogen will play a major role in this development with the help of cost reducing large scale liquefaction plants and efficient transport of this energy through great distances, or on site production solutions [78].

2.2. Internal Combustion Engine Vehicles

There are mainly two types of internal combustion engines: Spark Ignition (SI) and Compression Ignition (CI). Spark ignition engines operate according to Otto cycle consuming gasoline fuel, while compression ignition engines operate according to Diesel cycle consuming diesel fuel. There are some basic differences between Otto and Diesel cycles. These differences are specified in Table 2 [62, 70, 77, 79]. SI engines take air and fuel mixture in intake stroke, compress it in the ratios of about 1/7-1/14, and ignite this compressed mixture by spark plugs. They are mostly used for speed purposes as nearly every racing cars have engines that operates according to Otto cycle. On the other hand, CI engines take only air in intake stroke, compress it in the ratios of about 1/14-1/24 that is higher than SI engines have, and start combustion with this highly compressed air by injecting fuel. They are mostly used for torque purposes as nearly every heavy duty vehicles have engines that operates according to Diesel cycle. In other respects, initial and maintenance costs of gasoline engines are lower than equivalent diesel engines, but it is vice versa for fuel consumption rates.

Table 2. Main differences of Otto and Diesel cycles [62, 70, 77, 79]

	Otto cycle	Diesel cycle
Fuel	Gasoline	Diesel
Intake stroke	Air + fuel mixture	Only air
Compression rate	1/7 – 1/14	1/14 – 1/24
Energy efficiency	Lower	Higher
Ignition	By spark plugs	By fuel injection
General purpose	Speed	Torque
Equivalent energy efficiency	Lower	Higher
Equivalent weight	Lower	Higher
Equivalent cost & maintenance	Lower	Higher
Equivalent fuel consumption	Higher	Lower
Equivalent noise level	Lower	Higher

In internal combustion engines, not only gasoline or diesel is burned; but fuels such as Liquid Petroleum Gas (LPG), Compressed Natural Gas (CNG), ethanol, methanol, biodiesel or hydrogen may also be used. In the case of flexible fuel engines, it is possible to use two or more fuel mixtures. Engines that utilize fuel blends such as gasoline-ethanol, gasoline-methanol, or diesel-biodiesel are examples of flexible fuel engine. Many vehicles in the market today are able to work with similar fuel mixtures without the need for any modifications. Table 3 shows which fuels are burned by which fuel systems in what types of engines [69, 77, 79]. As seen from the table, hydrogen can be used in both SI and CI engines and in Fuel Cell (FC) systems in mono or bi-fuel form fuel systems [79].

Table 3. Appropriate fuels for engine types and fuel systems [69, 77, 79]

Fuel	Engine type	Fuel system
Gasoline	SI	mono
Diesel	CI	mono
LPG	SI	mono, bi-fuel
CNG	CI, SI	mono, bi-fuel
Hydrogen	SI, CI, FC	mono, bi-fuel
Ethanol	SI, CI, FC	mono, ff
Methanol	SI, CI, FC	mono, ff
Biodiesel	CI	mono, ff
mono : only one fuel is used		
bi-fuel : more than one fuel is used without mixing		
ff : more than one fuel is used with mixing		

Table 4 shows a comparison of gasoline, diesel and hydrogen in some items [1, 69, 77, 79]. Since hydrogen does not include any carbon content as gasoline and diesel fuels do, hydrogen powered engines do not give main ICE emissions such as Carbon Monoxide (CO) or Hydrocarbon (HC) [80-81]. Referring to Table 4, hydrogen has a high auto-ignition temperature when compared to gasoline and diesel fuels. Auto-ignition temperature is an important parameter for ICEs that it specifies the compression ratio of the engine, since if the auto-ignition temperature of the fuel is low, it may cause pre-ignition problems during compression process that rises the temperature of the combustion chamber before the spark plugs ignite the compressed air/fuel mixture. With its high auto-ignition temperature, compression ratios of hydrogen powered ICEs can be set to high values without any pre-ignition problems such as engine knocking, overheating, and mechanical damages in this context. Ignition range in percent by volume in air is the flammability proportion of a combustible fuel in air. Between these limits, the fuel/air mixture is flammable. It is seen from Table 4 that the ignition range of hydrogen in air is between about 4–74% which means that hydrogen has a wide range of flammability compared to gasoline and diesel fuels. This is a good property of hydrogen in terms of a high range of lean-rich mixtures can be maintained, however, it also causes undesirable results such as misfiring and backfiring. Proper designs of spark plugs, optimized designs of engine cooling passages to avoid hot spots, special hydrogen injection systems, optimizations of air-fuel charging strategies, and variable valve timings for effective exhaust discharging are some of precaution methods to avoid misfiring and backfiring problems in hydrogen powered ICEs [79]. On the other hand, hydrogen has an approximately 3 times more energy content per weight than gasoline and diesel fuel. This property is important to extent the driving period of vehicle without refueling. Therefore, when hydrogen is utilized in liquid form, the cruising time of vehicles can be considerably improved. If we briefly summarize the main properties of hydrogen when it is used as a fuel in ICEs, advantageously, it has a zero carbon rate, a higher auto-ignition temperature, and a higher heating value by mass. Disadvantageously, on the other hand, it has a large ignition range in air according to the table.

Table 4. Properties of gasoline, diesel and hydrogen [1, 69, 77, 79]

Property	Gasoline	Diesel	Hydrogen
Chemical formula	C_8H_{18}	$C_{12}H_{23}$	H_2
Molecular weight (kg/kmol)	114	167	2
Carbon rate (% by mass)	84	86	0
Hydrogen rate (% by mass)	16	14	100
Oxygen rate (% by mass)	0	0	0
Heat of vaporization (kJ/kg)	350	270	446
Specific heat (kJ/kg K)	2.4	2.2	9.69
Auto-ignition temperature (°C)	280	210	565

Higher heating value (kJ/kg)	47.3	46.1	141.8
Lower heating value (kJ/kg)	44.0	42.8	120.0
Burning velocity in air (cm/s)	37.43	30	265-325
Octane number	92-98	30	130
Flammability limits in air (% by volume)	1.4-7.6	0.7-5.0	4.0-75.0
Liquid density (kg/m^3 at 283 K)	737	856	71

2.3. Fuel Cell Vehicles

Hydrogen flows from the tank to the combustion chambers to be burned with air generating power in hydrogen powered internal combustion engines. A similar flow is encountered in state of the art fuel cell vehicles. Differently in fuel cell vehicles hydrogen is used to generate electricity [82]. The fuel cell vehicles are electric vehicles that utilize hydrogen in fuel cell units to generate electricity onboard of the vehicle, eliminating the need for heavy batteries and long periods of recharging times. As soon as Zero Emission Vehicle (ZEV) mandates begin in the near future, FCVs are expected to be commercially released in bulks by automotive companies for public and fleet use. The main obstacles encountered in FCVs are their higher costs, shorter life span, hydrogen cost and availability. Fuel cell technology has a potential of the highest efficiency and the lowest emissions among vehicle energy sources, if the hydrogen is produced from the right energy source with the right method [83].

