GRINREY

Efficient Engineering Systems

Volume 01

Sandip A. Kale
Editor

Engineering Research Transcripts

1

Effectiveness of Hydrogen Enrichment in CNG Fuelled SI Engine: A Review

Kiran P. Pawar[a,*] and Sanjay D. Yadav[a]

[a]Department of Automobile Engineering, Rajarambapu Institute of Technology, Rajaramnagar (Sangli), India

*Corresponding author: kppawar87@gmail.com

ABSTRACT

Across the world, the demand for fossil fuel is growing notably because of the growth in vehicle populace and heavy use in energy generation plants. Vehicle exhaust dangerous emission is inflicting global warming and heavy health issues. To tackle this issue developing country like India opted to follow strict BS-VI emission norms. One of the viable solutions is to shift towards alternate fuel is the need of the hour. In recent years, predominant attention was to choose fuels that reducing fossil fuel consumption and pollutant emissions. Natural Gas vehicles are increasing but it has some disadvantages like low flame speed, low performance, low brake thermal efficiency, and high emission. Gaseous fuels like methane and hydrogen are the most interesting fuel that can be used in SI Engine vehicles as an alternative fuel. The burning fleetness of the mixture is appreciably high, the ignition energy is low, and the lean-burn potentiality is good. Antiknock property of Hydrogen fuel facilitates to enhance the compression ratio, which results in thermal efficiency. Hydrogen is a non-carbonaceous fuel therefore; it does not lead to carbon content emissions. This chaptr offers reviews on HCNG blend compatibility with SI Engine and its Performance, Emission, and studies the combustion fundamentals of natural gas, hydrogen, and hydrogen-natural gas mixture.

Keywords: Alternative fuel, Combustion, Emission, Hydrogen, HCNG

Efficient Engineering Systems: Volume 1 | ISBN: 978-81-948951-8-3
Book Series: Engineering Research Transcripts | Vol: 01

1. INTRODUCTION

Automotive sector and power generation plant facing enormous challenges in fuel supply and demand chain and its cost in the past 2-4 decades. Fossil fuels like coal, diesel, natural gas facing a deficiency in various properties to meet the stricter emission norms and the economy of operations. Chimneys of the power plant and tailpipe of engines emit dangerous emission that pollutes the system and the environment. Oil price is very volatile and uncertain. It depends on the capacity of the originating source. Vehicles with Natural gas are increasing wherein it has many disadvantages like retarded flame speed, low performance, below average brake thermal efficiency, and high emission. Gaseous fuels like methane and hydrogen are the interesting fuel, which will be utilized in SI Engine vehicles as an alternate fuel. The burning fleetness of the mixture is interestingly high, the minimum ignition energy is low and the lean-burn potentiality is nice. Hydrogen's anti-knock characteristic enables it to reinforce the compression ratio, which ends up within the further enhancement of thermal efficiency.

To enhance the overall performance of the CNG engines at the lean-burn conditions, there need to increase its burning velocity, which may be consummated employing blending hydrogen (Hythane). Hythane has good flammability limits within the air with minimum ignition energy (0.02 mJ). Roopesh Kumar Mehra et al. [1] studied a mixture of Hythane 10% and 18%, and then compare it therewith of CNG. He concluded a 6% rise in thermal efficiency and a 4% reduction in engine emission. The single-cylinder CI engine is modified and fuelled by HCNG is studied by S. M.V. Sagar et al. [2]. The engine was tested at a speed of 1500 rpm at 250 BTDC; 30% Hythane blend confirmed the pleasant anti-knocking characteristics among all HCNG mixtures. Rohit Singh Lather, Changming Gong et al [3.4], investigated the relation of ignition timing on combustion and emissions of Hythane fuelled SI engine at constant engine speeds. They also dealt with the various parameters and concluded that the rise in IMEP, rise in-cylinder pressure, good heat loss rate, and increased combustion length at low engine speeds at numerous ignition timings and excess air ratio of 1.40. Selim Tangoz et al. [5] operated Hythane blend at 1500, 2000, and 2500 rpm underneath full load conditions on Isuzu three L engine, having a compression ratio of 12.5, the highest efficiency was usually obtained with Hythane 5 (five% Hydrogen in natural fuel) gasoline.

The HC and CO emissions usually not up to the Euro-5 and Euro-6 standards. Liu et al. [6], full-fledged the reduction of the heat loss and increase of indicated thermal efficiency of HCNG combination of the Atkinson cycle with high compression ratio and low heat rejection with a 55% hydrogen blend. Due to prolonged and quicker flame propagation, wide flammability limits, and low minimum ignition energy of the gas, it's a perfect condition to mix hydrogen that enhances lean-burn capabilities [7]. Traditional, hybrid, electric, biofuel, fuel cell, and hydrogen-fueled ICE vehicles are relatively assessed supported their carbon dioxide and SO_2 emissions. Once the engine operates at partial load the throttle causes high pumping losses that decrease the engine efficiency, it is often overcome by lean mixture condition ends up in the misfiring of fuel. The combustion limits can be extended by the addition of hydrogen to the regular fuel [7, 8].

Spark ignition engine equipped with an indirect injection system with the result of Hythane addition for PFI and DI configurations was evaluated on an equivalent engine at 2000 rpm throttled condition [9]. Willian Cezar Nadaleti et al. [7, 8] experimented on the three cylinders naturally aspirated SI engine. Throughout the tests, the engine worked with a set speed of 1500 RPM. For all fuel mix, the engine output power has been 18% of most power (for 1500 RPM) reached by the engine for ratio combustion of HCNG fuel. Hydrogen Gas Enrichment is a promising and trending technology within which numerous researchers are working globally. Hydrogen gas will produce freely by the unconventional technique and with sustainable sources.

2. FUNDAMENTAL PHYSICOCHEMICAL PROPERTIES OF HCNG

2.1. Lower heating value

Heat Release rate after the combustion of the fuel when complete combustion is achieved. Natural gas like Methane, Ethanol, and hydrogen have a comparatively better value per unit mass than gasoline and diesel-fueled engine, Lower heating value per unit volume is lower as compared to gasoline which causes declination in the air-breathing capacity of the engine or volumetric efficiency. Although the volumetric efficiency of Hydrogen gas is low relative to methane of gasoline fuel, however, hydrogen requires very less air per unit volume. Fig.1 represents the volumetric lower heating value of fuel-air mixtures is compared with hydrogen fraction. For various mixtures and at various excess air-fuel ratios the hydrogen addition shows the declination in LHV after λ -1.6.

2.2. Adiabatic Flame Temperature and Auto-Ignition Temperature

Adiabatic flame temperature (Tad) of the fuel/air mixture having strong influences on the combustion rates inside the combustion chamber. Elevated combustion temperature is helpful for more complete combustion and hence could reduce HC and CO emissions, but it adversely affects by increasing NOx emission. Theoretical calculation indicated that the Tad of Hythane and the air mixture flame goes on increasing with an increasing fraction of Hydrogen. The upgrading trend of adiabatic flame temperature with hydrogen fractions similar in the least excess air ratios (λ) as shown in Fig.2 Increase of excess air ration λ leads to a drastic decrease in combustion temperature [10]. Although hydrogen addition can increase the peak flame temperature of Hythane mixtures from a theoretical point of view, in real engine applications, however, its effects on maximum in-cylinder gas temperature (Tmax) may depend upon other factors like charge efficiency, combustion phasing, heat loss, etc.

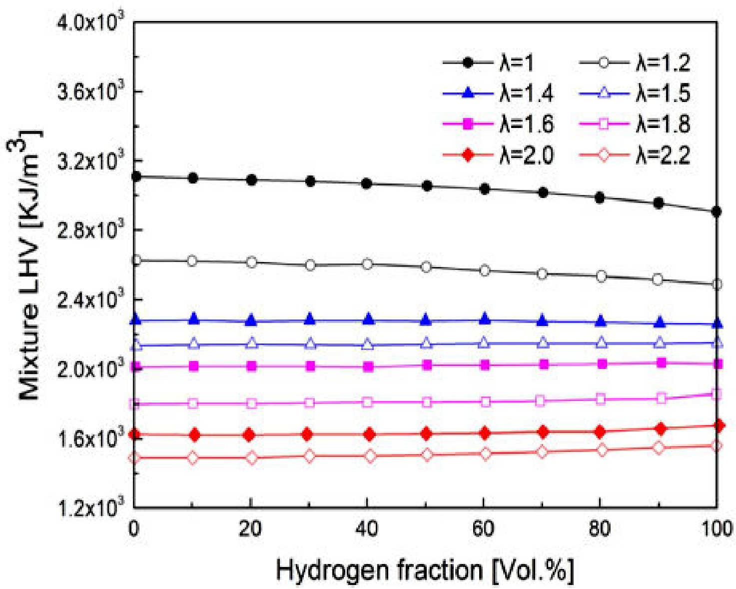

Fig. 1. Hydrogen fraction Versus the LHV value [5]

