237. Compatibility Issues of HHO Cell With Internal Combustion Engine

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Abstract

This study presents the analysis of hydrogen (H_2) gas, gasoline (octane), and their mixture using a nonlinear vehicle dynamic model. These fuels, with their corresponding A/F ratios, are used to generate the engine torque and fuel flow rates. The vehicle model is based on the continuous-time domain and simulates the real dynamics of the sub-vehicle models for steady-state and transient operations. The heat of combustion and A/F ratios for both fuels and their mixture are determined using the combustion stoichiometry and Hess's Law. The simulation results show that the pure H_2 gas generates more torque and consumes less fuel than pure octane fuel. The A/F of H_2 gas is fuel-lean mixture while for octane it is fuel-rich mixture. Using the H_2 gas as an additive fuel with octane (mixture of both fuels) improves the torque generation and reduces the octane consumption from 37% to 45%. These fuels are not tested on a stationary test rig but in a dynamic (moving) model which means the simulation results can be highly useful for developing the experimental model, its detailed testing, and implementation.

Keywords:* "*HHO; IC-Engine; Torque; Vehicale dynamics;"

1. Introduction

It is a very well-known fact that fossil fuels are used as the source of energy for the internal combustion engines. However, due to their higher depleting rates and increasing prices, a number of researchers have dedicated their research work on investigating alternative sources of energies for the internal combustion engines. Some of the researchers have focused on the methanol and organometallic (MnO_2) fuels [1], vegetable oil [2], natural gas [3], neem oil methyl ester [4], HHO gas [5-6], etc. as alternative fuels or additive fuels. Water is most abundant element on this earth and recently used as a free energy source and has been introduced to the automobile industry as a new source of energy named as Brown Gas (HHO). It is used as a supplementary fuel in petrol, diesel, CNG [7-9] engines etc. to improve the power production and to reduce the hazardous gases such as CO_2, HC, NOx, CO, [10-11] etc. in the emission.

Hydrogen is widely acknowledged as a non-polluting, renewable, and recyclable fuel. The major dissimilarity between hydrocarbon fuels and hydrogen fuel is the absence of carbon. Moreover, as compared to other hydrocarbon fuels, hydrogen has greater flame speed, faster burning velocity and wider flammability limits [12]. This helps the engine to complete the combustion process and to run on very lean mixtures which results in less unburnt fuels and reduced pollutants in the emission. Hydrogen could become an important element, allowing us to accumulate and transfer energy in a clean way. Hydrogen can be used in cars as a fuel additive which increases the combustion efficiency of the fuel-air mixture. H_2 gas ensures noteworthy ability as a supplemental fuel to rally the emissions and performance of SI and CI engines. Some of the characteristics which justify the use of hydrogen as fuel are as follows [12].

1.1 Wide Range of Flammability

The flammability limits are very wide for hydrogen, which ensures that by using an appropriate air-fuel ratio the engine load can be controlled. The engine can be run all time using a wide open throttle which results in increased efficiency.

1.2 Low Ignition Energy

The quantity of energy required to ignite H_2 gas is about one order of magnitude less than that required for gasoline. This allows H_2 engines to burn lean mixtures and guarantees swift ignition.

1.3 Small Quenching Distance

Hydrogen flames travel closer to the cylinder wall than other fuels before they extinguish.

1.4 High Auto Ignition Temperature:

The high auto ignition temperature of hydrogen allows larger compression ratios to be used in a hydrogen engine than in a hydrocarbon engine.

1.5 High Flame Speed

Hydrogen has high flame speed at stoichiometric ratios. This means that hydrogen engines can more closely approach the thermodynamically ideal engine cycle.

1.6 High Diffusivity

It facilitates the formation of a uniform mixture of fuel and air.