Fuel cell unit converts hydrogen energy into electrical energy by electrochemical principle. This operation is not a process of combustion. Hydrogen is combined in a fuel cell by a chemical reaction with oxygen from the air. As a result of this reaction, the electric energy to be used for the mechanical movement of the vehicle is obtained. Only water vapor is emitted through the fuel cell unit as the end product of the reaction. With different types of batteries and electrolytes, there are several types of fuel cells available in the market, where the Proton Exchange Membrane (PEM) fuel cell units are the most commonly used [84].

2.4. Vehicle Air Conditioners

VAC systems regulate temperature, humidity, air quality, and air flow of vehicle cabins for occupants. The vapor compression cycle is still dominant in VAC systems. The power source of this system is a compressor, which is driven mechanically by the engine of the vehicle in ICEVs or electrically by the battery of the vehicle in FCVs. When the system is turned on, the compressor causes an increase in the load of the engine. The engine has to increase the fuel consumption to meet this load. The compressor is the heart of the system. It pumps the refrigerant through the system, also heating up the refrigerant at the same time. This warming period of the refrigerant is a required process so as to establish a big temperature difference with outside and discharge more heat to the environment by the condenser of the VAC system. The refrigerant gets into the condenser in gas phase and leaves it in liquid phase. Then the liquid refrigerant is directed to the expansion valve through a group of valves, switches, and fluid reservoirs for controlling the flow. The main purpose of using an expansion valve in VAC systems is to decrease the pressure of the refrigerant to prepare it for evaporation. The refrigerant is sent to the evaporator device in spray form from the expansion valve unit. This vaporization process, which is a heat drawing process, causes the air to cool down. Pressure decrease of the refrigerant leads to the decrease of the evaporation temperature of the refrigerant. Therefore, the refrigerant will be easily vaporized by the air, which can be totally fresh air taken from the outside or return air taken from the vehicle cabin, or mixture of both, and thereby cooling of the vehicle interior cabin can be maintained. After the refrigerant is vaporized by the air, the cycle is completed, and then the refrigerant goes to the compressor again starting a new course. Actually, it is difficult to use hydrogen as a refrigerant in these AC systems with its ultralow critical temperature, but, since hydrogen has good refrigerant properties such as low boiling temperature and high latent heat, it can be used as refrigerant in addition to their main purpose in the systems that store liquid hydrogen and use it in gaseous form. An evaporator and air blower unit may be added to these systems to get the cooling ability of hydrogen.

As briefly discussed above, refrigerants circulate through the pipes between the equipments of AC systems in a closed loop. For doing their job in the best possible way, ideal refrigerants should have some properties such as low boiling point, high latent heat of vaporization, and high critical temperature. In addition to these required properties, ideal refrigerants also should not have some undesirable characteristics like being corrosive, toxic, explosive, and flammable. In the past, R11 (Trichlorofluoromethane), R12 (Dichlorodifluoromethane), and R22 (Chlorodifluoromethane) were generally used as refrigerants in VAC systems. They are no longer in use due to their high Ozone Depletion Potential (ODP) and Global Warming Potential (GWP) values. R134a (1,1,1,2-Tetrafluoroethane) has been replacing the previous ones for a while, and is the dominant refrigerant in VAC systems today [48]. But, R1234yf (2,3,3,3-tetrafluoro-1-propene) and R744 (Carbon dioxide) are currently started to be used as new VAC refrigerants in most countries [18, 85, 86] due to their lower GWP potentials. In Table 5, together with new refrigerants, mostly used VAC system refrigerants are compared to hydrogen which is the very topic of this study. Although the extremely low critical temperature

Table 5. Comparison of hydrogen with some refrigerants [88-95]

Refrigerant	R11	R12	R22	R134a	R744	R1234yf	R702
Common name	Trichlorofluoromethane	Dichlorodifluoromethane	Chlorodifluoromethane	1,1,1,2-Tetrafluoroethane	Carbon dioxide	2,3,3,3-tetrafluoropropene	Hydrogen
Chemical formula	CCl_3F	CCl_2F_2	$CHClF_2$	$CH_2FC\ F_3$	CO_2	$C_3H_2F_4$	H_2
Refrigerant class	CFC	CFC	HCFC	HFC	Natural	HFO	Natural
Molecular mass (g/mol)	137.37	120.91	86.47	102.03	44.01	114	2.016
Density (kg/L)	1.47	1.34	1.21	1.22	0.298	1.094	0.0707
Vapor density (kg/m^3)	4.8	4.2	3	3.5	1.977	5.98	0.0898
Boiling point (°C)	-23.8	-29.8	-40.8	-26.1	-78.4	-29.45	-252.8
Critical point (°C)	198	111.8	96.2	101.08	31.06	94.7	-239.95
Critical pressure (bar)	44.1	41.1	49.9	40.6	73.84	33.8	1300
ODP	1	1	0.07	0	0	0	0
GWP (100 years)	3400	8500	1700	1300	1	4	5.8
Latent heat of vaporization at 1 atm (kj/kg)	227.3	165.24	233.75	216.87	230.5	180.1	445.7
Life in the atmosphere (years)	45	130	15	16	29.3k-36.1k	0.030116	-
Flammability	A1 (No)	A1 (No)	A1 (No)	A1 (No)	A1 (No)	A2L (Low)	A3 (High)

(−239.95 °C) of hydrogen makes it not appropriate for normal refrigeration cycle [87], it can be used in some other system designs for refrigerating purposes, thus it is compared to the conventional and new refrigerants.

Regarding the information given in Table 5, main advantages and disadvantages of hydrogen as a refrigerant can be specified briefly as in the following:

+ Hydrogen has a lower boiling point, which provides easily evaporation of a liquid refrigerant in the evaporator that is exposed to the temperature of the blown air at the outside surface. If the boiling temperature of the refrigerant is higher than the air temperature, no boiling of the refrigerant takes place, no heat is absorbed from the air, and air cannot be cooled down.