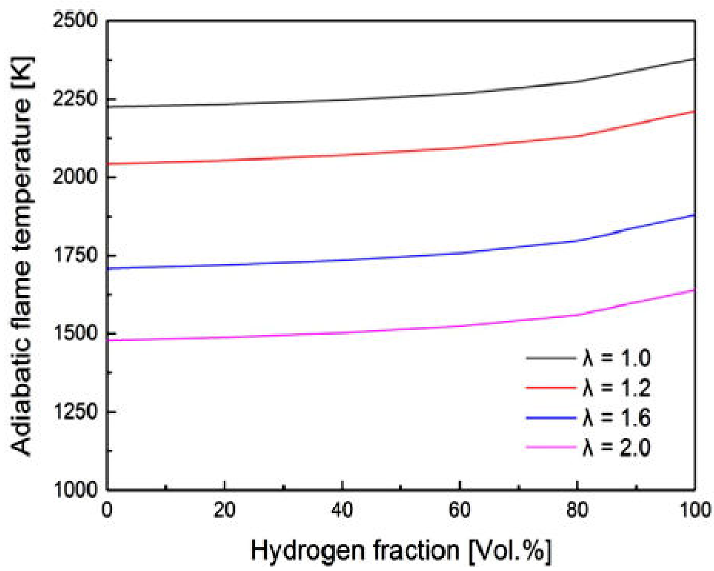

Fig. 2. Variation of adiabatic flame Temperature versus hydrogen fraction [5]

2.3. Minimum Ignition Energy and Flammability Limits

Spark plug supplies the spark to ignite and burn the air and fuel mixture in SI engines. The least initial energy required for burning and developing the flame of the fuel in the combustion chamber is termed as Minimum Ignition Energy. Explosion hazards are defined by this property, hence for designing the chamber and selects the source of burning is also verified with the property. The various properties of hydrogen are presented in Table No.1 by comparison with gasoline and natural gas methane fuel. Hydrogen has a good range of flame development limits compared to methane as shown in Fig.3. The addition of Hydrogen in Natural gas has a notable increase in the flame development limit. After burning and power stroke leftover flue gases are not getting expelled into the atmosphere even after exhaust stroke, low scavenging, and cylinder wall temperature also affect flame limit [21].

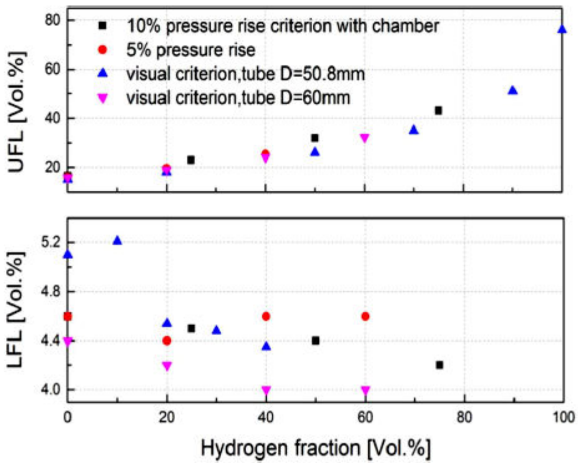

Fig. 3. Variation Hydrogen fraction and its effect on upper and lower flammability limits[5]

Table1. Hydrogen fuel Properties Compared to Diesel, Methane and Gasoline [1, 5, 7]

Properties of Fuel	Methane	Gasoline	Diesel	Hydrogen
Lower Heating Value (MJ/kg)	46.72	44.79	42.5	119.7
Volumetric Low Heating Value (MJ/m^3)	32.97	216.38	-	10.22
LHV For Stoichiometric mixture (MJ/m^3)	3.13	3.83	-	3.02
Density (kg/m^3)	0.67	720-775	833-881	0.08
Molar Mass (kg/Mol)	16.04	100-105	204	2.02
Diffusion Coefficient (cm^2/s)	0.189	-	-	0.61
Flammability Limits (Vol%)	5.3-15	1.2-6	0.7-5	4-75
Laminar Flame Speed (m/s)	0.38	0.37-0.43	-	2.65-3.25
Auto Ignition Temperature (K)	813	500-750	553	858
Adiabatic Flame Temperature (K)	2224	2470	2327	2379
Minimum Ignition Energy(mJ)	0.28	0.25	-	0.02
Quenching Distance (mm)	2.03	2	-	0.64

The lean burning ability of CNG or Natural Gas engine is very poor and leads to misfiring due to insufficient fuel, this can be overcome by adding the fast burning and highest lean-burn ability fuel, i.e. Hydrogen that can increase the thermal efficiency and emits low emission as plotted on the graph in Fig.4.

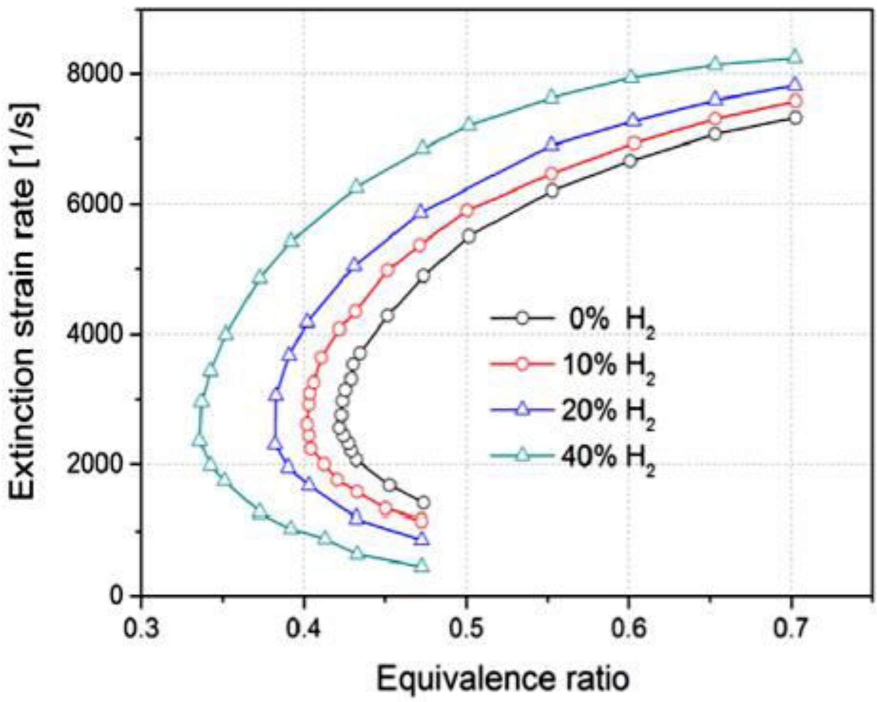

Fig. 4. Effects of hydrogen fraction on Equivalence ratio [5]

2.4. Quenching Distance

During the combustion in SI engine fuel is atomized by injector or design of intake manifold, after burning which controls the motion of the flame propagation. Due to the intricate shape of the combustion chamber when the flame is reaching towards faraway space where relatively the cold surface is observed, it may shorten the length of the flame. This phenomenon is called Flame Quenching and it results in the heat loosed at those surfaces, which are the sources of incomplete combustion and finally produce the unburned HC and CO in the SI engine. As plotted in Fig. 5, in the fixed excess air ratio condition, as hydrogen fraction increases three is a decrease in the quenching distance. It also verified by various researchers as pointed out in the property Table no.1. Hydrogen has less quenching distance (0.64 mm) as compared to that of methane (2.03 mm).

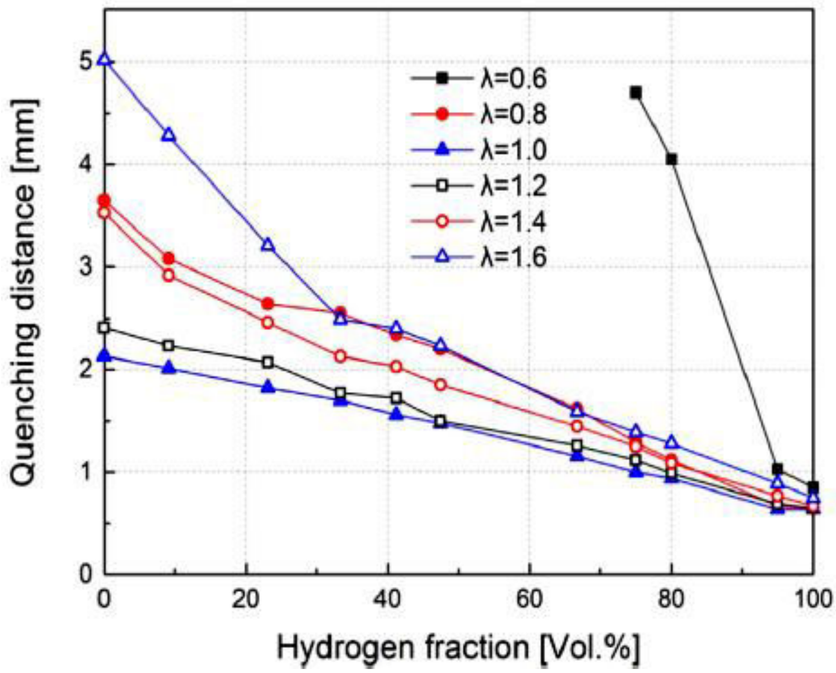

Fig. 5. Quenching Distances and its variation with Hydrogen Fraction [5]