2. Schematic Diagram of HHO Dry Cell Integration with I. C. Engine

The schematic diagram of HHO dry cell is shown in Fig. 1. It consists of a 12 volts battery connected to a 20 amperes fuse. The fuse is generally joined to a switch. An ammeter is used to determine the amount of current flowing from battery to the HHO dry cell. The negative wire is connected to the car grounding and the positive wire from the ammeter is connected to the HHO dry cell. Once the system is started then HHO is generated and fed to the carburettor with the help of a silicon pipe as shown in Fig. 1.

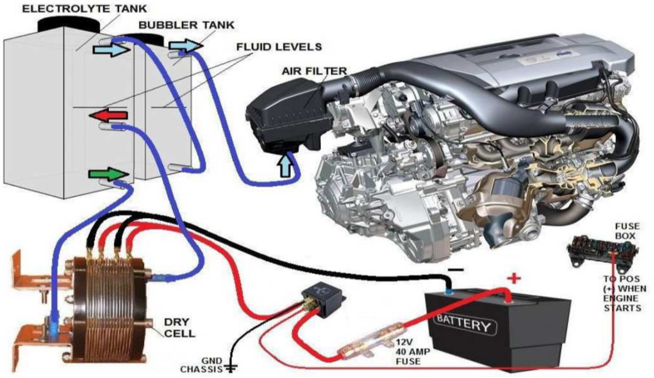


Fig.1. Schematic Diagram of HHO Dry Cell Integration with IC Engine

Numerous attempts have been demeanour all around the world for using hydrogen as supplementary fuel to improve combustion efficiency of engine. Y. Hacohen and E. Sher [13] found, for the operation conditions used, the brake specific fuel consumption was reduced by 10 to 20% by addition of hydrogen to gasoline mass ratio of 2 to 6%. Shrestha and Narayanan [14] proposed that under fuel-lean mixture conditions adding 3% hydrogen to a spark ignited engine running on landfill gas increased the thermal efficiency of that engine by 15.07% and the power output by 12.5%. Saravanan and Nagarajan [15] suggested that under optimized diesel engine operating conditions, addition of 7.5 liters/min of hydrogen produced a brake thermal efficiency increase of 9% as compared to normal diesel operation.

Core intimation of this research study is to focus on automobile industry. This research focuses on the integration of HHO (brown gas) generator and to study the problems arises during the integration of HHO gas generator with the petrol engine. There has been a rising global interest towards the HHO integration with the existing internal combustion engines. Supplementing a certain quantity of Hydrogen gas to the intake manifold of a petrol engine may decrease the consumption of fuel and can substantially improve the emissions. Continuous generation of H_2 gas from water electrolysis can resolve numerous potential difficulties of using hydrogen as a supplement fuel to increase combustion of fuel. This study mainly focuses on the integration of HHO gas generator with petrol engine without any physical modification in the overall system. It is essential to figure out various factors when integrating the HHO gas generator with the petrol engine. The most important problem is to find out the air-fuel ratio of air, gasoline, and HHO gas. The vehicle cannot be analyzed by hit and trial methods to find out this air-fuel ratio. Therefore, a detailed mathematical analysis is mandatory for the appropriate solution. In order to reduce the fuel consumption it is essential to investigate that how much fuel supply should be reduced and how much HHO gas should be added to get the same torque and speed as from gasoline. Moreover, the compression ratio for this new combination and spark plug timings have not been addressed in the previous studies. These all factors should be properly addressed so the proposed HHO generator model can be utilized effectively. The bottom line of this study is to investigate the A/F ratio associated with the integration of HHO generator with the petrol engine to generate the optimum torque and its corresponding fuel consumption.

3. Aims and Objectives of the Research Study

Objective of this research is to integrate the HHO gas generator with petrol engine as a supplementary fuel, and the measureable steps under consideration to resolve these issues are as follows:

Key aims and objectives of this research include:

- Investigate the amount of gasoline and hydrogen required to acquire the same torque and speed as from gasoline.
- Determination of heat of combustion and A/F ratio of both fuels.
- Determination of vehicle millage with and without of HHO generator.

