Chapter 6
Compressed Natural Gas and Hythane for On-road Passenger and Commercial Vehicles

Tadveer Singh Hora and Avinash Kumar Agarwal

Abstract This chapter discusses implementation of hydrogen-enriched compressed natural gas (HCNG, also called hythane) in automotive engines. Existing passenger vehicles (PV) and commercial vehicles (CVs) are mainly dependent on fossil fuels such as gasoline and diesel. Due to depleting fossil fuel reserves, stringent emission legislations and on-road fuel economy requirements, IC engines are required to use cleaner alternate fuels. Several prominent alternative fuels have emerged such as alcohols, biodiesel and LPG but none of them are widely accepted for large-scale commercial applications. However, most countries have implemented blending of gasoline with alcohol (up to 5–15% v/v) for commercial applications. Compressed natural gas (CNG) has also been widely successful as a commercial automotive fuel. Over last couple of decades, number of CNG vehicles on the roads has increased drastically worldwide. CNG as an automotive fuel is commercially implemented for PVs and heavy-duty CVs. Most important quality of CNG is its lower emissions and it is accepted as a clean transport fuel. However, CNG suffers from severe shortcomings, especially related to its chemical and physical properties such as lower diffusivity, lean-burn limits, high ignition energy requirement, lower flame speed and large flame quenching distance compared to hydrogen. To improvise the properties of CNG as well as for implementing hydrogen for automotive applications, drawbacks of CNG are countered with hydrogen blending. This mixture is known as hydrogen-enriched compressed natural gas (HCNG/ H_2CNG or hythane). HCNG also improves feasibility of implementing hydrogen in automotive industry, which otherwise has serious safety concerns because of low ignition energy and wide flammability range of hydrogen. In this scenario, HCNG is fast emerging as a feasible alternative fuel to meet stringent emissions and fuel economy norms with minimal increase in cost and hardware of existing conventional gasoline/diesel engine.

Keywords Hydrogen · Hythane · Emission · Combustion · HCNG projects

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T. S. Hora · A. K. Agarwal (✉)
Indian Institute of Technology, Kanpur, India
e-mail: akag@iitk.ac.in

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6.1 Gaseous Alternative Fuels

Since the invention of IC engines, fossil fuels such as gasoline and diesel have been used commonly for producing mechanical power, which is derived from the chemical energy stored in these fuels. With growing concerns of climate change and fossil fuel depletion, researchers are investigating various fuels as alternative to conventional gasoline and diesel. Initially, alcohol blends were implemented in the automotive engines but this led to marginal reduction in tailpipe emissions. Figure 6.1 shows reduction in greenhouse gas (GHG) emissions from alternate fuels compared to baseline gasoline.

In this scenario, gaseous fuels such as liquefied petroleum gas (LPG), comprising of propane, propylene, butane and butylene, were investigated as transport fuel. LPG is a by-product of crude oil refining and natural gas extraction. LPG emits 10–15% (Environmental protection agency 2007) lower CO_2 compared to gasoline; however, LPG is still not commercially successful. Major factor is variable composition of LPG, which causes variable engine performance as well as cold-starting issues. LPG also causes safety concerns due to its higher density then ambient air, which makes LPG difficult to disperse in the atmosphere, leading to fire accidents in the event of leakage. However, LPG has higher energy density than gasoline and diesel. Though LPG has emerged as popular cooking gas, its implementation in automotive engines is rather restricted. To achieve the target of lowering the overall CO_2 emission globally, LPG is not the best alternative to fossil fuels. LPG liquefies under moderate pressures at room temperature and is considered dangerous. It can turn explosive or can cause fire if there are traces of LPG in the atmosphere. It can also cause suffocation because its tendency to displace air in enclosed spaces, which decreases the oxygen quantity in the air.