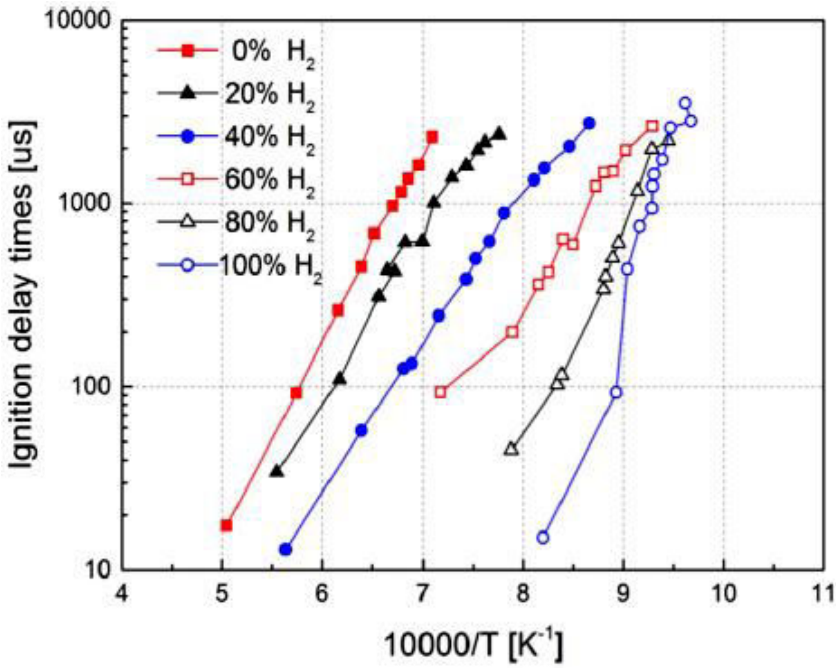

Fig. 6. Effect of hydrogen fraction on ignition delay at 0.5 Equivalence ratio [5]

2.5. Ignition Delay and Laminar Flame Speed

Inside SI Engine, the flame front compresses burnt gases, which results in the rise of pressure and temperature of the unburnt charge, which transfers the heat to the remaining charge and auto-ignition takes place. This delay of flame reaches the farthest end where a charge is waiting for the flame that can be defined as ignition delay in the combustion chamber. To overcome this undesirable phenomenon laminar speed or streamline flame flow is necessary. Hydrogen addition in the CNG can increase the laminar speed of the flame propagation

2.6. Wobbe Index and Methane Number

When utilizing gases in a thermal system, a parameter “Wobbe Index” can be defined, this indicates the interchangeability of gaseous fuels. If two gases have the same Wobbe Index, it is possible to directly substitute either of the gas, without any change in the fuel system [4]. The Wobbe Index of natural gas does not vary much when blended with small percentages of hydrogen, by volume. The knocking characteristics of gaseous fuels for internal combustion engines are measured using Methane Number (MN). The MN of Methane is 100, and of hydrogen, MN is 0. A higher value of MN indicates good anti-knocking characteristics [5]. Increasing the hydrogen percentage of methane, decrease the MN. Therefore, it is observed that hydrogen more than 20% by volume in CNG will not produce the desired performance in internal combustion engines [4].

3. FACTORS INFLUENCING PERFORMANCE AND EMISSION CHARACTERISTICS OF HCNG ENGINES

3.1. Lean Burn Combustion

It is the combustion process, in which the air percentage is more as compared to the standard stoichiometric value of the air and fuel mixture. Hythane SI engines work smoothly with a very less misfire. Ultra-lean and lean burning upper and lower limit of natural gas is elevated by the addition of hydrogen in natural gas. The Upper lean burn limit can achieve higher performance efficiency by reaching peak cylinder pressure and less coefficient of Variation.

3.2. Exhaust Gas Recirculation (EGR)

The Addition of hydrogen increases the heat generation and subsequently increases the temperature, which results in the emission of NOx species in the tailpipe. To tackle the emission of NOx exhaust gas recirculation method is a viable solution.

3.3. Direct Fuel Injection System

In the SI engine recently, direct injection system increases the fuel economy. Port fuel injection and direct fuel injection are the modern methods of fuel injection in IC engines, but the complexity in the process increases. Ignition timing and injection timing are the key parameters on which the performance of the engine can be judged. Hythanefuelled SI engine are very much depends on the direct fuel injection system from a homogeneous mixture of hydrogen and natural gas [10].

3.4. Stoichiometric A/F Mixture

The theoretical air-fuel mixture is called a stoichiometric air-fuel ratio when the excess air-fuel ratio having value one. Exhaust emissions like CO and HC need to convert into CO2 and water vapors by using a three-way catalytic converter in the exhaust tailpipe. However, the limitations to the use of a three-way catalytic converter for reduction of emission are that the engine should run at a stoichiometric air-fuel ratio. Overall, thermal efficiency depends on the conversion of these harmful products by the complete combustion of fresh charge or converting it into final less harmful products like CO2 [6].

3.5. Ignition Timings

If the ignition is extremely early, and therefore the combustion occurs before the compression stroke is ended, because of which the developed pressure opposes the piston motion and lowers the engine power. If the ignition is just too late, the piston would have already completed some a part of the expansion stroke before the pressure rise occurs, which resulted in a significant loss in engine power [3].

3.6. Engine Speed

Brake thermal efficiency, indicated thermal efficiency, as well as the power output, is having a linear relation with engine speed. But we can run the engine at a higher speed because it will deteriorate the combustion process by producing very high unburnt charges. To get a higher speed without affecting the combustion process requires high quality of fuel, higher lean-burn ability, good scavenging, and precise ignition and injection timing [3].

4. PERFORMANCE AND EMISSION OF HCNG ENGINE

Mechanical Power, thermal efficiency, power/torque output of the engine are the most important performance parameters of the engine.

4.1. Energy Consumption, Power Output, and Engine Torque

The minimum ignition energy of hydrogen fuel is on the higher side than the gasoline and natural gas fuels, which results in a higher amount of energy consumption as hydrogen percentage increases in addition to natural gas. From Fig. 7 at different excess ratio variations in the energy consumption due to the availability of oxygen for complete combustion higher energy is required.

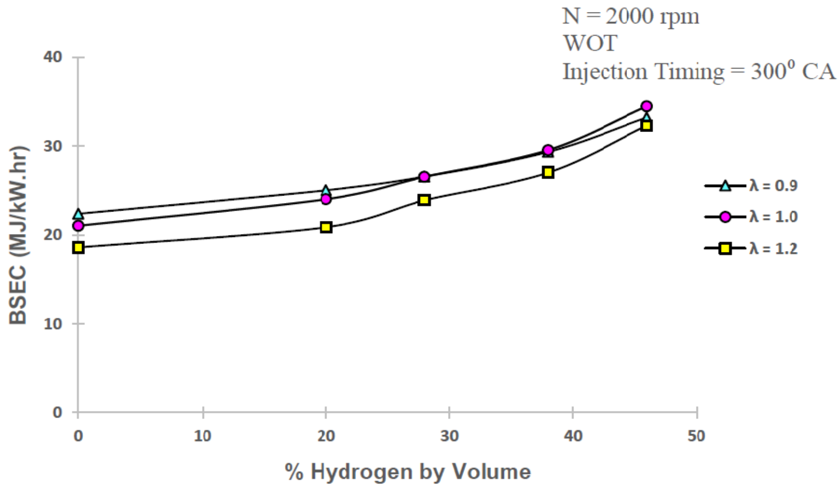

Fig. 7. Energy Consumption at different hydrogen fraction with different air-fuel ratio [26]

Hythane blend fuelled engines prominently signifies the better results compared to natural gas engines. The high heat dissipation rate from the cylinder compartment results in higher thermal efficiency and power output. Fig. 8. Shows the relation of the power output versus different hydrogen fractions at various RPM and it shows the increasing trend in power.The Power output at a different fraction of hydrogen from 0 to 50% at different excess ratios also shows an increasing trend with an increase in hydrogen percentage as shown in Fig. 9.