In this study, a nonlinear vehicle model is tested under realistic dynamic load conditions and it is capable of finding out the required A/F ratio of any fuel for the desired power generation. The investigation of hydrogen fuel and its mixture with gasoline for a nonlinear vehicle dynamic model have not been conducted in previous studies. This study will help in understanding the impact of hydrogen gas as a supplementary fuel on the automobile industry.

4. Methodology

The HHO generator is the heart of the system that produces the HHO gas and cools down the engine. Mounting position of HHO cell is very important for smooth operation, as no any physical modification is required inside the chamber, as well as in the compartment of vehicle. After the proper placement of HHO cell, the HHO gas will be injected through the air intake manifold of the engine using the appropriate tubing, after that it would be mixed with the existing air-fuel mixture for the combustion inside the engine during power stroke of the engine cycle. It is important to mention here that existing air-fuel ratio must be altered for the complete combustion of the Hydrogen along with the existing fuel.

For the purpose of investigation, a nonlinear vehicle dynamic model has been adopted from [16] for the detailed and realistic investigations. The vehicle dynamic model includes the engine dynamics, automatic transmission dynamics, wheel dynamics, and vehicle’s longitudinal dynamics.

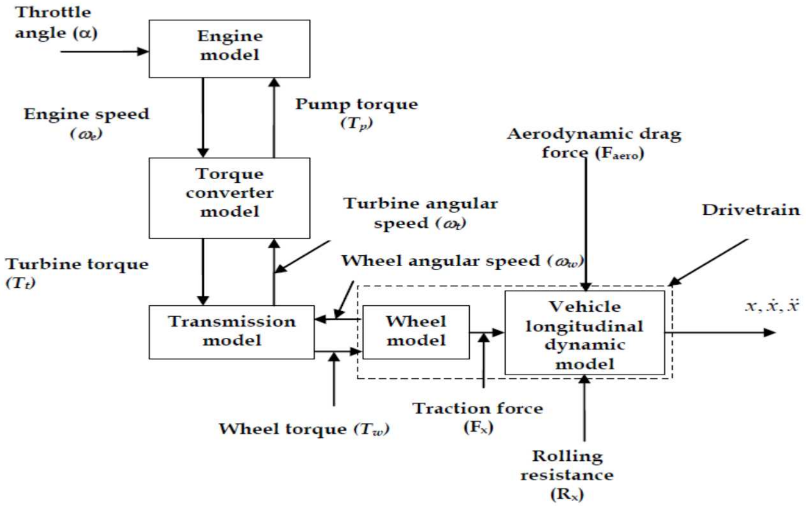


Fig. 2. Block Diagram of the Nonlinear Vehicle Dynamic Model [16]

A 3.8L spark-ignition engine model with six cylinders and a five-speed automatic transmission for a typical front-wheel-drive passenger car is used where the input to the engine model is the throttle angle (α). The engine model is used as a torque-producing device with one inertia where the engine torque is the function of the throttle angle (α), mass flow rate of fuel ($\dot{m}_f$), and the engine speed (ω_e). The vehicle model is based on the physical principles and captures the power train dynamics in the continuous-time domain. For the details of the nonlinear vehicle model the readers are referred to the PhD thesis [16].

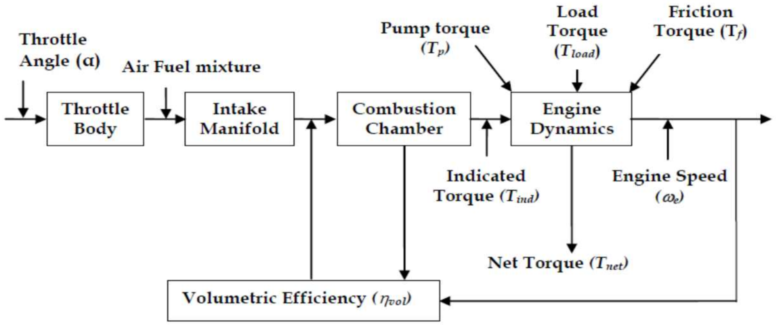


Fig. 3. Block diagram for the Engine Model [16].