Researchers tested methane, commonly known as natural gas, in automotive engines and found them to be the best alternative to fossil fuels. Natural gas is commonly used either in compressed form or in liquefied form, known as compressed natural gas (CNG) and liquefied natural gas (LNG), respectively. CNG proved to be immediate replacement for gasoline and diesel, and CNG engine generated equivalent power and lower emissions. CNG combustion emits 25% (Environmental protection agency 2007) lower greenhouse gases (GHGs) compared to gasoline. Combustion of CNG produces less soot and particulate matter (PM) making environment less polluting. Also, CNG is cheaper than fossil fuels as well as LPG. Unlike LPG, CNG has lower density compared to air and disperses easily, which makes it less flammable. Benefits of CNG were considered around the world and the number of natural gas-fuelled vehicle (NGV) increased rapidly (Fig. 6.2).

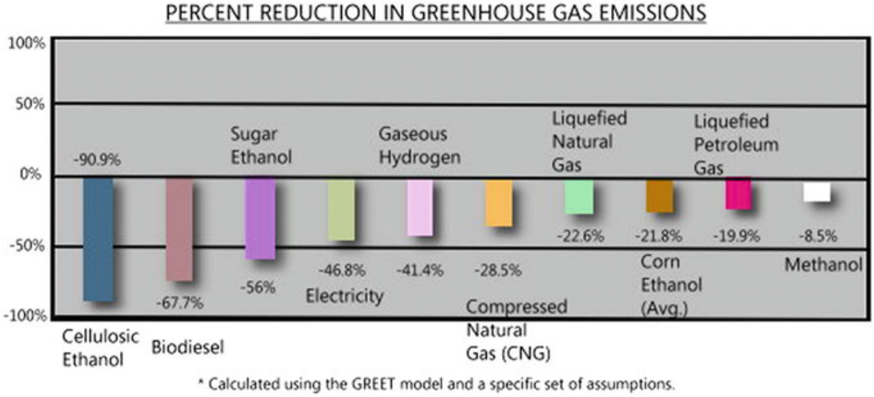


Fig. 6.1 Reduction of GHG emissions from different alternative fuels (Environmental protection agency 2007)

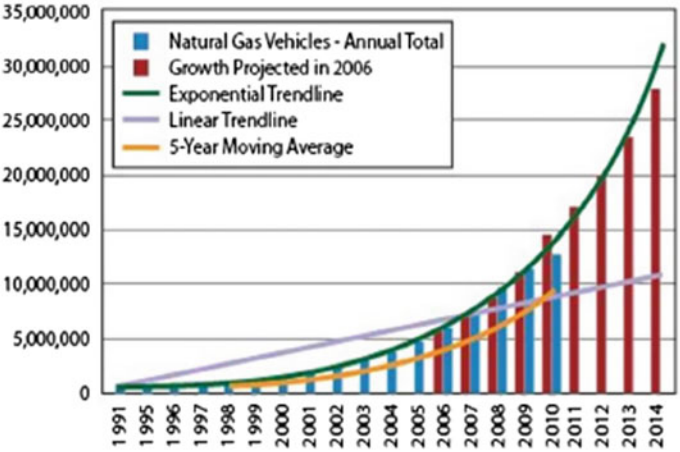


Fig. 6.2 Growth in on-road natural gas-fuelled vehicles worldwide (http://www.investmentu.com/article/detail/2266)

Moreover, CNG can be easily mixed with other gases such as biogas, bio-methane and hydrogen, leading to further reduction in emissions. Conventional diesel and gasoline engines can be easily modified for implementation of CNG. The number of natural gas vehicles has increased globally and CNG dispensing stations have also increased proportionally across the globe.

6.1.1 CNG and Hydrogen

Various chemical and physical properties of CNG make it possible to be utilized as automotive fuel. Following subsection describes the important properties of CNG and hydrogen in contrast to gasoline. Subsection describes technical challenges of CNG as an automotive fuel and a potential solution of introduction of hydrogen-enriched compressed natural gas (HCNG) in the engines. Benefits associated with HCNG compared to CNG are also enlisted.