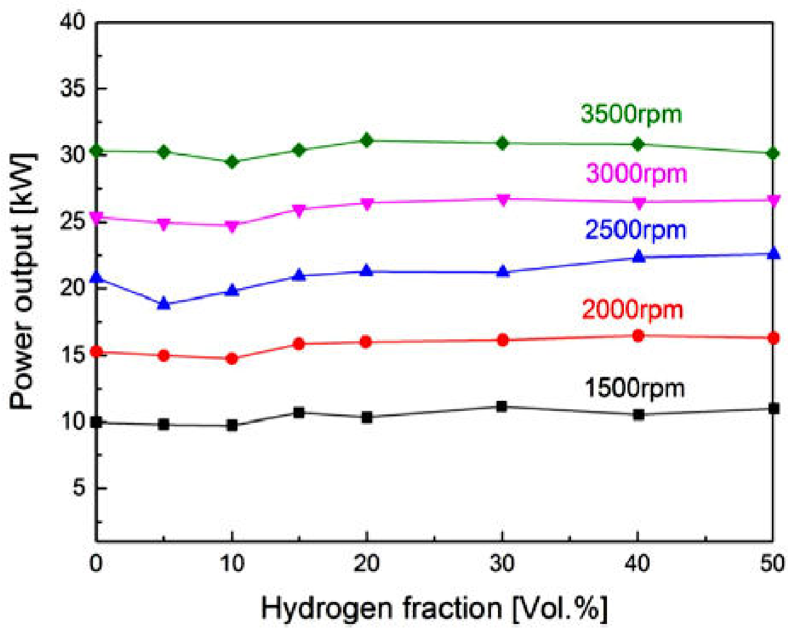

Fig. 8. Effect on the Hydrogen different percentage of power output [5]

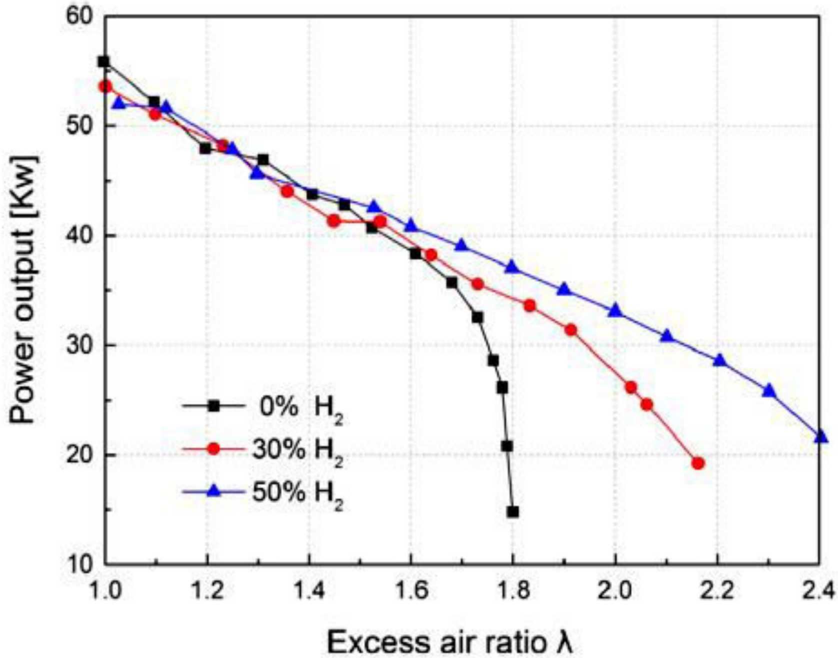

Fig. 9. Effect of the different Hydrogen percentage on power output with different excess air ratio[5]

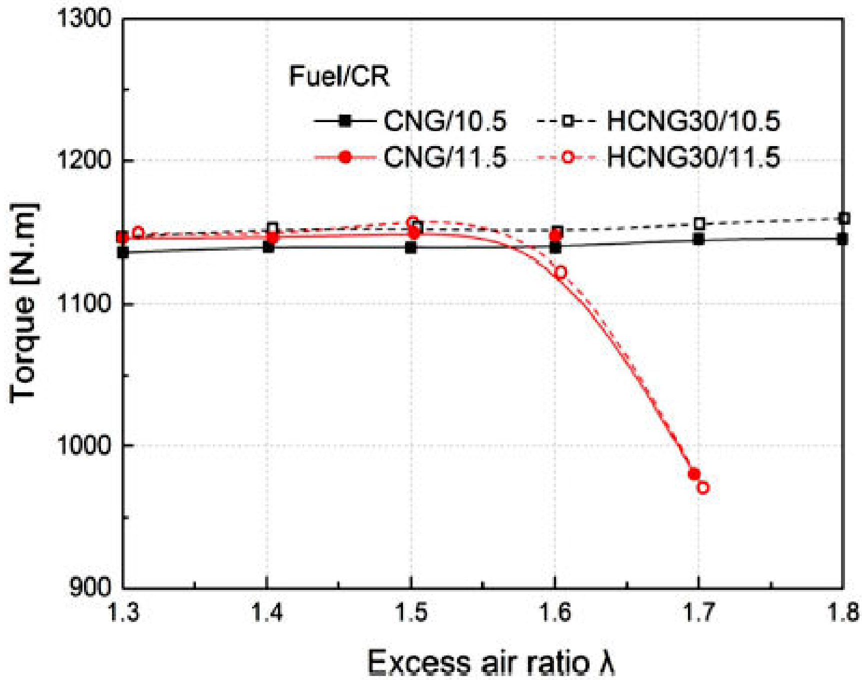

Fig. 10. Engine Torque variation at different excess air ratio at different hydrogen fraction[5]

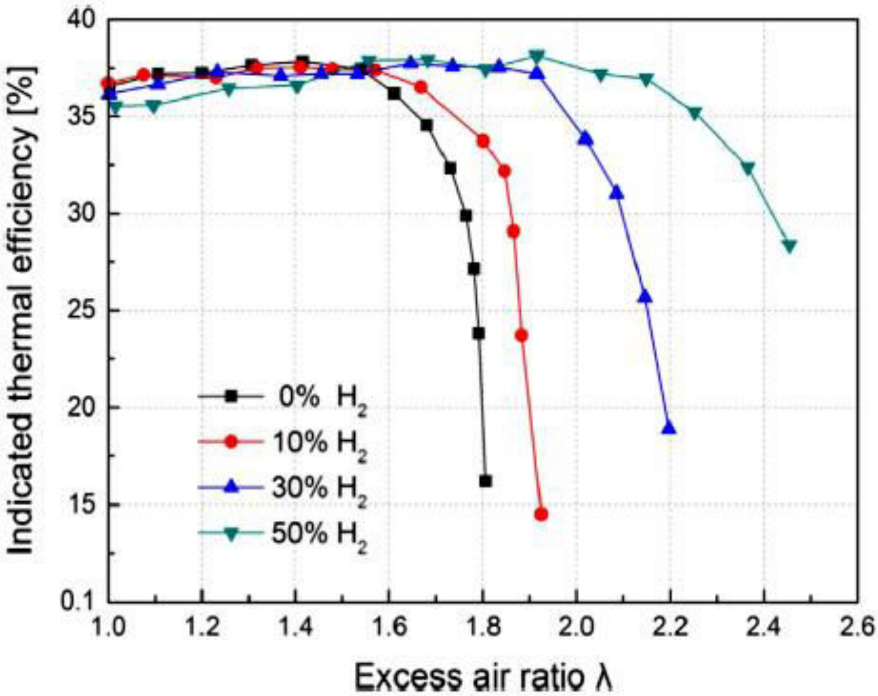

Fig. 11. Indicated thermal efficiency at different excess air ratio at different hydrogen fraction [5]

Torque output defines the load levitating capacity as within the graph shown in Fig.10 Relation between excess air ratios, hydrogen fraction, compression ratio, and torque of the engines at the shaft. The lean-burn ability of the hydrogen fraction is nice and it can help to extend the compression ratio of the engine for better power output performance and thermal efficiency.

Fig.11 represents the relation between the surplus air ratios and indicated thermal efficiency at a different fraction of the hydrogen. As hydrogen percentage increases the indicated thermal efficiency increases with the good lean-burn ability [5].

4.2. Emission Performances

The most fascinating and deserving property of the Hythane blend has the power to supply low levels of carbon monoxide, Hydrocarbon, CO2, and sulfur dioxide emissions as compared to Diesel, NG, and Gasoline engines. But there are chances of a rise within the level of the NOx because of high burning temperature. The graph is shown in Fig.12 ad 13 at 50% Hydrogen blends the best NOx emission. Ignition timing also plays a crucial role as an immediate relation with the retardation and NOx emission [5, 6].