The vehicle dynamic model is very useful for the comparison of various fuels, the comparison of the torque generated by each fuel, and the fuel consumption of each fuel in the simulated environment. There are many other variables which could be measured using the same vehicle dynamic model which will be discussed in the results and discussion Section of this paper. The types of fuel used for the investigation and comparison are gasoline (Octane, C_8H_{18}) and Hydrogen (H_2) gas. For the purpose of investigation, both fuels are used separately and as a mixture for the comparison purpose.

The vehicle model used requires the heat of combustion or calorific values of each fuel and its corresponding air/fuel ratio for the required torque generation. Heat of combustion is the measure of the heat released during complete combustion whereas, the air/fuel ratio defines amount of air required for the complete combustion of the fuel. Therefore, it is necessary to determine the heat of combustion and the air/fuel ratios of each fuel and their mixture.

5. Combustion Stoichiometry

5.1 Heat of combustion and A/F ratio of Octane and Hydrogen gas

During the complete oxidation of hydrocarbon fuels carbon dioxide (CO_2) and H_2O along with the heat of combustion are formed. The general chemical equation for the oxidation of a hydrocarbon fuel is as follows [17].

$$C_nH_m + (n+\frac{m}{4})O_2 \rightarrow nCO_2 + \frac{m}{4}H_2O \tag{1}$$

Eq. (1) can be used for the computation of the heat of combustion generated during the complete oxidation of a fuel. For example, heat of combustion of Octane (C_8H_{18}) from its chemical stoichiometric equation can be determined as

$$C_8H_{18} + \frac{25}{2}O_2 \rightarrow 16CO_2 + 18H_2O \tag{2}$$

Using the standard enthalpies from Table 3.2 [17], heat of combustion for C_8H_{18} comes out as

$$(-249.35) + \frac{25}{2}(0) \rightarrow \frac{16}{2}(-393.52) + \frac{18}{2}(-285.84)$$
$$\therefore -249.35 + 0 \rightarrow -3148.16 - 2572.56$$
$$\therefore -5471.37 KJ/mol$$

Since the molecular mass of one mole of C_8H_{18} is 114 grams, therefore, there are 8.77 moles of C_8H_{18} in one kilogram of fuel. The heat of combustion of C_8H_{18} per kilogram is 47.98 MJ/kg. Similarly, using Eq. (1) and standard enthalpies from Table 3.2 [17] the heat of combustion of hydrogen gas per mole can be computed as -241.83 KJ/mol. Since the molecular mass of one mole of H_2 is 2 grams, therefore, there are 500 moles of H_2 in one kilogram of fuel. The heat of combustion of one kilogram of H_2 is 120.1 MJ/kg.

Eq. (1) can be used for finding out the heat of combustion of any fuel and it uses pure oxygen for the complete combustion. Since air is composed of N_2 (79.1%), O_2 (20.9), and small amounts of other gases, therefore, for the purpose of this study it is perfectly reasonable to consider as a mixture of nitrogen and oxygen in mole basis. As per this percentage, for every one mole of oxygen required for combustion, 3.78 mol of nitrogen must be introduced as well. Under this condition the Eq. (1) can be revised as

$$C_nH_m + (n+\frac{m}{4})(O_2 + 3.78N)_2 \rightarrow nCO_2 + \frac{m}{2}H_2O + 3.78(n+\frac{m}{4})N_2 \tag{3}$$

Using Eq. (3) for the C_8H_{18}, we get

$$C_8H_{18} + 12.5(O_2 + 3.78N_2) \rightarrow 8CO_2 + 9H_2O + 47.25N_2 \tag{4}$$

It is obvious from Eq. (4) that for each mole of C_8H_{18} burned, 59.75 mol of air is required for the complete combustion. The air/fuel ratio for C_8H_{18} can be computed as

$$\frac{m_a}{m_f} = \frac{12.5\times(32+3.78\times28)}{114} = 15.1$$

Similarly, the air/fuel ratio for H_2 can be computed as 34.46. The calorific values and air/fuel ratios of both fuels are used to simulate the response of the nonlinear vehicle dynamic model.