6.1.1.1 Physico-Chemical Properties of CNG and Hydrogen

Natural gas compressed to high pressures is known as compressed natural gas (CNG) while natural gas stored in cryogenic cylinders in liquid form is known as liquefied natural gas (LNG). Major constituent of CNG is methane, which has one carbon atom attached to four hydrogen atoms.

Other minor constituents include ethane, propane, butane, nitrogen, carbon dioxide and traces of other gases. LNG consists of relatively higher percentage of methane than CNG. Typical composition of CNG available commercially in India is shown in Table 6.1. Since CH_4 is the largest constituent, properties of CNG are in close approximation to that of methane. CNG and Hydrogen, being in gaseous state, do not cause problems of vapour lock and cold starting in the engines. Both gases have higher auto-ignition temperature and cannot be burnt in compression ignition (CI) mode. They require external source of ignition for combustion such as an electrical spark. CNG and hydrogen can be used in spark ignition engines and their properties suggest these gases are better fuels than conventional gasoline.

Octane numbers of natural gas and hydrogen are higher than gasoline; hence, they exhibit superior anti-knock characteristics, which allow combustion at higher compression ratios. Higher octane number makes engine run smoother with low noise levels. Main properties of CNG and Hydrogen in comparison to gasoline are shown in Table 6.2.

Table 6.1 Typical composition of natural gas (% v/v)

Methane	CH_4	94.42
Ethane	C_2H_6	2.29
Propane	C_3H_8	0.03
Butane	C_4H_{10}	0.25
Carbon dioxide	CO_2	0.57
Oxygen	O_2	0–0.2
Nitrogen	N_2	0.44
Other gases		2
Rare gases	Ar, He, Ne, Xe	Traces

(Central U.P. Gas limited)

Table 6.2 Comparative properties of CNG, hydrogen and gasoline (Serrano et al. 2010; Agarwal et al. 2009)

Properties	CNG	Hydrogen	Gasoline
Formulae	CH_4	H_2	$C_{7.1}\ H_{12.56}$
Molar mass	16	2	98
Octane number	120	130	70–97
Auto-ignition temperature (°C)	540	585	230–500
Flammability limit (vol.% air)	5.0–15	4.0–75	1.0–7.6
Quenching distance (mm)	2.03	0.64	2.84
Minimum ignition energy (mJ)	0.29	0.02	0.24
Mass stoichiometric A/F ratio	17.16	34.33	14.7
Lower heating value (MJ/kg)	47.3	120	40–45
Diffusion coefficient (cm^2/sec)	2.0	6.1	0.5
Laminar burning velocity in air (m/s)	0.4	2.9–3.5	0.5
Molar carbon to hydrogen ratio	0.25	0	0.44
Density (kg/m^3)	0.717	0.0899	726

Hydrogen has low ignition energy and high flammability range; therefore, chances of undesirable combustion, pre-ignition and backfire in hydrogen engines are dominant. Pre-ignition is mainly caused by hot spots, heated exhaust valves or hot carbon deposits in the combustion chamber. However, higher diffusivity of hydrogen allows it to disperse rapidly in the air and diffuse out of flammability range in case of leakage. Higher diffusivity of hydrogen allows uniform air and fuel mixture formation, leading to more complete combustion, which gives superior fuel economy.

Quenching distance is defined as the closest gap between engine cylinder walls and flames before the flames are extinguished. Smaller quenching gap is a desired feature for a good fuel. Quenching distance for CNG and gasoline is higher than hydrogen. Smaller quenching distance allows the flame to travel and reach even in smaller spaces, therefore, producing lesser unburnt hydrocarbon (UHC) emissions and particulates. Lower quenching gap, however, can also increase the chances of backfire in intake manifold, since the flames can travel through the nearly closed intake valves into the intake manifold, where the fuel–air mixture is available. Thus for hydrogen-fuelled engines, low quenching gap is desirable but it also is a major drawback. Flame speed of combustion affects efficiency and cyclic variability in the engine. Higher flame speed allows the combustion to approach ideal cycles, i.e. combustion takes place closer to TDC and lesser cyclic variations in power are observed. High flame speed engines are operated with retarded ignition timings, i.e. ignition closer to the TDC. Hydrogen has very high flame speed (2.9–3.5 m/s), while CNG has low flame speed (0.4 m/s). Higher flame speed of hydrogen also causes concerns related to knocking in the engine.