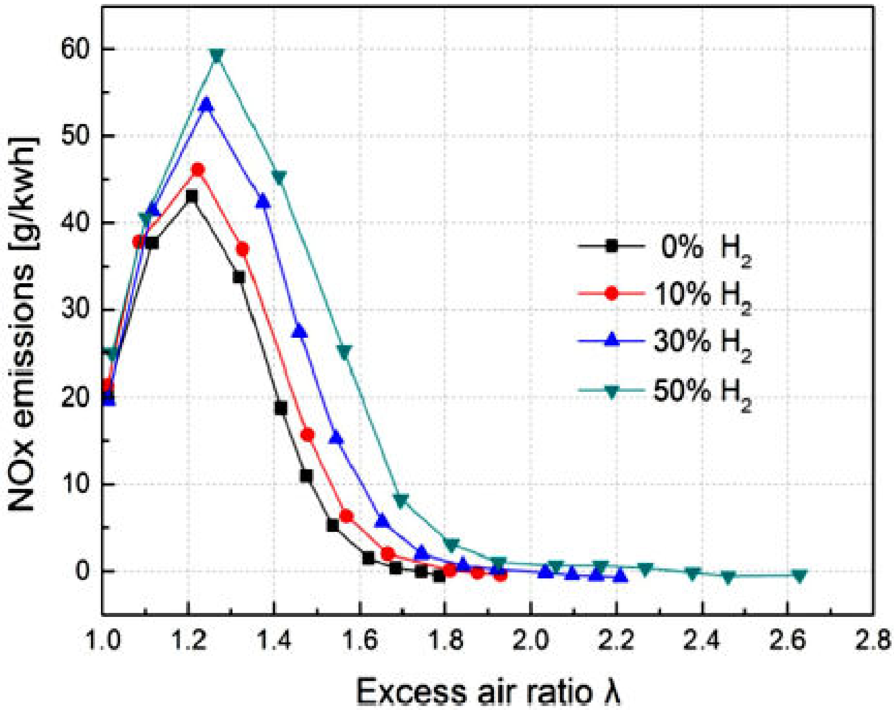

Fig. 12. NOx emission at different Excess Air Ratio and Hydrogen Fraction [5]

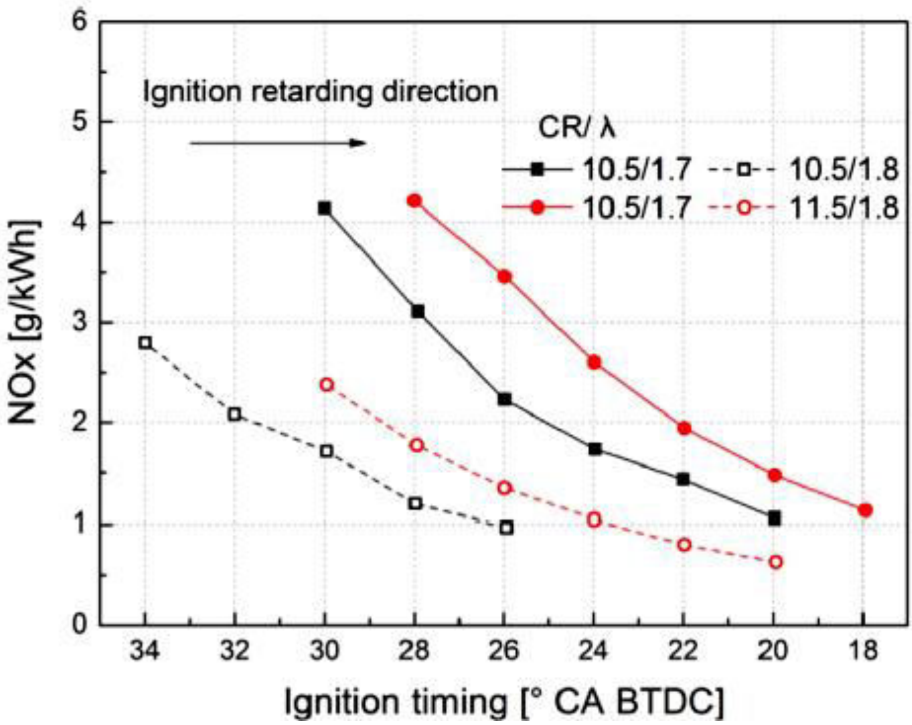

Fig. 13. NOx emission at different Excess Air Ratio and Hydrogen Fraction [5]

4.2.1 Total HCs Emissions

The predominant causes of hydrocarbon emissions in S.I. engines are that the incompletely burned fuel trapped within the combustion chamber's intricate spaces where flame cannot reach. Incomplete burning of fuel by flame quenching within the vicinity of the cold combustion chamber wall or nearby spaces as well as air-fuel homogeneity is another source [53]. A mix of Hythane can effectively reduce the flame atomization distance and extend the flammability region.

4.2.2 CO Emissions, Particulates, and Other Unregulated Emissions

The addition of hydrogen in natural gas reduces the emissions of carbon monoxide and it has a decreased trend if the continuous addition of increased hydrogen percentage [39]. Particulate matter emission is very less in the case of Hythane as compared to gasoline and natural gas engines. Fig.14 and 15 shows, emission trend compared with λ by adding a special fraction of hydrogen, it shows that the addition of hydrogen decreases the overall emission species.

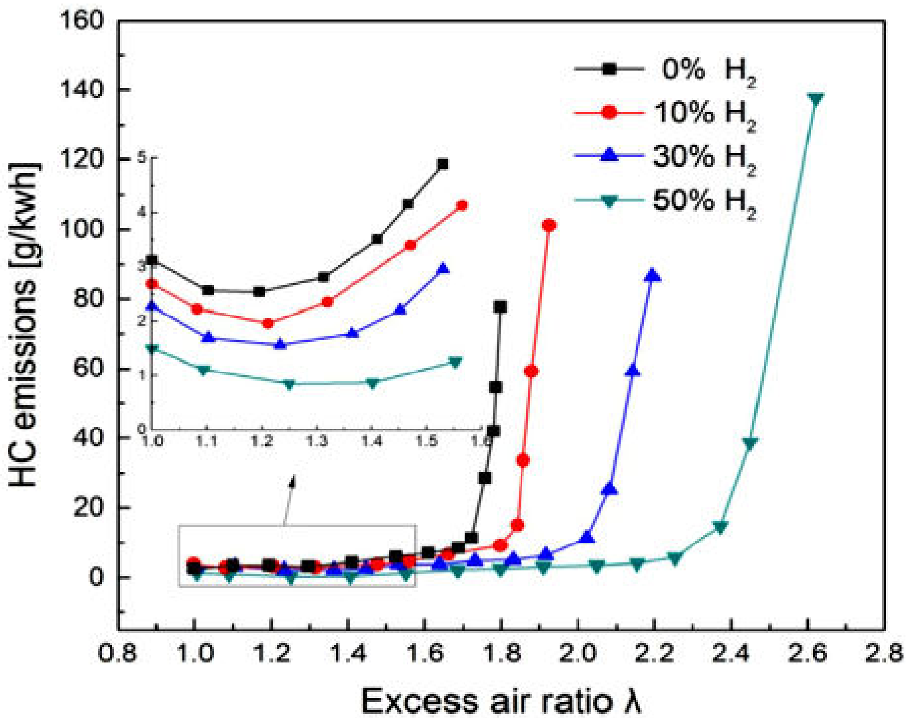

Fig. 14. Hydrocarbon emission at different excess ratio and different hydrogen fraction [5]

4.3. Lean Burn Limit

Hydrogen addition to natural gas is one of the key reasons to increase the lean-burn ability which signifies the rise of power output and a reduction in the engine emission. The fuel economy has also increased because of higher lean-burn ability, but it may result in frequent misfires.

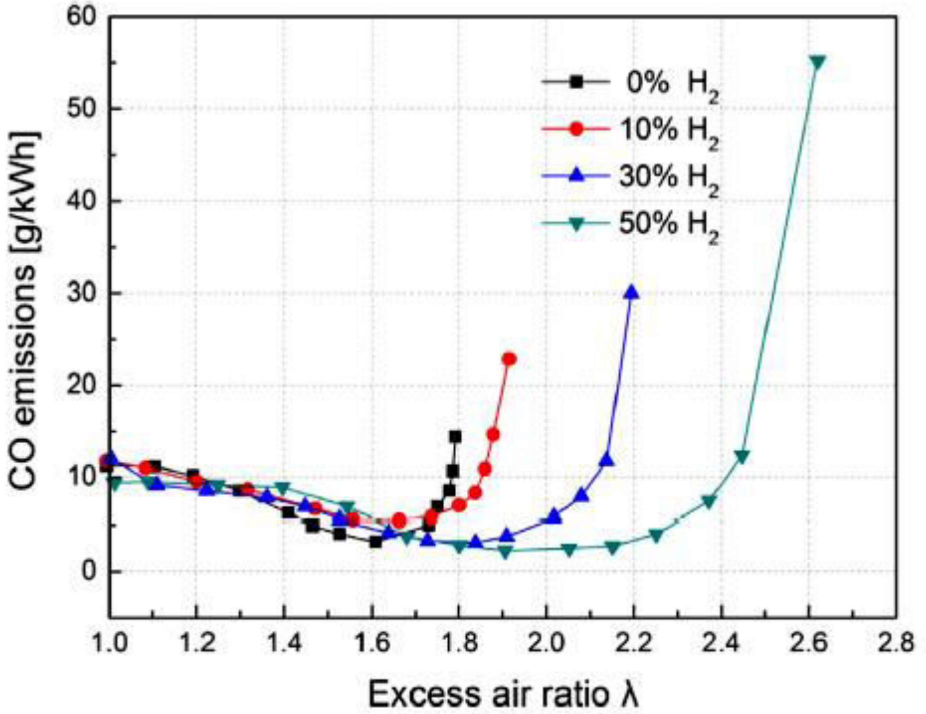

Fig. 15. Carbon Monoxide emission at different excess ratio and different hydrogen fraction [5]

4.4. Excess air ratio (λ)

It is the quotient of the actual air-fuel mixture to the standard stoichiometric air-fuel ratio, it is denoted by λ. When the value of λ is more than one, then it is the rich air-fuel mixture and if it is less than one, then the mixture of air and fuel is taken as lean. Stable engine combustion is the function of the variation of the various properties at peak cylinder pressure and effective pressure on indicated power.