5.2 Heat of combustion and A/F ratio of the mixture of Octane and Hydrogen gas

One of the objectives of this study is to determine the heat of combustion and A/F ratio of the mixture of both fuels, i.e. octane and hydrogen gas. It should be noted that Eq. (3) cannot be simply used for to find out the heat of combustion and A/F ratio of the mixture of both fuels. Since both fuels are mixed for the combustion and in turn for the power generation of the engine, therefore, according to the Hess's Law the chemical equation of both fuels should be added to compute the heat of combustion and A/F ratio of their mixture as follows.

$$8.77C_8H_{18} + 8.77 \times \frac{25}{2}(O_2 + 3.78N_2) \rightarrow 8.77 \times 8CO_2 + 8.77 \times 9H_2O + 8.77 \times 47.25N_2 \tag{5}$$

$$500H_2 + \frac{500}{2}(O_2 + 3.78N_2) \rightarrow 500H_2O + 500 \times 1.887N_2 \tag{6}$$

Adding above two equations we get

$$8.77C_8H_{18} + 500H_2 + 359.625(O_2 + 3.78N_2) \rightarrow 70.16CO_2 + 578.93H_2O + 1357.8825N_2 \tag{7}$$

$$\frac{m_a}{m_f} = \frac{359.625(32 + 3.78 \times 28)}{8.77 \times 114 + 500 \times 2}$$

$$= \frac{49570.71}{2000}$$

$$\frac{m_a}{m_f} = 24.7853 \quad \text{A/F ratio}$$

According to the Hess's Law, when two chemical equations are combined algebraically then their heat of enthalpies can be added algebraically. Since both reactions in Eq. (5) and Eq. (6) are exothermic, therefore, their heat of combustion will be added. The total heat of combustion of both fuels determined as 168.08 MJ/kg.

6. Simulations Results and Discussion

This section presents the simulation results of the nonlinear vehicle model for octane fuel, hydrogen gas, and their mixture. The required calorific values and their corresponding A/F ratios are used for the nonlinear vehicle model. The objectives of these simulation results are to investigate the response of vehicle model for H_2 gas separately and then its mixture with octane fuel. These results will be then compared with the simulation results of the vehicle model when running on pure octane fuel. The aim of this comparison is to find the differences in torque generated and the fuel consumption in all conditions. For the purpose of comparison, the nonlinear vehicle model is tested for various cases as follows.

- Pure H_2 gas with its actual stoichiometric A/F ratio, i.e. 34.46.
- Pure Octane fuel with its actual stoichiometric A/F ratio, i.e. 15.1.
- Pure H_2 gas with the A/F ratio to be computed to generate the same torque as for pure octane in case 2. This will help to find the required A/F ratio and H_2 flow rate for the required torque generation.
- The mixture of H_2 and octane fuel with their correspondent A/F ratio computed using the Hess's Law.

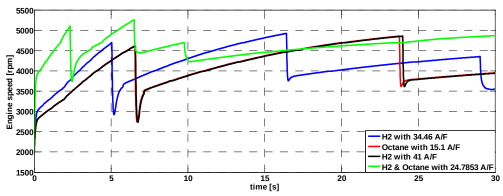
Table 1 shows the vehicle and power train parameters used for these simulations. The initial velocity of the vehicle is 10m/s. The corresponding initial engine speed, throttle input, and gear ratio for the vehicle model are 1967 rpm, 70◦, 2nd gear respectively.