+ Hydrogen has a higher latent heat of vaporization, which ensures higher heat absorption from the air with a lower hydrogen amount during the evaporation process. If the latent heat of vaporization is low, too much refrigerant should be circulated through the system to perform adequate cooling.

+ Hydrogen has a lower ODP and GWP, which effect environment badly. These numbers of a refrigerant should be very low or preferably zero, so that utilization of that refrigerant could not harm the environment.

- Hydrogen has a lower critical temperature, which means it easily exceeds its critical temperature. This results that it cannot be liquefied in the condenser and cannot throw away the heat that it absorbs from the air. This negative property of hydrogen prevents it to be used in conventional cooling devices.

- Hydrogen has a lower vapor density, which causes the vapor to occupy a maximum volume at the outlet of the evaporator coil, and thus pipeline diameter and compressor size cannot be kept small and compact.

- Hydrogen has a higher flammability, which causes fire hazards in some dangerous circumstances.

- Hydrogen is readily available in nature, but it is expensive to produce it in today's technology.

Researchers work on more efficient and environmental friendly AC systems, and thus they propose not only alternative refrigerants or refrigerant blends but also new systems, new equipments, controlling algorithms, insulation materials, insulation strategies, auxiliary systems, and so on. With its good refrigerating properties, hydrogen may be evaluated as a refrigerant in some special systems that store liquid hydrogen. Therefore, refrigerating capability of hydrogen may not be wasted in vain, which is an important phenomenon today as the costs and emissions of energy have been gaining importance each passing day.

3. METHODOLOGY

3.1. Description of the VAAC system

The proposed VAAC system aims to use the latent heat energy of LH_2 to provide for cooling while gasified hydrogen produces power or electricity in ICEVs or FCVs, respectively. As the layout of the system is shown in Fig. 1, the system consists of two main circuits: hydrogen and air. While the hydrogen circuit maintains hydrogen for internal combustion engine or fuel cell unit of the vehicle, the air circuit supplies additional cooling capacity for the vehicle cabin. Cooling down of the air is provided by the gasification of the hydrogen passing through the evaporator of the system and decreases the cooling load of the vehicle, which is the most significant additional load in today's vehicles; its energy consumption even outweighs the energy loss to rolling and aerodynamic resistances, or power train losses for typical vehicles [96]. Therefore, the more hydrogen is supplied to the powering of the vehicle, the more cooled-down air is supplied to the cooling of the vehicle cabin. Hydrogen is stored in the cryogenic tank in liquid form under pressure. Vehicle power generator needs hydrogen in gaseous form at atmospheric pressure. A pressure regulation valve decreases the pressure of the hydrogen. An evaporation process follows this pressure decrease. Hydrogen is evaporated by the air blown along the outer surface of the evaporator. This cooled-down air is sent to the vehicle compartment to decrease the AC cooling load, which depends on the environmental factors such as: the sun, outside temperature and humidity, number of passengers, etc. There is a similar scheme in parking vehicles that has no need to hydrogen for power production but needs an amount of hydrogen leakage according to the environmental circumstances for safety reasons. This required amount of hydrogen to be delivered from the tank is sent to the atmosphere through the evaporator unit cooling down the air. This air will decrease the AC load of the vehicle when parking; even it is at a slight amount. FCVs can also generate power using this small amount of hydrogen at the time of parking, establishing cooling of the cabin at the same time.

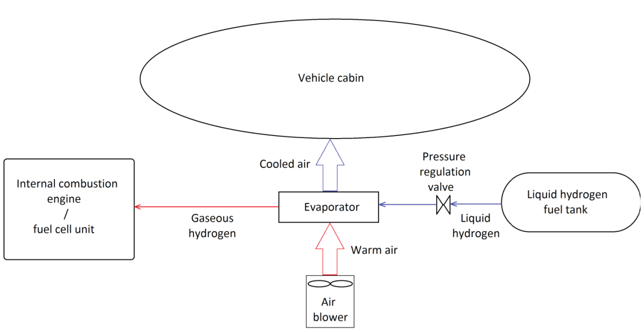

Figure 1. Layout of the auxiliary air conditioning system for vehicles storing liquid hydrogen

3.2. GEHICEV Analysis

Analyses of GEHICEVs have been conducted according to Eqs. (1-6). Eq. (1) shows the calculation of the average gasoline consumption (l/s) of a Gasoline Internal Combustion Engine Vehicle (GICEV). FC_g (l/100 km), which is declared by the manufacturer of the GICEV, is determined according to the NEDC. This cycle lasts 1180 s and the vehicle covers a road of 11,007 km during the cycle [97-98]. In this study, analyses of GEHICEVs have been conducted using FC_g values between 0 and 30 l/100 km as to be consisted to vehicles on the market. Therefore, the calculation of $\dot{v}_g$ at different conditions can be performed, and an easy comparison of GICEVs and GEHICEVs can be established through the analysis.

$$\dot{v}_g = \frac{\frac{FC_g \times 11{,}007}{100}}{1180} \quad (1)$$

The average gasoline consumption in mass flow rate ($\dot{m}_g$) is calculated as seen from Eq. (2) using ρ_g, which is the average density of gasoline taken from the literature [93] which specifies between 0.72-0.78 kg/l.

$$\dot{m}_g = \dot{v}_g \times \rho_g \quad (2)$$

Approximate hydrogen consumption of the vehicle in mass flow rate ($\dot{m}_{h,GEHICEV}$) is calculated using the equivalent heating value rate of gasoline and hydrogen ($r_{HV,h/g}$) as seen in Eq. (3). Arithmetic means of lower and higher heating values for gasoline and hydrogen were used in this equivalent rate. Lower and higher heating values for gasoline and hydrogen are 44,000 kJ/kg, 47,300 kJ/kg, 120,000 kJ/kg, and 141,800 kJ/kg, respectively [93]. Since heating values of hydrogen is higher than that of gasoline, the required amount of hydrogen mass flow rate is found to be approximately 0.3488 times lower than mass flow rate of gasoline, which is also comparable to the works encountered in the literature [11, 69, 99].

$$\dot{m}_{h,GEHICEV} = \dot{m}_g \times r_{HV,h/g} \quad (3)$$

Calculation of the cooling capacity to be maintained from the gasification of liquid hydrogen is given in Eq. (4). In this formula, $\dot{Q}_c$ shows the cooling amount (W) that the system takes from the air to be sent to the vehicle cabin, $\dot{m}_{h,GEHICEV}$ 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 J/kg from the literature [93].