Figure 16 shows the mass of the particulate size at different percentages of Hythane Fraction like 0, 10, 20, and 30Percent at various engine loads. Table 2, 3 & 4 gives detailed information about the parameters that need to consider while studying Hythane Blend.

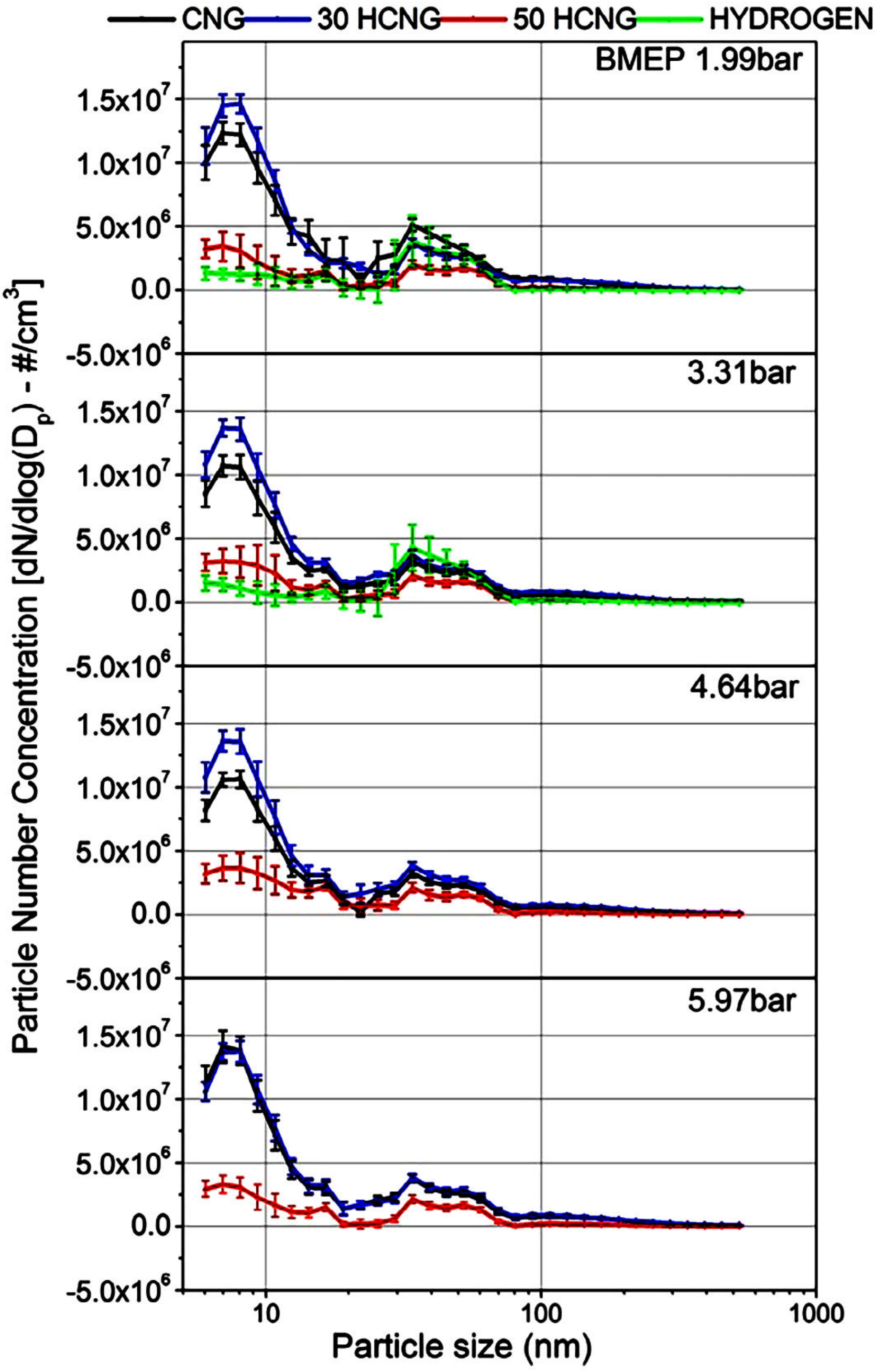

Fig. 16. Particle Size Versus Particle Mass Concentration at different fractions of Hythane fuel [2]

Table2. Engine Parameter needs to study

Parameters of Engine to Control or Optimized	Parameters of study to meet objectives	Instrument for Measurement
Equivalence ratio(λ), Air-fuel ratio	Maximum brake torque (MBT),	Suitable Lambda Sensor, customized high volume flow rate solenoid injectors
Brake torque, Fuel mass flow rate, Engine speed, Exhaust gas temperature, Calorific values of the test fuels, and volumetric energy density of the test fuel.	Indicated thermal efficiency (ITE)	Dynamometer
HCNG Vol %	Brake thermal efficiency (ITE), brake power	
Pressure-crank angle, Crank Angle Degree, Spark, and Injection Timing	Maximum in-cylinder pressure	Pressure Transducer, Data acquisition system, Flowmeter, Gas sensor
	Peak cylinder pressure	
Heat release rate (HRR), Rich A/F Ratio	Brake specific fuel consumption (BSFC), Brake mean Effective Pressure (BMEP), Brake Specific energy (BSEC), Volumetric efficiency	

Table3. Operating Parameters to be focused

Parameters of Engine to Change or Optimized	Parameters of study to meet objectives	Instrument for Measurement
Wide-open throttle, valve overlap timing, RAFR, port fuel injection, engine loads	Engine backfire, Research Octane Number	Precision shaft encoder
Port injection system, injection timing	Lean Burn Limits	
CR, crank angle position for various test fuels, shorter burning duration	Heat release rate	

Fuel injection pressure, fuel injection system, compression ratio	Peak pressure, coefficient of variation of indicated mean effective pressure	
Decreased Combustion Duration with an increase in BMEP	Mass fraction burned, Effective Pressure	
	Coefficient of variation knock's tendency	
Flame speed, adiabatic flame temperature	Peak cylinder temperature	Thermocouples

Table 4. Emission Parameters under consideration

Parameters of Engine to Change or Optimized	**Parameters of study to meet objectives**	**Instrument for Measurement**
Optimizing Compression ratio, Lean combustion. Excess-air ratio and Ignition timing, EGR rates, exhaust gas temperature	Reduce HC, NOx and CO Emissions, unburned hydrocarbons, CO2, particulate matter	Measurement and Plotting Graph by exhaust gas emission analyzer, Nitric Oxide sensor
Valve overlap angle, low carbon content	Total Hydrocarbon(THC)	
Hydrogen-to-carbon ratio	Greenhouse	
	gas emissions	
Incomplete combustion, misfire, insufficient oxygen	HC, CO, NOx,	

Table 5. Summary of the Literature

Authors	**Findings**	**Research Gap**	**Ref.**
Roopesh Kumar Mehra [2017]	Hydrogen addition allows the engine to works on higher compression ratio without any combustion instability compared to CNG, which improves thermal efficiency.	Finding perfect mixture proportion is a major problem with implementing HCNG fuel Optimum spark timing and A/F ratio for best performance Delayed ignition timing	[1]

		and lean combustion are the area should be focused in future to regulate NOx emissions level.	
S.M.V. Sagar [2018]	Investigate particulate emissions from HCNG fueled prototype engine, for diverse test fuel mixture compositions	Very little research has been done on particulate emissions from gaseous fuels, especially HCNG mixtures	[2]
Rohit Singh Lather. [2018]	This paper is comprehensive overview of combustion fundamentals of hydrogen-natural gas mixture in SI Engine, The air-fuel ratio, the time of injection, the compression ratio and speed play a major role in blending HCNG in an SI engine	It is necessary to develop a strategy to control the NOx emissions under the promise of successful start of engine.	[3]
Changming Gong [2019]	Experimentally investigated the effects of ignition timing on combustion and emissions of an SI methanol engine with added hydrogen at different engine speeds	The relationship between NOX and soot emissions with added hydrogen needs to be clarified on future research work	[4]
Fuwu Yan [2017]	The physicochemical properties of hydrogen and its mixture with natural gas were firstly Analyzed	The hydrogen fractions need to be optimized and corresponding adjustments are required for various other engine operating and design parameters	[5]
Canan Acar [2018]	hydrogen-fueled internal combustion engines have the lowest GHG emissions, hydrogen fueled internal combustion engines have the lowest social cost of carbon	Hydrogen widespread use is still likely to be hindered by many practical difficulties of large scale hydrogen production, storage, fueling infrastructures as well as engine abnormal	[6]

		combustion.	
Willian C_ezar Nadaleti [2017]	Experimental study of H-CNG fuel with partial load analysis of SI engine for road transport application.	The combustion duration had a significant effect on both performance and emission characteristics of the engine. It is another factor that should be designed carefully to achieve the best results from the engine's work	[7]
S.M.V. Sagar, [2017]	Experiment was conducted on SI using various % of HCNG mixtures having 0, 10, 20, 30, 50, 70 and 100%.The performance and combustion characteristics of these test fuels were compared with that of baseline CNG, versatile dynamic HCNG mixing System is used for correct composition	In order to conduct a comprehensive study and make sound conclusions, it is necessary to investigate entire span (0 to 100%) of hydrogen fraction in the HCNG mixtures.	[8]
F. Catapano [2016]	This paper is comparison between CH4 and different CH4/H2 mixtures in a single-cylinder Port Fuel/Direct Injection spark ignition (PFI/DISI) engine operating under steady state conditions.	Further improvement can be obtained reducing the duration of injection by using higher injection pressure.	[9]
G.M. Kosmadakis [2016]	This analysis considers engine load variation through a variable equivalence ratio, with the application of an in-house research, three-dimensional computational fluid dynamics code (3DCFD) for detailed in-cylinder simulations	Comprehensive study can be expanded to identify engine configurations and strategies for reducing pollutant emissions	[11]