Lower heating value (LHV) of CNG and gasoline is close to each other but hydrogen has almost three times higher LHV than CNG; therefore, significantly lesser quantity of hydrogen is required to produce unit power; thus, it improves the BSFC. Hydrogen combustion leads to high flame temperature and combustion temperature, resulting in higher thermal NO_x emissions but leads to more complete combustion, therefore, lower HC and CO emissions. Combustion equations for methane and hydrogen are shown below. Lower C/H ratio of CNG and hydrogen makes them better fuel than liquid petroleum fuels for GHG emissions. Application of CNG and hydrogen results in lesser HC, CO and CO_2 emissions. Increased NO_x emissions observed in case of hydrogen can be reduced by use of HCNG.

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$
$$2H_2 + O_2 \rightarrow 2H_2O$$

6.1.2 Implementation of HCNG

Pure hydrogen theoretically has qualities of an ideal engine fuel such as higher diffusivity, infinite hydrogen/carbon ratio (Carbon-free fuel), lower quenching gap, wide flammability range, high burning velocity and high calorific value. However, operating an IC engine on 100% hydrogen is practically challenging and inherently unsafe. Benefits of excellent combustive properties of hydrogen can be used to improve combustion of CNG by adding certain fraction of hydrogen into it. Mixture of 5% hydrogen with CNG on energy basis or 20% on volume basis is known as Hythane®, which is a commercially available fuel and is regarded as optimum mixture.

The idea of blending hydrogen and CNG was first realized in 1989, when a company called Hydrogen Components, Inc. (HCI) prepared blends of different proportions of hydrogen and natural gas. They reported that 20% (v/v) blend produces significantly lesser emissions. This particular blend was named as Hythane®. Many countries have actively shifted their research to explore HCNG as potential engine fuel. Most of them tried different percentages of hydrogen to detect optimum mixture with lowest emissions and higher power output.

Hydrogen and CNG are two different prospective alternate transport fuels with significantly different properties, while properties of HCNG blend lies in between these two fuels. Comparative properties of Hydrogen, HCNG 5% (v/v) blend and CNG are shown in Table 6.3. Table 6.3 shows that various important combustive properties of HCNG fall in-between hydrogen and CNG, thus offering advantage from both fuels and disadvantages of none.

Flammability limit of HCNG is much wider compared to CNG. This improves lean-burn limit of CNG, therefore, reduces the NO_x emissions. Lower ignition energy of hydrogen increases in HCNG, thus making HCNG safer than hydrogen. Burning velocity of HCNG also increases with addition of hydrogen, providing higher efficiency than CNG engines. Higher quenching gap of CNG is reduced in HCNG, which results in lower HC emissions compared to CNG. Equivalence ratio

Table 6.3 Properties of HCNG, CNG and hydrogen (Nanthagopal et al. 2011)

Properties	H_2	HCNG	CNG
Flammability limit in air (% v/v)	4–75	5–35	5–15
Stoichiometric composition in air (% v/v)	29.53	22.8	9.48
Minimum ignition energy in air (mJ)	0.02	0.21	0.29
Auto-ignition temperature (K)	858	825	813
Flame temperature in air (K)	2318	2210	2148
Burning velocity at NTP (cm/sec)	325	110	45
Quenching gap in air at NTP (cm)	0.064	0.152	0.203
Thermal energy radiated (%)	17–25	20–26	23–33
Diffusivity in air, (cm^2/sec)	0.63	0.31	0.2
Normalized flame emissivity	1.00	1.50	1.70
Equivalence ratio	0.1–7.1	0.5–5.4	0.7–4

Table 6.4 Properties of HCNG blends (Flekiewicz et al. 2012)