The vehicle response has been simulated in Fig. 4 which shows the (a) engine speed, (b) engine torque, (c) fuel flow rate, (d) gear shifting pattern, (e) vehicle velocity, and (f) vehicle position. The Fig. 4 shows that for the case 1 (blue curve) for pure H_2 gas with 34.46 A/F ratio the engine speed (Fig. 4(a)) is higher than the octane fuel (red curve) with 15.1 A/F ratio. The torque generated is also higher in the case of H_2 gas. The A/F ratio for case 1 and case 2 shows that for H_2 a fuel-lean mixture while for the gasoline a fuel-rich mixture is required. This is also evident from Fig. 4(c) that the fuel consumption of pure H_2 is far less than pure octane. This kind of comparison is not evident in the previous studies. This finding is one of the important contributions of this study.

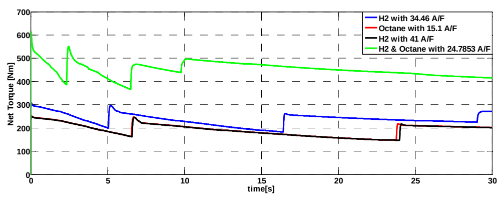
In case 3 pure H_2 is used and then using the hit-in-trail method the required A/F ratio is determined which can generate the same torque as generated by pure octane fuel with its actual stoichiometric A/F ratio. It was observed from case 3 that a further fuel-lean mixture i.e. from 34.46 to 41 A/F is required to run the vehicle at its optimum torque. Fig. 4(c) shows that fuel flow rate of H_2 is just below 3 g/s (black curve) which is the minimum fuel flow rate among all simulation results. The simulation results of this nonlinear vehicle model shows that if the A/F ratio of around 41 can be maintained for the H_2 gas then it could be highly economical to run the vehicle. This is another significant finding of this study.

Table 1. Vehicle and Powertrain Parameters

Engine displacement	V_d	0.0038 m^3
Intake manifold volume	V_{man}	0.0027 m^3
Universal gas constant	R	287
Manifold temperature	T_{man}	293 K
Max. Flow rate of air in the intake manifold	MAX	0.1843 kg/s
Air/fuel equivalence ratio	λ	1
Stoichiometric air/fuel mass ratio for gasoline (Octane fuel)	L_{th}	15.1
Fuel energy constant [MJ/kg] (for Octane)	H_u	47.98 MJ/kg
Thermal efficiency	η_i	0.32
Moment of inertia of engine	I_e	0.1454 kg.m^2
1st gear speed reduction ratio	R_1	0.3424
2nd gear speed reduction ratio	R_2	0.6379
Final drive speed reduction ratio	R_d	0.3521
1st gear speed reduction ratio	R_1	0.3184
2nd gear speed reduction ratio	R_2	0.505
3rd gear speed reduction ratio	R_3	0.73
4th gear speed reduction ratio	R_4	1
5th gear speed reduction ratio	R_5	1.3157
Final drive speed reduction ratio	R_d	0.3257
Moment of inertia of wheel	I_w	2.8 kg.m^2
Effective radius	r_{eff}	0.3 m
Longitudinal tyre stiffness (for both tyres)	$C_{\sigma f}$	80000 N
Air density	ρ	1.225 kg/m^3
Aerodynamic drag coefficient	C_d	0.4
Wind velocity	V_{wind}	10 m/s
Mass of the vehicle	m	1644 kg



(a)



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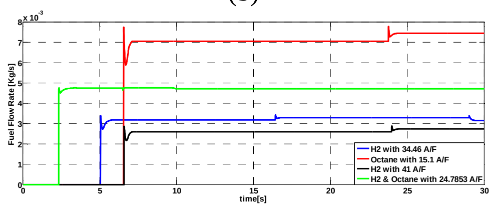