$$\dot{Q}_{c,GEHICEV} = \dot{m}_{h,GEHICEV} \times h_{fg,h} \quad (4)$$

AC savings (%) of the VAAC system on vehicles at various cooling loads are calculated through Eq. (5). S_{AC} is the percent saving, $\dot{Q}_{c,GEHICEV}$ is cooling capacity of the system (W), and L_c is the cooling load of the vehicle (W). L_c values are chosen according to the literature [100], which reports that average cooling load values for subcompact, compact, and standard automobiles are 3,62 kW, 4,15 kW, and 5,12 kW, respectively. As L_c of vehicles constantly takes different values according to the weather conditions, size of the vehicles, and number of the occupants, 1000 W, 2000 W, 3000 W, 4000 W, 5000 W, and 6000 W values were chosen for the determination of the AC savings at different conditions. These values are compatible with the works of Meier et al. [82] and Fayazbakhsh and Bahrami [96] also.

$$S_{AC,GEHICEV} = \frac{Q_{c,GEHICEV}}{L_c} \quad (5)$$

Last part of the GEHICEV analysis constitutes COP calculation of the VAAC system as shown in Eq. (6). $COP_{R,GEHICEV}$ is the performance measurement of the VAAC system that is an air conditioning system. The COP calculation of the VAAC system has been performed regarding Peltier effect thermoelectric coolers. Unlike conventional air conditioners and refrigerators, there is no compressor in thermoelectric coolers. Similarly the VAAC system proposed in this work does not have any compressor, because the liquid hydrogen in the tank is pressurized. And if the pressure becomes insufficient for the flow, the tank is refilled with hydrogen in fuel stations. The operating costs of the engine that consumes hydrogen are not included in energy consumption of the VAAC. The only energy consumed by the VAAC system creating cooling effect is fan power (P_f) required to circulate the air through the hydrogen evaporator. The fan used in the calculations of the VAAC system is selected as a standard one working at three positions. The energy amounts of the fan which draws from the battery are 24 W, 48 W, and 72 W, respectively for the three positions. These constant electric fan powers were chosen accordingly that they are widely used in literature and suitable for the proposed VAAC system [101]

$$COP_{R,GEHICEV} = \frac{Q_c}{P_f} \quad (6)$$

3.3. DEHICEV Analysis

Analyses of DEHICEVs have been conducted similar to GEHICEV analysis as seen Eqs. (7-12). Differently in Eq. (7), FC_d values between 0 and 60 l/100 km were chosen for the calculations regarding both automobiles and heavy vehicles appear on the market. ρ_d in Eq. (8), which is the average density of diesel fuel, was taken from the literature [93] as between 0.78-0.88 kg/L. The equivalent heating value rate of diesel and hydrogen ($r_{HV,h/d}$) in Eq. (9) was calculated using the arithmetic means of lower and higher heating values for diesel and hydrogen with the values of 42,800 kJ/kg, 46,100 kJ/kg, 120,000 kJ/kg, and 141,800 kJ/kg, respectively [93]. The required amount of hydrogen mass flow rate is found to be approximately 0.3394 times lower than mass flow rate of diesel. Calculations of the cooling capacity, AC savings, and COP have similar formulas with GEHICEV analysis.

$$\dot{v}_d = \frac{\frac{FC_d \times 11{,}007}{100}}{1180} \quad (7)$$

$$\dot{m}_d = \dot{v}_d \times \rho_d \quad (8)$$

$$\dot{m}_{h,DEHICEV} = \dot{m}_d \times r_{HV,h/d} \quad (9)$$

$$\dot{Q}_{c,DEHICEV} = \dot{m}_{h,DEHICEV} \times h_{fg,h} \quad (10)$$

$$S_{AC,DEHICEV} = \frac{Q_{c,DEHICEV}}{L_c} \quad (11)$$

$$COP_{R,DEHICEV} = \frac{Q_{c,DEHICEV}}{P_f} \quad (12)$$

3.4. FCV Analysis

In FCV analysis, although the calculation of the cooling capacity, AC savings, and COP have the same formulas with the previous GEHICEV and DEHICEV analyses, some differences are encountered in the calculation of the $\dot{m}_{h,FCV}$. Fuel consumption of commercial FCVs is generally given as kg H_2/100 km. Eq. (13) shows the calculation of the average hydrogen consumption (kg/s) of an FCV. $\dot{m}_{h,FCV,NEDC}$ (kg/100 km), which is declared by the manufacturer of the FCV, is determined according to the NEDC. The analyses of FCVs have been conducted using $\dot{m}_{h,FCV,NEDC}$ values between 0 and 6 kg/100 km as to be easily comparable to vehicles on the market. Today's commercially available FCVs like Toyota Mirai, Honda Clarity Fuel Cell, Hyundai Nexo etc. have an average hydrogen consumption, which is calculated using the hydrogen tank capacity and total range in NEDC with full capacity of the tank, of 1 kg/100 km is also compatible with the literature [82]. Therefore, $\dot{m}_{h,FCV,NEDC}$ values between 0 and 6 kg/100 km are suitable for a great variety of vehicles in a wide range of driving conditions.

$$\dot{m}_{h,FCV} = \frac{\frac{m_{h,FCV,NEDC} \times 11{,}007}{100}}{1180} \quad (13)$$

$$\dot{Q}_{c,FCV} = \dot{m}_{h,FCV} \times h_{fg,h} \quad (14)$$

$$S_{AC,FCV} = \frac{Q_{c,FCV}}{L_c} \quad (15)$$

$$COP_{R,FCV} = \frac{Q_{c,FCV}}{P_f} \quad 16)$$

3.5. Parking Analysis of All Types of Vehicles Storing Liquid Hydrogen

Since it has a very low evaporating temperature, liquid hydrogen can only be stored in special tanks in special circumstances. When hydrogen consumption of a vehicle stops, hydrogen pressure in the tank increases in time depending on to the environmental conditions. The hydrogen in the tank should be discharged in a required amount so as not to damage the tank due to the increasing pressure of evaporating hydrogen [10]. So, in this part of the study, cooling effect of this amount of hydrogen has been analyzed for parking vehicles. Eq. (17) shows the calculation of cooling capacity of hydrogen venting out from the tank through the evaporator. Here, c_v is the venting coefficient of the tank according to outside conditions (temperature, capacity, fullness etc.). For c_v, values between 0 and 3 have been taken for the analysis. $\dot{m}_{h,PV}$ is the average venting flow rate of the hydrogen when the vehicle is parking. A constant value of 16 g/h has been taken for $\dot{m}_{h,PV}$ in the parking analysis, which is compatible with the literature [10, 64]. Therefore, venting fluctuations of the hydrogen have been established by just the c_v coefficient. As to the COP of the VAAC system when the ICE/FC is not working, it depends on the cooling capacity ($\dot{Q}_{c,PV}$) and the fan power (P_f) as given in Eq. (18).