Properties	CNG	HCNG10	HCNG20	HCNG30
H_2 (% v/v)	0	10	20	30
H_2 (% w/w)	0	1.21	2.69	4.52
H_2 (% energy)	0	3.09	6.68	10.94
LHV (MJ/kg)	46.28	47.17	48.26	49.61
Density (kg/m^3)	0.717	0.653	0.590	0.526

(inverse of excess air-to-fuel ratio) is increased for HCNG, which increases the lean-burn limit at different excess air ratios. Lower density of hydrogen requires more storage volume for given fuel mass. Hythane has higher density than hydrogen, therefore, requires relatively lower volume storage tank. Properties of HCNG differ with varying proportion of hydrogen in the mixture. As the hydrogen percentage increases, combustive properties approach that of hydrogen. LHV and density of different HCNG blends (on volume basis) are listed in Table 6.4.

6.1.3 Advantages of Gaseous Fuels Over Petroleum Fuels

Major benefits of HCNG/CNG are:

1. They can be effectively used in existing petrol–diesel engine with minor hardware modifications.
2. HCNG is safer to handle compared to hydrogen.
3. HCNG engines produce lower emissions and are capable of comply with the Euro-6 emission legislations.
4. HCNG emits lesser greenhouse gases, NO_x, CO, particulates and soot.

5. HCNG has lower lean-burn limit and delivers better fuel economy.
6. HCNG has higher flame speed and combustion temperature, which ensures greater degree of complete combustion of fuel.
7. C/H ratio decreases as the hydrogen fraction increases in HCNG mixture.
8. HCNG demonstrates lower coefficient of variation (COV) or cyclic variability of engine power output and maintains stable engine operation with higher efficiency.
9. CNG is cheaper than fossil fuels and lower government taxes are imposed on it.
10. Existing CNG networks can be utilized for HCNG dispensing with minor hardware modifications.

6.2 Single Cylinder HCNG Engine Development

To study the effect of hydrogen addition to CNG, extensive experiments were performed at Engine Research Laboratory, IIT Kanpur, India. The study was performed in a modified diesel engine which was converted to a manifold injection HCNG-fuelled engine by appropriate hardware changes. Intake manifold was modified to accommodate HCNG rail and injector. Cylinder head of diesel engine was modified to accommodate a spark plug instead of the diesel injector. The pistons were machined to reduce the compression ratio from 17 to 10/11/12. Test cell housed this customised single cylinder engine, which was coupled to an AC dynamometer. The experiments were performed at constant engine speed (1500 rpm) at varying engine load and HCNG fractions at fixed injection timing at the start of intake stroke and ignition timing of 20° CA before top dead centre (BTDC). HCNG injection quantity was governed by a customized electronic solenoid injector control circuit, which controlled the solenoid CNG injector (Bosch; 280150842). The injector was supplied gas (HCNG/CNG) at a constant injection pressure (4 bar) at all operating conditions. Figure 6.3 shows the schematic of the experimental setup with its subassemblies and instrumentation.

A Coriolis mass flow meter (Emerson; CMF010M) was installed to measure fuel (gas) consumption at each engine operating point. Suction line was connected to a laminar flow element (LFE) (Cussons; P7205/150) for smoothening the intake air flow pulsations. Engine crankshaft was coupled to a precision angle encoder (Encoder India; ENC 58/6-720ABZ), which generates a square signal at every 0.5° CA rotation of the shaft. A piezoelectric pressure sensor (Kistler; 6631CQ09-01) was mounted flush on the cylinder head for measuring the in-cylinder pressure. A high-speed combustion data acquisition system (Hi-technique; Me-DAQ) acquires in-cylinder pressure signal at each crank angle position. A capacitive discharge ignition (CDI) system was used to initiate the combustion of the fuel–air mixture. An exhaust gas emission analyser (Horiba; Mexa-584L) was used to measure gaseous species in the exhaust. A Lambda sensor