BarisAcıkgoz [2015]	Decrement of fuel consumption by 14.04%. Taking into account the power costs, the fuel saving is 8.03%.	The operating parameter and design parameter such as spark timing and Compression ratio should be optimized.	[13]
Selim Tangoz [2017]	Isuzu 3.9 L engine having a 12.5 compression ratio at 1500, 2000 and 2500 rpm using ignition timings of 5, 10, 15 and 20 deg. CA BTDC fuelled by pure CNG, HCNG5, HCNG10, HCNG20. The HC values were generally obtained as lowest values at HCNG5 for given engine speeds and advance.	Optimization of Hydrogen CNG mixture need to select carefully and the selection of optimum ignition timing.	[14]
Silvana Di Iorio [2015]	Engine investigations were carried out at constant engine speed of 1500 rpm 42 for different H/C ratios, Spark timing and RAFR kept constant. It shows higher peak pressure, but lower maximum Brake torque (MBT), BTE was higher and NOx emissions also	HCNG engine fueled with a higher hydrogen fraction may cause abnormal combustion such as pre-ignition, knock and backfire Numerical modeling and CFD analysis of combustion model and fuel injection timing are having big scope for the analysis of combustion performance.	[15]
Yang Liu [2019]	Combination of Atkinson cycle with high compression ratio and low heat rejection on the hydrogen-enriched Compressed natural gas prototype engine with 55% hydrogen blend	Validation by Software is need to study n depth	[16]
B.G. Agaie [2018]	Investigated the effects of hydrogen on the combustion stability and	Production and storage of hydrogen can be made completely sustainable	[18]

	thermal efficiency of a T-GDI engine in stoichiometric to lean conditions with low to high loads	which also could dramatically enhance the contribution of fuel cell and hydrogen internal combustion engines in the transportation sector.	
Deymi Dashtebayaz [2016]	Engine's work is important factor need to improve by using different mixtures of methane and hydrogen	Engine's work is important factor need to improve by using different mixtures of methane and hydrogen.	[21]
Tadveer Singh Hora [2015]	Experiments were performed to study the effect of varying content of hydrogen in HCNG. Effect of 0%, 10%, 20% and 30% (v/v) of HCNG was experimentally analyzed at constant engine speed 1500 rpm	Optimization HCNG blend composition	[23]
Saheed Wasiu [2018]	An experimental study has been performed to study the brake specific energy consumption (BSEC) and exhaust emission characteristics of the direct injection hydrogen enriched compressed natural gas engine (DI-HCNG) at various air-fuel ratios., BSEC increases, BSCO decreases, BSNOx Decreases and BSUHC Decreases as H2 % increases	Brake Specific Energy Consumption need to calculate accurately	[26]
Santiago Martinez [2018]	900 rpm and WOT, with methane as baseline fuel, 25%vol and 50%vol of hydrogen addition to methane, and finally two syngas equivalent Mixtures, with 50%vol and 75% vol hydrogen content	Spark timing re-calibration is required in order to fully take advantage of fuel properties such as higher laminar flame speed and increased stability	[32]

Rajesh Kumar Prasad [2016]	Investigated the effect of initial CVCC filling pressure, k and H2 percentage in the HCNG mixture on flame kernel evolution, peak cylinder pressure during combustion, and combustion duration, when laser ignition was used to initiate the combustion in the CVCC.	Addition of H2 in the HCNG blends must be optimized to get superior engine combustion, depending on the application.	[34]
Javad Zareei [2018]	For stoichiometric operation, the addition of hydrogen to CNG has produced a brake-specific fuel combustion (bsfc) reduction ranging between 2% and 7% and a brake-specific total unburned hydrocarbons (bsTHCs) decrease up to 40%.	Engine characterization should not be made on the basis of one cylinder only	[38]

5. CONCLUSION

This study reviews the compatibility of the Hythane blend in SI Engines. Hydrogen has good characteristic sort of a lean mixture burning ability, minimum ignition energy, and a wide range of flammability and when blended with natural gas it elevates laminar and streamlines burning velocity of the combustion which caused high flame travel for complete combustion of fuel. Because of complete combustion and streamline flame velocity lower fuel combustion to brake power of the engine. Various studies concluded that overall thermal efficiency increases with compared natural gas-fueled SI engines, considering the parameters like lean mixture and different sparking timing. Variation in natural gas operations in the process is more and unstable operations of the engine. Hythane predominantly decreases this instability of vehicle performance. Due to high flame speed and more amount of energy produced during power strong results in temperature rise at the end which causes NOx emission. Other species of tailpipe emissions like HC, CO, CO2, and SO2 significantly reduces due to carbon-free hydrogen gas. Due to the high auto-ignition temperature of the Hythane and air mixture compared to diesel and gasoline fuel compression of the engines is often increased to urge the higher power output. The methane number of Hydrogen is zero as a Hydrogen fraction increases over 40%, then it's having limits to use as a fuel in engines. Currently, hydrogen generation and storage are facing huge challenging issues which are the scope for future studies. CNG infrastructure is insufficient for the extensive use of hydrogen.

NOMENCLATURE

BSEC	:	Brake Specific Energy Consumption
BSECO	:	Brake Specific Emission Carbon Monoxide
BSFC	:	Brake specific fuel consumption
BTE	:	Brake thermal efficiency
CFD	:	computational fluid dynamics
CNG	:	Compressed natural gas
CO	:	carbon monoxide
CO_2	:	carbon dioxide
EGR	:	Exhaust Gas Recirculation
HC	:	hydrocarbon
HCNG	:	Hydrogen and Compressed natural gas
Hythane	:	Hydrogen and Compressed Natural Gas Blend
IC	:	internal combustion
NOx	:	Nitrogen Oxides
SI	:	spark ignition
η_{bth}	:	Brake thermal efficiency

REFERENCES

1. Roopesh Kumar Mehra, HaoDuan, RomualdasJuknelevičius, Fanhua Ma, Junyin Li, Progress in Hydrogen Enriched Compressed Natural Gas Internal Combustion Engines-A Comprehensive Review, *Renewable, and Sustainable Energy Reviews*, 80, 2017, 1458–1498.
2. S.M.V. Sagar, Avinash Kumar Agarwal, Knocking Behavior, and Emission Characteristics of a Port Fuel Injected Hydrogen Enriched Compressed Natural Gas-Fueled Spark Ignition Engine, *Applied Thermal Engineering*, 141, 2018, 42–50.
3. Rohit Singh Lather, L.M. Das, Performance and Emission Assessment of A Multicylinder S.I Engine Using CNG & HCNG as Fuels, *International Journal of Hydrogen Energy*, 44, 2019, 21181-21192.
4. Changming Gong, Zhaohui Li, YulinChend, Jiajun Liu, Fenghua Liu, Yongqiang Han, Influence of Ignition Timing on Combustion and Emissions of A Spark-Ignition Methanol Engine With Added Hydrogen Under Lean-Burn Conditions, *Fuel*, 235, 2019, 227–238.