$$\dot{Q}_{c,P} = c_v \times \dot{m}_{h,P} \times h_{fg,h} \quad (17)$$

$$COP_{R,P} = \frac{Q_{c,P}}{P_f} \quad (18)$$

3.6. Validity of the Methodology

The most important term in the calculations of the methodology of this work is the latent heat of hydrogen. Latent heat is important for air conditioning systems, since the cooling capacity is mainly depends on the heat amount derived by the refrigerant when changing state from liquid to vapor. This heat absorption, which occurs at the time of the refrigerant changes state, makes the air cooler. Then the cooled air is sent to the vehicle indoor cabin blown by an air fan through the air channels. Therefore, analyses of cooling capacities, COP and AC saving variations were conducted using latent heat of hydrogen for LH_2 powered vehicles. It is assumed in the analyses that continuously evaporated hydrogen takes all of its latent heat of vaporization from the air, blown to the hydrogen evaporator, at 100% efficiency. Losses in the evaporator or other system equipments are neglected in this context. Sensible heat gain of hydrogen is also neglected for the analyses. This simple but logical approach provides a great convenience to determine whether the proposed system is feasible or not. Since the VAAC system does not include a compressor, the analysis performed in this study does not include compressor based expressions which AC systems with compressor have.

4. RESULTS AND DISCUSSION

4.1. Results of the GEHICEV Analysis

Table 6 shows hydrogen flow rate, cooling capacity, COP, and AC saving variations of GEHICEVs according to the GEHICEV analysis, conducted for fuel consumption values between 0-30 l/100 km. Although SI engines consume less fuel when they are operated at a constant speed, their fuel consumptions increase if their speeds are changed. And also they spend too much fuel in some circumstances such as cold start, excessive loads, sudden acceleration, steep ways climbing etc. Increasing fuel consumption in gasoline vehicles increases hydrogen consumption as well, which GEHICEV demonstrates gasoline vehicles converted to be powered by hydrogen fuel. According to Table 6, hydrogen consumption rises to the value of about 0.0007 kg/s for 30 l/100 km gasoline consumption. For this consumption, cooling capacity of the VAAC system is 326 W, which means the system can absorb and throw out 326 J heat from the vehicle cabin per second. This cooling power may be sufficient for the vehicle when the system is operated even alone in some cases. In other occasions with a high cooling load, the VAAC system will assist the main AC system of the vehicle. As to the COP variations of the proposed VAAC system, since the only energy wasting equipment is the fan in the system, and the calculation method includes accordingly, COP variations are higher than normal AC systems. The highest COP values of the system are 13.6, 6.8, and 4.5 respectively for 24 W, 48 W, and 72 W fan powers. The highest assisting percentages of the VAAC system to the main AC system are as follows: 33% for 1 kW AC load, 16%, for 2 kW AC load, 11% for 3 kW AC load, 8% for 4 kW AC load, 7% for 5 kW AC load, and 5% for 6 kW AC load. Decreasing fuel consumption and increasing AC load in the cabin decrease the assisting percentages of the VAAC system as seen from the table. It can be concluded that these AC saving values are high enough for the proposed VAAC system, since it cuts the AC system operation by one third, also cutting the fuel consumption increase of the vehicle due to the AC system with a low power consuming fan. If we do not use this cooling capacity of the evaporating hydrogen in liquid hydrogen powered vehicles, it will be wasted in vain. This waste of energy is aimed to be prevented with the proposed VAAC system.

4.2. Results of the DEHICEV analysis

Hydrogen flow rate, cooling capacity, COP and AC saving results of the DEHICEV analysis are given in Table 7. As diesel engines are generally utilized in heavy vehicles and they consume much fuel when compared to gasoline vehicles, between 0-60 l/100 km fuel consumption values were determined for DEHICEVs. However, the first few lines of the table also demonstrate today's light-duty diesel vehicles, which have low fuel consumptions. When a diesel vehicle is converted to operate by hydrogen fuel, the amount of the hydrogen that the vehicle consumes is shown in the second column of the table. The highest hydrogen flow rate occurs 0.0016 kg/s for 60 l/100 km diesel consumption according to the DEHICEV analysis. For this flow rate, the VAAC system gives a 704 W cooling power. And the highest achievable COPs of the system at this cooling capacity are 29.3, 14.7, 9.8 for 24 W, 48 W, 72 W fan powers, respectively. The proposed VAAC system can substitute as highly as 70% of the main AC system of the vehicle when the AC load is 1 kW. If the AC loads of the vehicle passenger compartment are taken as 2, 3, 4, 5 and 6 kW, the assistance of the VAAC system decreases to the percentages of 35%, 23%, 18%, 14%, and 12%, respectively. Even for the highest AC load in the analysis, the proposed VAAC system can supply a high cooling power which substitutes 12% of the AC unit of the vehicle. It is clear from the DEHICEV analysis that the proposed VAAC system is more suitable for heavy vehicles, considering their small cabin volumes – that means small AC loads – and high fuel consumption values. With the use of this system in LH_2 powered heavy duty vehicles, little or no usage of main AC system provides little or no compressor operation, and thus lower fuel consumption and exhaust emissions. Main AC systems can be designed very compact in those vehicles, and even in some vehicle examples, there can be included no AC system at all, since the VAAC system can maintain required cooling power for all operation scenarios.