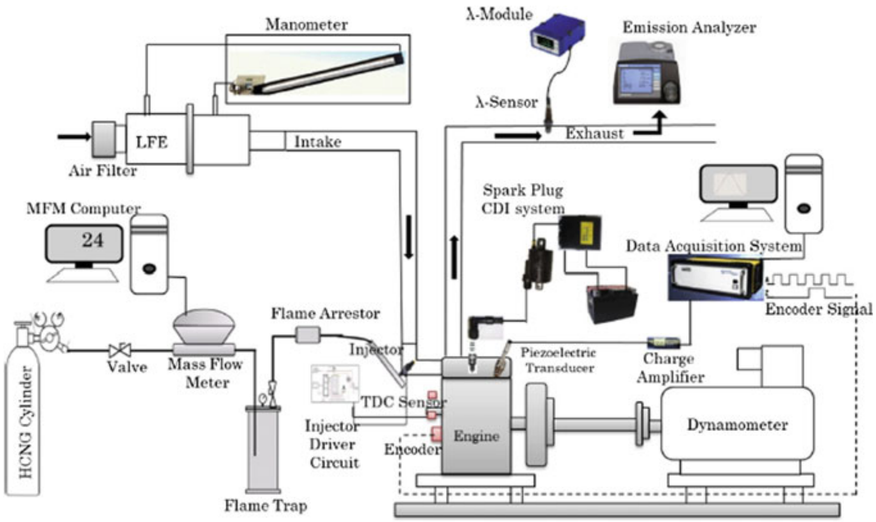


Fig. 6.3 Experimental setup for HCNG evaluation (Hora and Agrawal 2015)

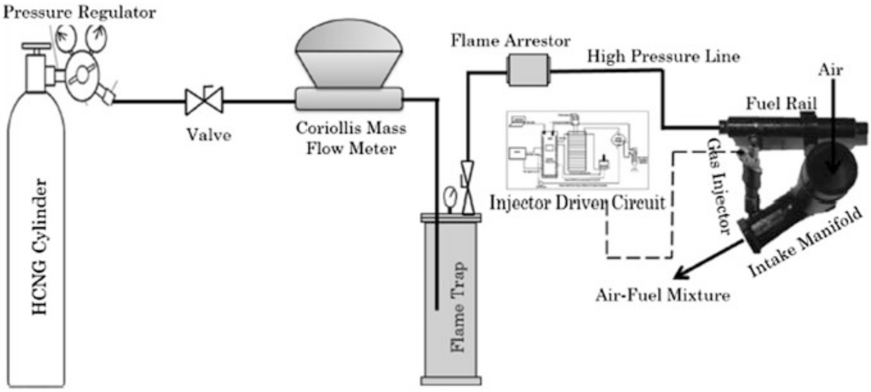


Fig. 6.4 Fuel system layout (Hora and Agrawal 2015)

(Bosch; LSU 4.9) and a K-type thermocouple were also mounted in the exhaust pipe in order to measure the air-to-fuel ratio (AFR) and the exhaust gas temperature.

Figure 6.4 shows the schematic of fuel system layout and gaseous injection system, which delivers HCNG to the engine cylinder during the intake stroke. HCNG mixture of desired mixture strength was pre-bottled before each experiment. Mixtures were prepared using Dalton’s law of partial pressures. Experiments were performed at different engine loads (2.98, 4.10, 5.30 to 6.18 bar BMEP) to analyse the effect of varying content [0, 10, 20 and 30% (v/v)] of hydrogen in the HCNG mixture at constant engine speed of 1500 rpm. Engine in-cylinder combustion, performance and emission characteristics were experimentally evaluated and the results are shown in the following subsections. Nanoparticles emitted by CNG/HCNG cannot be ignored due to their potentially carcinogenic nature. Hence, particulate number, particle surface area and particle mass distributions w.r.t. particle size were also analysed.