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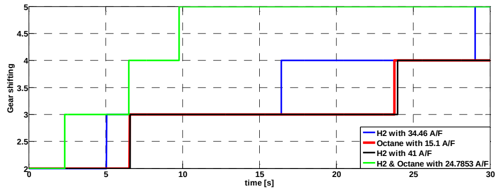

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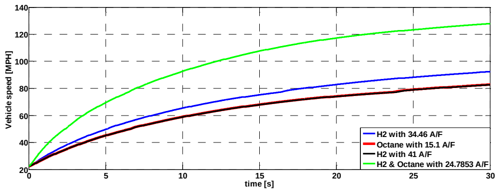
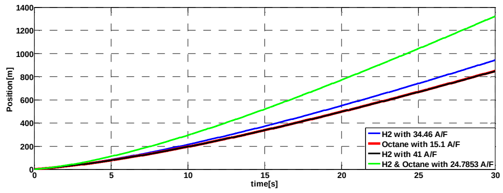


(e)



(f)

Fig. 4. Vehicle Response for H_2 Gas, Gasoline, and their Mixture (a) Engine Speed (b) Engine Torque (c) Fuel Flow Rate (d) Gear Shifting (e) Vehicle Velocity (f) Vehicle Position

Using Eq. (5) to Eq. (7), both fuels are added with their corresponding amount of air required for the stoichiometric combustion. The A/F ratio for the mixture of octane and H_2 gas is then determined which turns out as 24.7853 for both fuels. Their combined heat of combustion is computed as 168.08 KJ/kg. The A/F mixture is an important feature for the complete combustion of a fuel. The green curve in Fig. 4 shows the vehicle response for the H_2 gas and octane mixture. Fig. 4(b) shows that the engine generates the highest torque (green curve) for the mixture of both fuels and a fuel-lean mixture is required for the combustion with the A/F ratio of 24.7853. The engine generates higher engine speed (Fig. 4(a)), less fuel consumption then pure octane (Fig. 4(c)), rapid gear shifting (Fig. 4(d)), higher longitudinal speed which is more than 120 Km/h (Fig. 4(e)), and covers more distance (Fig. 4 (f)) than other cases. It can be clearly seen in Fig. 4(e) that the vehicle millage with H_2 gas is lot higher than without H_2 gas.

It was observed and computed from Fig. 4(c) that the 37% to 45% of octane consumption is reduced when used in addition with H_2 gas with the computed A/F ratio. Octane consumption can be further reduced if a fuel-lean mixture is used for the same vehicle. This is the paramount finding of this study. Using the advanced technology and efficient sensing devices, the required mixture of octane and H_2 gas with their corresponding A/F ratio can be achieved which can solve many problems of automobile industry, power production units using heat sources, and in general the energy crises.

7. Conclusion

A nonlinear vehicle dynamic model is used to investigate the torque generated and fuel consumption using the A/F ratios and heat of combustion of H_2, gasoline (octane), and their mixture. The heat of combustion and required A/F ratio for mixture is determined using the combustion Stoichiometry and Hess's Law. The nonlinear vehicle model includes the engine dynamics, transmission dynamics, wheel dynamics, and vehicle longitudinal dynamics which capture the vehicle response in continuous time-domain. The simulation results show that the H_2 gas is far more economical than pure octane and if the required size of dry cell HHO generator with the given A/F ratio is used then it will significantly reduce the reliance on the fossil fuels which are depleting rapidly and at the same time the emission of the gasoline can be reduced which produce a large amount of pollutants. The mixture of both fuels with their required A/F ratio can reduce the octane consumption up to 37% to 45%. It is, therefore, recommended that H_2 gas as a supplement fuel should be used to improve the vehicle efficiency and to reduce the combustion emissions. Moreover, the simulation of the nonlinear vehicle dynamic model using the H_2, gasoline, and its mixture can be useful for developing the experimental model, its testing, and its implementation.

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