4.3. Results of the FCV Analysis

Hydrogen consumption (in kg/s), cooling power, COP, and AC saving variations according to the FCV analysis are given in Table 8. 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. According to the table, cooling capacity of the VAAC system in FCVs rises to the highest value of 250 W, which is the lowest cooling power among all the vehicle types in the analyses. The reason for this is mainly FCVs are consuming less fuel when compared to equivalent gasoline and diesel vehicles. Therefore the cooling ability of the VAAC system decreases in FCVs. 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. On the other hand, AC saving variations of the VAAC system, which are lower than that of GEHICEV and DEHICEV analyses as the hydrogen consumption in FCVs is lower when compared to GEHICEVs and DEHICEVs. The highest reachable AC savings are 25%, 12%, 8%, 6%, 5%, 4%, respectively for 1-6 kW AC loads. The VAAC system can supply a cooling power that decreases the main AC usage as high as 25% when the vehicle consumes 6 kg hydrogen per 100 km and the AC load of the cabin is 1 kW according to the analysis. If the hydrogen consumption increases –e.g. heavy FCVs – or the AC load decreases, the VAAC system would provide all the cooling need of the vehicle when the fuel cell unit is in operation consuming hydrogen.

4.4. Results of the Parking Analysis

Table 9 shows the hydrogen ventilation flow rate, cooling capacity, and COP variations according to the changing of hydrogen ventilation coefficient in parking vehicles. When the ventilation coefficient is at its peak value, which is taken as 3 in this analysis, the cooling capacity of the VAAC system is 5.9 W, which supplies very low cooling effect for the vehicle cabin. However, there are some systems that just ventilate the vehicle cabin with a fan without the cooling of the air when the vehicle is parking. Therefore, the proposed VAAC system will assist those systems blowing some cooled air instead of the ventilated warm air in the cabin even at a small amount. The VAAC system operates with COP values of 0.25, 0.12, and 0.08, respectively for 24 W, 48 W, and 72 W fan powers.

Table 6. Approximate hydrogen consumption, cooling, COP, and AC Saving variations according to the GEHICEV analysis

FC_g (l/100 km)	$\dot{m}_{h,GEHICEV}$ (kg/s)	$\dot{Q}_{c,GEHICEV}$ (W)	$COP_{R,GEHICEV}$ @P_f=24 W	$COP_{R,GEHICEV}$ @P_f=48 W	$COP_{R,GEHICEV}$ @P_f=72 W	$S_{AC,GEHICEV}$ @1 kW load (%)	$S_{AC,GEHICEV}$ @2 kW load (%)	$S_{AC,GEHICEV}$ @3 kW load (%)	$S_{AC,GEHICEV}$ @4 kW load (%)	$S_{AC,GEHICEV}$ @5 kW load (%)	$S_{AC,GEHICEV}$ @6 kW load (%)
0	0.0000	0	0.0	0.0	0.0	0	0	0	0	0	0
1	0.0000	11	0.5	0.2	0.2	1	1	0	0	0	0
2	0.0000	22	0.9	0.5	0.3	2	1	1	1	0	0
3	0.0001	33	1.4	0.7	0.5	3	2	1	1	1	1
4	0.0001	44	1.8	0.9	0.6	4	2	1	1	1	1
5	0.0001	54	2.3	1.1	0.8	5	3	2	1	1	1
6	0.0001	65	2.7	1.4	0.9	7	3	2	2	1	1
7	0.0002	76	3.2	1.6	1.1	8	4	3	2	2	1
8	0.0002	87	3.6	1.8	1.2	9	4	3	2	2	1
9	0.0002	98	4.1	2.0	1.4	10	5	3	2	2	2
10	0.0002	109	4.5	2.3	1.5	11	5	4	3	2	2
11	0.0003	120	5.0	2.5	1.7	12	6	4	3	2	2
12	0.0003	131	5.4	2.7	1.8	13	7	4	3	3	2
13	0.0003	141	5.9	2.9	2.0	14	7	5	4	3	2
14	0.0003	152	6.3	3.2	2.1	15	8	5	4	3	3
15	0.0004	163	6.8	3.4	2.3	16	8	5	4	3	3
16	0.0004	174	7.3	3.6	2.4	17	9	6	4	3	3
17	0.0004	185	7.7	3.9	2.6	19	9	6	5	4	3
18	0.0004	196	8.2	4.1	2.7	20	10	7	5	4	3
19	0.0005	207	8.6	4.3	2.9	21	10	7	5	4	3
20	0.0005	218	9.1	4.5	3.0	22	11	7	5	4	4
21	0.0005	229	9.5	4.8	3.2	23	11	8	6	5	4
22	0.0005	239	10.0	5.0	3.3	24	12	8	6	5	4
23	0.0006	250	10.4	5.2	3.5	25	13	8	6	5	4
24	0.0006	261	10.9	5.4	3.6	26	13	9	7	5	4
25	0.0006	272	11.3	5.7	3.8	27	14	9	7	5	5
26	0.0006	283	11.8	5.9	3.9	28	14	9	7	6	5
27	0.0007	294	12.2	6.1	4.1	29	15	10	7	6	5
28	0.0007	305	12.7	6.3	4.2	30	15	10	8	6	5
29	0.0007	316	13.2	6.6	4.4	32	16	11	8	6	5
30	0.0007	326	13.6	6.8	4.5	33	16	11	8	7	5

Table 7. Approximate hydrogen consumption, cooling, COP, and AC Saving variations according to the DEHICEV analysis