5. Fuwa Yana, Lei Xua, Yu Wanga, Application of Hydrogen Enriched Natural Gas in Spark Ignition IC Engines: From Fundamental Fuel Properties to Engine Performances and Emissions, *Renewable And Sustainable Energy Reviews*, 82, 2017, 1125-1157.
6. CananAcar, Ibrahim Dincer, The Potential Role of Hydrogen as a Sustainable Transportation Fuel to Combat Global Warming, *International Journal of Hydrogen Energy*, 2018.
7. Willian, EzarNadaleti, Grzegorz Przybyla, Paulo Belli Filho, Samuel Souza, Methane-Hydrogen Fuel Blends For SI Engines in Brazilian Public Transport-Efficiency and Pollutant Emissions, *International Journal of Hydrogen Energy*, 20, 2018, 1-15.
8. S.M.V. Sagar, A. K. Agarwal, Experimental Investigation of Varying Composition of HCNG on Performance and Combustion Characteristics of a SI Engine, *International Journal of Hydrogen Energy*, 20, 2017.
9. F. Catapano, S. Di Iorio, P. Sementa, B.M. Vaglieco, Analysis of Energy Efficiency of Methane and Hydrogen-Methane Blends In a PFI/DI SI Research Engine, *Energy*, 2016, 1-20.
10. Changming Gong, Dong Li, Zhaohui Li, Fenghua Liu, Numerical Study on Combustion and Emission in a DISI Methanol Engine With Hydrogen Addition, *International Journal of Hydrogen Energy*, 45, 2015.
11. G.M. Kosmadakis, D.C. Rakopoulos, C.D. Rakopoulos, Methane/Hydrogen Fueling A Spark-Ignition Engine For Studying NO_x, CO And HC Emissions With a Research CFD Code, *Fuel*, 2016, 185, 903–915.
12. G.M. Kosmadakis, D.C. Rakopoulos, C.D. Rakopoulos, Investigation of Nitric Oxide Emission Mechanisms in a SI Engine Fueled With Methane/Hydrogen Blends Using a Research CFD Code, *International Journal of Hydrogen Energy*, 40, 2015, 15088-15104.
13. BarisAcıkgoz, CenkCelik, Hakan S. Soyhan, BurakGokalp, Bilal Karabag, Emission Characteristics of a Hydrogen–CH_4Fuelled Spark Ignition Engine, *Fuel*, 159, 2015, 298–307.
14. SelimTangeoz, NafizKahraman, SelahaddinOrhanAkansu, The Effect of Hydrogen on The Performance and Emissions of an SI Engine Having a High Compression Ratio Fuelled By Compressed Natural Gas, *International Journal of Hydrogen Energy*, 2017.
15. Silvana Di Iorio, Paolo Sementa, Bianca Maria Vaglieco, Analysis of Combustion of Methane and Hydrogen Methane Blends In Small DISI (Direct Injection Spark Ignition) Engine Using Advanced Diagnostics, *Energy*, 2015, 1-20.

16. Yang Liu, Yuan He, Cuijie Han And Chenheng Yuan, Combustion And Energy Distribution of Hydrogen-Enriched Compressed Natural Gas Engines With Low Heat Rejection Based on Atkinson Cycle, *Advances In Mechanical Engineering*, 11, 2019, 1-12.
17. Tanveer Singh Hora, Avinash Kumar Agarwal, Experimental Study of The Composition of Hydrogen Enriched Compressed Natural Gas on Engine Performance, Combustion and Emission Characteristics, *Fuel*, 160, 2015, 470–478.
18. B.G. Agaie, I. Khan, Z. Yacoob, I. Tlili, A Novel Technique of Reduce Order Modelling Without Static Correction for Transient Flow of Non-Isothermal Hydrogen-Natural Gas Mixture, *Results In Physics*, 10, 2018, 532–540.
19. Roopesh Kumar Mehra, Fanhua Ma, DuanHao, Study of Turbulent Entrainment Quasi-Dimensional Combustion Model for HCNG Engines With Variable Ignition Timings, *SAE International*, 21, 2018, 1-12.
20. J. Pradeep Bhasker, E. Porpatham, Effects of Compression Ratio and Hydrogen Addition on Lean Combustion Characteristics and Emission Formation in a Compressed Natural Gas Fuelled Spark Ignition Engine, *Fuel*, 208, 2017, 260–270.
21. [21] DeymiDashtebayaz M, EbrahimiMoghadam A, Pishbin Si, Pourramezan M, Investigating the Effect of Hydrogen Injection on Natural Gas Thermo-Physical Properties with Various Compositions, *Energy*, 2018, Doi:10.1016/J.Energy.2018.10.186.
22. HaoDuan, Yue Huang, Roopesh Kumar Mehra, Panpan Song, Fanhua Ma, Study on Influencing Factors of Prediction Accuracy of Support Vector Machine (SVM) Model for NO_x Emission of a Hydrogen Enriched Compressed Natural Gas Engine, *Fuel*, 234, 2018, 954–964.
23. Tadveer Singh Hora, Pravesh Chandra Shukla, Avinash Kumar Agarwal, Particulate Emissions from Hydrogen Enriched Compressed Natural Gas Engine, *Fuel*, 166, 2016, 574–580.
24. Hora, T.S., Agarwal, A.K., Effect of Varying Compression Ratio on Combustion, Performance, and Emissions of a Hydrogen Enriched Compressed Natural Gas Fuelled Engine, *Journal of Natural Gas Science & Engineering*, 2016, Doi: 10.1016/J.Jngse.2016.03.041.
25. Yue Huang, Fanhua Ma, Intelligent Regression Algorithm Study Based on Performance and NO_x Emission Experimental Data of a Hydrogen Enriched Natural Gas Engine, *International Journal of Hydrogen Energy*, 2016.
26. SaheedWasiu, Rashid Abdul Aziz And PuteriMegat, Brake Specific Energy Consumption (BSEC) and Emission Characteristics of the Direct Injection Spark Ignition Engine Fuelled by Hydrogen Enriched

Compressed Natural Gas at Various Air- Fuel Ratios, *International Journal of Applied Engineering Research*, 13, 2018, 677-683.

27. SaheedWasiu, Rashid Abdul Aziz And MuazamGhozali, Engine Performance Characteristics Fuelled by In-Situ Mixing of Small Amount of Hydrogen and Compressed Natural Gas at Various Relative Air-Fuel Ratios, *International Journal of Applied Engineering Research*, 13, 2018, 714-719.
28. Adrian Irimescu, Francesco Catapano, Silvana Di Iorio, Paolo Sementa, Influence of Combustion Efficiency on the Operation of Spark Ignition Engines Fueled With Methane and Hydrogen Investigated in a Quasi-Dimensional Simulation Framework, *SAE International*, 15, 2018, 1-15.
29. RomualdasJuknelevičius, R. Kumar Mehra, Fanhua Ma, In-Cylinder Combustion Analysis of a SI Engine Fuelled With Hydrogen Enriched Compressed Natural Gas (HCNG): Engine Performance, Efficiency and Emissions, *Journal of Kones Powertrain and Transport*, 2018,
30. Sunyoup Lee, Changgi Kim, Young Choi, Gihun Lim, Cheolwoong Park, Emissions, and Fuel Consumption Characteristics of an HCNG-Fueled Heavy-Duty Engine at Idle, *International Journal of Hydrogen Energy*, 39, 2014, 8078-8086.
31. J. Zareei, A.Rohani, Wan Mohd, Combined Effect of Ignition and Injection Timing along with Hydrogen Enrichment to Natural Gas in a Direct Injection Engine on Performance and Exhaust Emission, *International Journal of Automotive Engineering*, 8, 2018, 2614-2631.
32. Santiago Martinez, Pedro Lacava Pedro Luis Curto, Adrian Irimescu, Simona Silvia Merola, Effect of Hydrogen Enrichment on Flame Morphology and Combustion Evolution in a SI Engine under Lean Burn Conditions, *SAE International*, 2018.
33. Simona Silvia Merola, Silvana Di Iorio, Adrian Irimescu, Paolo Sementa, Bianca Maria Vaglieco, Spectroscopic Characterization of Energy Transfer and Thermal Conditions of The Flame Kernel in a Spark-Ignition Engine Fueled with Methane and Hydrogen, *International Journal of Hydrogen Energy*, 39, 2017, 8078-8086.
34. Rajesh Kumar Prasad, Siddhant Jain, Gaurav Verma, Avinash Kumar Agarwal, Laser Ignition and Flame Kernel Characterization of HCNG in a Constant Volume Combustion Chamber, *Fuel*, 208, 2016, 260–270.
35. Anas Rao, Roopesh Kumar Mehra, HaoDuan, Fanhua Ma, Comparative Study of the NO_x Prediction Model of HCNG Engine, *International Journal of Hydrogen Energy*, 31, 2017, 1021-1034.
36. S. M. V. Sagar, Avinash Kumar Agarwal, Experimental Validation of Accuracy of Dynamic Hydrogen-Compressed Natural Gas Mixing

System using a Single Cylinder Spark Ignition Engine, *International Journal of Hydrogen Energy*, 20, 2016, 1201-1213.

37. Gaurav Verma, R. Kumar Prasad, R. A. Agarwal, S. Jain, A. Kumar Agarwal, Experimental Investigations of Combustion, Performance and Emission Characteristics of a Hydrogen Enriched Natural Gas Fuelled Prototype Spark Ignition Engine, *Fuel*, 208, 2016, 297–298.
38. JavadZareei, Abbas Rohani, Wan Mohd, Simulation of a Hydrogen/Natural Gas Engine, and Modelling of Engine Operating Parameters, *International Journal of Hydrogen Energy*, 39, 2018, 8078-8086.
39. Bo Zhang, Changwei Ji, Shuofeng Wang, Combustion Analysis and Emissions Characteristics of a Hydrogen-Blended Methanol Engine at Various Spark Timings, *International Journal of Hydrogen Energy*, 40, 2015, 4707-4716.
40. S. D. Yadav, Bimlesh Kumar, S. S. Thipse, Characteristics of Biogas Operated Automotive SI Engine to Reduce Exhaust Emission for Green Development, *SAE Technical Papers*, 5 2013.

Cite this article

Kiran P. Pawar and Sanjay D. Yadav, Effectiveness of Hydrogen Enrichment in CNG Fuelled SI Engine: A Review, In: Sandip A. Kale editor, Efficient Engineering Systems: Volume 1, Pune: Grinrey Publications, 2021, pp. 1-28.