FC_d (l/100 km)	$\dot{m}_{h,DEHICEV}$ (kg/s)	$\dot{Q}_{c,DEHICEV}$ (W)	$COP_{R,DEHICEV}$ @P_f=24 W	$COP_{R,DEHICEV}$ @P_f=48 W	$COP_{R,DEHICEV}$ @P_f=72 W	$S_{AC,DEHICEV}$ @1 kW load (%)	$S_{AC,DEHICEV}$ @2 kW load (%)	$S_{AC,DEHICEV}$ @3 kW load (%)	$S_{AC,DEHICEV}$ @4 kW load (%)	$S_{AC,DEHICEV}$ @5 kW load (%)	$S_{AC,DEHICEV}$ @6 kW load (%)
0	0.0000	0	0.0	0.0	0.0	0	0	0	0	0	0
2	0.0001	23	1.0	0.5	0.3	2	1	1	1	0	0
4	0.0001	47	2.0	1.0	0.7	5	2	2	1	1	1
6	0.0002	70	2.9	1.5	1.0	7	4	2	2	1	1
8	0.0002	94	3.9	2.0	1.3	9	5	3	2	2	2
10	0.0003	117	4.9	2.4	1.6	12	6	4	3	2	2
12	0.0003	141	5.9	2.9	2.0	14	7	5	4	3	2
14	0.0004	164	6.8	3.4	2.3	16	8	5	4	3	3
16	0.0004	188	7.8	3.9	2.6	19	9	6	5	4	3
18	0.0005	211	8.8	4.4	2.9	21	11	7	5	4	4
20	0.0005	235	9.8	4.9	3.3	23	12	8	6	5	4
22	0.0006	258	10.7	5.4	3.6	26	13	9	6	5	4
24	0.0006	281	11.7	5.9	3.9	28	14	9	7	6	5
26	0.0007	305	12.7	6.4	4.2	30	15	10	8	6	5
28	0.0007	328	13.7	6.8	4.6	33	16	11	8	7	5
30	0.0008	352	14.7	7.3	4.9	35	18	12	9	7	6
32	0.0008	375	15.6	7.8	5.2	38	19	13	9	8	6
34	0.0009	399	16.6	8.3	5.5	40	20	13	10	8	7
36	0.0009	422	17.6	8.8	5.9	42	21	14	11	8	7
38	0.0010	446	18.6	9.3	6.2	45	22	15	11	9	7
40	0.0011	469	19.5	9.8	6.5	47	23	16	12	9	8
42	0.0011	492	20.5	10.3	6.8	49	25	16	12	10	8
44	0.0012	516	21.5	10.7	7.2	52	26	17	13	10	9
46	0.0012	539	22.5	11.2	7.5	54	27	18	13	11	9
48	0.0013	563	23.5	11.7	7.8	56	28	19	14	11	9
50	0.0013	586	24.4	12.2	8.1	59	29	20	15	12	10
52	0.0014	610	25.4	12.7	8.5	61	30	20	15	12	10
54	0.0014	633	26.4	13.2	8.8	63	32	21	16	13	11
56	0.0015	657	27.4	13.7	9.1	66	33	22	16	13	11
58	0.0015	680	28.3	14.2	9.4	68	34	23	17	14	11
60	0.0016	704	29.3	14.7	9.8	70	35	23	18	14	12

Table 8. Approximate hydrogen consumption, cooling, COP, and AC Saving variations according to the FCV analysis

$\dot{m}_{h,FCV,NEDC}$ (kg/100 km)	$\dot{m}_{h,FCV}$ (kg/s)	$\dot{Q}_{c,FCV}$ (W)	$COP_{R,FCV}$ @P_f=24 W	$COP_{R,FCV}$ @P_f=48 W	$COP_{R,FCV}$ @P_f=72 W	$S_{AC,FCV}$ @1 kW load (%)	$S_{AC,FCV}$ @2 kW load (%)	$S_{AC,FCV}$ @3 kW load (%)	$S_{AC,FCV}$ @4 kW load (%)	$S_{AC,FCV}$ @5 kW load (%)	$S_{AC,FCV}$ @6 kW load (%)
0	0.0000	0	0.0	0.0	0.0	0	0	0	0	0	0
0.2	0.0000	8	0.3	0.2	0.1	1	0	0	0	0	0
0.4	0.0000	17	0.7	0.3	0.2	2	1	1	0	0	0
0.6	0.0001	25	1.0	0.5	0.3	2	1	1	1	0	0
0.8	0.0001	33	1.4	0.7	0.5	3	2	1	1	1	1
1	0.0001	42	1.7	0.9	0.6	4	2	1	1	1	1
1.2	0.0001	50	2.1	1.0	0.7	5	2	2	1	1	1
1.4	0.0001	58	2.4	1.2	0.8	6	3	2	1	1	1
1.6	0.0001	67	2.8	1.4	0.9	7	3	2	2	1	1
1.8	0.0002	75	3.1	1.6	1.0	7	4	2	2	1	1
2	0.0002	83	3.5	1.7	1.2	8	4	3	2	2	1
2.2	0.0002	92	3.8	1.9	1.3	9	5	3	2	2	2
2.4	0.0002	100	4.2	2.1	1.4	10	5	3	2	2	2
2.6	0.0002	108	4.5	2.3	1.5	11	5	4	3	2	2
2.8	0.0003	116	4.9	2.4	1.6	12	6	4	3	2	2
3	0.0003	125	5.2	2.6	1.7	12	6	4	3	2	2
3.2	0.0003	133	5.5	2.8	1.8	13	7	4	3	3	2
3.4	0.0003	141	5.9	2.9	2.0	14	7	5	4	3	2
3.6	0.0003	150	6.2	3.1	2.1	15	7	5	4	3	2
3.8	0.0004	158	6.6	3.3	2.2	16	8	5	4	3	3
4	0.0004	166	6.9	3.5	2.3	17	8	6	4	3	3
4.2	0.0004	175	7.3	3.6	2.4	17	9	6	4	3	3
4.4	0.0004	183	7.6	3.8	2.5	18	9	6	5	4	3
4.6	0.0004	191	8.0	4.0	2.7	19	10	6	5	4	3
4.8	0.0004	200	8.3	4.2	2.8	20	10	7	5	4	3
5	0.0005	208	8.7	4.3	2.9	21	10	7	5	4	3
5.2	0.0005	216	9.0	4.5	3.0	22	11	7	5	4	4
5.4	0.0005	225	9.4	4.7	3.1	22	11	7	6	4	4
5.6	0.0005	233	9.7	4.9	3.2	23	12	8	6	5	4
5.8	0.0005	241	10.1	5.0	3.4	24	12	8	6	5	4
6	0.0006	250	10.4	5.2	3.5	25	12	8	6	5	4

Table 9. Average hydrogen ventilation, cooling and COP variations according to the parking analysis

c_v	$\dot{m}_{h,P}$ (kg/s)	$\dot{Q}_{c,P}$ (W)	$COP_{R,P@P_f=24\,W}$	$COP_{R,P@P_f=48\,W}$	$COP_{R,P@P_f=72\,W}$
0	0.000000	0.0	0.00	0.00	0.00
0.1	0.000000	0.2	0.01	0.00	0.00
0.2	0.000001	0.4	0.02	0.01	0.01
0.3	0.000001	0.6	0.02	0.01	0.01
0.4	0.000002	0.8	0.03	0.02	0.01
0.5	0.000002	1.0	0.04	0.02	0.01
0.6	0.000003	1.2	0.05	0.02	0.02
0.7	0.000003	1.4	0.06	0.03	0.02
0.8	0.000004	1.6	0.07	0.03	0.02
0.9	0.000004	1.8	0.07	0.04	0.02
1	0.000004	2.0	0.08	0.04	0.03
1.1	0.000005	2.2	0.09	0.05	0.03
1.2	0.000005	2.4	0.10	0.05	0.03
1.3	0.000006	2.6	0.11	0.05	0.04
1.4	0.000006	2.8	0.12	0.06	0.04
1.5	0.000007	3.0	0.12	0.06	0.04
1.6	0.000007	3.2	0.13	0.07	0.04
1.7	0.000008	3.4	0.14	0.07	0.05
1.8	0.000008	3.6	0.15	0.07	0.05
1.9	0.000008	3.8	0.16	0.08	0.05
2	0.000009	4.0	0.17	0.08	0.06
2.1	0.000009	4.2	0.17	0.09	0.06
2.2	0.000010	4.4	0.18	0.09	0.06
2.3	0.000010	4.6	0.19	0.09	0.06
2.4	0.000011	4.8	0.20	0.10	0.07
2.5	0.000011	5.0	0.21	0.10	0.07
2.6	0.000012	5.2	0.21	0.11	0.07
2.7	0.000012	5.4	0.22	0.11	0.07
2.8	0.000012	5.6	0.23	0.12	0.08
2.9	0.000013	5.7	0.24	0.12	0.08
3	0.000013	5.9	0.25	0.12	0.08

5. CONCLUSIONS

Conventional air conditioning systems significantly contribute to energy consumption in vehicles. Liquid hydrogen powered vehicles, on the other hand, have a potential of latent heat of hydrogen to be vaporized for the need of feeding the internal combustion engine or fuel cell unit of the vehicle depending on its type. Therefore there is a need to produce a new technology that utilizes this energy and reduces costs. An auxiliary air conditioning system for liquid hydrogen vehicles has been proposed and theoretically analyzed in this study. The internal combustion engine vehicles and fuel cell vehicles were included in the analyses. Hydrogen consumption, cooling capacity, COP, and AC saving variations were presented according to the vehicles that have specified fuel consumptions. Parking analyses of vehicles were also performed. The results of the analyses show that the system can supply adequate cooling with a COP that is comparable to the conventional vapor compression cycle. This system can assist VAC systems in ICEVs or FCVs storing liquid hydrogen with small initial and operating costs.

Since the achievable cooling capacity of the VAAC system proposed in this study for vehicles consuming high hydrogen is more sufficient for assisting the VAC system, vehicles like lorries or trucks with a higher fuel consumption and lower indoor volume seem to be more suitable than the vehicles that have lower fuel consumption and higher cooling demand. However, the system reduces the main air conditioning operation, thus reducing fuel consumption and emissions in any case.

On the other hand, the analyses reveal that the auxiliary system proposed in this study could supply adequate cooling capacity to the vehicle compartment only in mild weather conditions when the main AC system of the vehicle is off. If the same situation is in question, performance of the system would decrease dramatically with decreasing fuel consumption and outside ambient temperature. At this condition, the main VAC system should be automatically activated, which in any case puts a lower load on the engine of the ICEVs or battery of the FCVs.

It is also important to discuss the effect of varying hydrogen flow rates on the cooling behavior of the VAAC system. Depending on the varying vehicle loads such as different traffic situations, number of occupants, baggage loads, and slope of the road, hydrogen flow changes thus changing the cooling capacity of the VAAC system. Therefore, there should be a higher requirement of a control strategy for the VAC system when the VAAC system is implemented. New system regulating algorithms have to be developed for optimized working conditions between the proposed VAAC and the VAC system to avoid not regulating the desired air conditions in the cabin of the vehicle and unnecessary usage of the VAC system, which influences the driving performance of the vehicle and increases fuel consumption.

In addition, apart from the application of the VAAC system for the vehicle interior cabin, especially for FCVs, a further possible integration concept of the system is the cooling of the vehicle components such as the power electronics, the battery or the electric motor, which, for an overall propulsion efficiency of 80%, between 0.75-2.5 kW of waste heat of an FCV is produced from these components [82].

As a result, the proposed VAAC system is a suitable and environmental friendly system for vehicles that use liquid hydrogen as fuel. It can support the conventional air-conditioning system of the vehicles that have low fuel consumption with a high air conditioning load, or replace it for vehicles that have high fuel consumption with low air conditioning load like lorries or trucks. A further promising integration concept is the direct cooling of vehicle interior or propulsion components. In future studies, the system has to be directly coupled with a fuel cell and solutions for a homogeneous cooling power have to be examined.

Nomenclature

AAC	Auxiliary Air Conditioning
AC	Air Conditioning
c_v	Venting Coefficient of the Tank
CH_4	Natural Gas
CI	Compression Ignition
CNG	Compressed Natural Gas
CO	Carbon Monoxide
COP	Coefficient Of Performance
COP_R	Refrigeration Coefficient Of Performance
DEHICEV	Diesel Equivalent Hydrogen Internal Combustion Engine Vehicle
FC	Fuel Cell
FC_d	Diesel Fuel Consumption, l/100 km
FC_g	Gasoline Fuel Consumption, l/100 km
FCV	Fuel Cell Vehicle
GEHICEV	Gasoline Equivalent Hydrogen Internal Combustion Engine Vehicle
GICEV	Gasoline Internal Combustion Engine Vehicle
GWP	Global Warming Potential
H_2O	Water
$h_{fg,h}$	Enthalpy of Vaporization of Hydrogen, kJ/kg
HC	Hydrocarbon
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
L_c	Cooling Load of the Vehicle
LH_2	Liquid Hydrogen
LN_2	Liquid Nitrogen
LNG	Liquid Natural Gas
LPG	Liquid Petroleum Gas
$\dot{m}_d$	Diesel Fuel Consumption, kg/s
$\dot{m}_g$	Gasoline Fuel Consumption, kg/s
$\dot{m}_h$	Hydrogen Consumption, kg/s
NEDC	New European Driving Cycle
NO_x	Nitrogen Oxides
ODP	Ozone Depletion Potential
P_f	Fan Power, W
PEM	Proton Exchange Membrane
$\dot{Q}_c$	Cooling Capacity, W
ρ_d	Diesel Density, kg/L
ρ_g	Gasoline Density, kg/L
$r_{HV,h/d}$	Equivalent Heating Value Rate of Diesel and Hydrogen
$r_{HV,h/g}$	Equivalent Heating Value Rate of Gasoline and Hydrogen
S_{AC}	AC Saving, %
SI	Spark Ignition
VAAC	Vehicle Auxiliary Air Conditioning

VAC	Vehicle Air Conditioning
$\dot{v}_d$	Diesel Fuel Consumption, L/s
$\dot{v}_g$	Gasoline Fuel Consumption, L/s
ZEV	Zero Emission Vehicle

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