6.2.1 *Effect of Hydrogen Fraction*

6.2.1.1 Performance Characteristics of HCNG Engine

Figure 6.5 shows various critical engine performance variables such as brake thermal efficiency (BTE), brake-specific fuel consumption (BSFC), brake-specific energy consumption (BSEC), relative excess air–fuel ratio (λ) and exhaust gas temperature (EGT) at different loads (BMEP) for 0, 10, 20 and 30% HCNG mixtures. BTE shows the overall conversion efficiency of fuel's chemical energy into mechanical energy, which is available at the engine shaft. HCNG enhanced the BTE of CNG at all loads. Increase in hydrogen fraction increased BTE due to

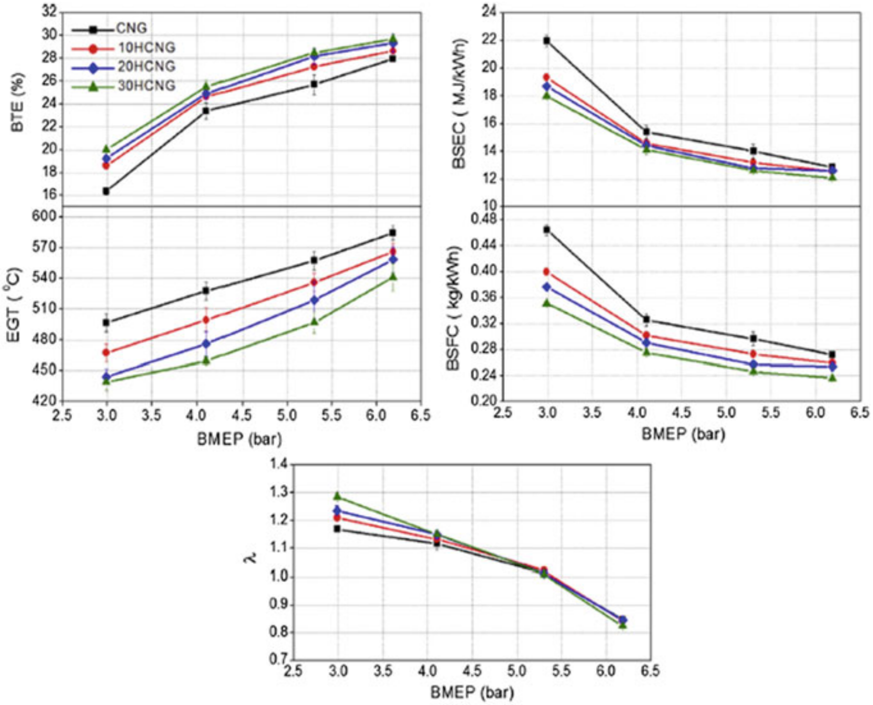


Fig. 6.5 Performance characteristics of HCNG mixtures (Hora and Agrawal 2015)

relatively higher combustion efficiency and superior combustion stability. At lower BMEP, same power output could be produced by slightly leaner HCNG–air mixture compared to CNG–air mixture, while at higher BMEP, relatively richer fuel–air mixture was required. This showed that hydrogen addition to CNG increased lean limit of CNG operation.

EGT increased for all fuels with increasing BMEP. Relatively lower EGT was observed for HCNG mixtures in spite of higher combustion temperatures due to hydrogen. Addition of hydrogen to CNG increased the burning speed (rate of heat release) of HCNG, resulting in shorter combustion duration. Due to this, large fraction of chemical energy was released earlier in the expansion stroke as heat and relatively lesser after-burning took place.

Reduction in BSFC with increasing BMEP shows that less fuel quantity was consumed to generate unit power at higher engine loads and vice versa. This is because BTE was higher at higher engine loads. HCNG showed lower BSFC compared to CNG at a given BMEP. This was due to increasing calorific value (Lower heating value: LHV) of HCNG because of hydrogen addition, which was responsible for lower BSFC. BSEC showed reducing trend with increasing BMEP and increasing hydrogen fraction in HCNG at a given BMEP. This reflected that lesser fuel input energy was required to produce unit power output for HCNG vis-a-vis CNG due to improved BTE.

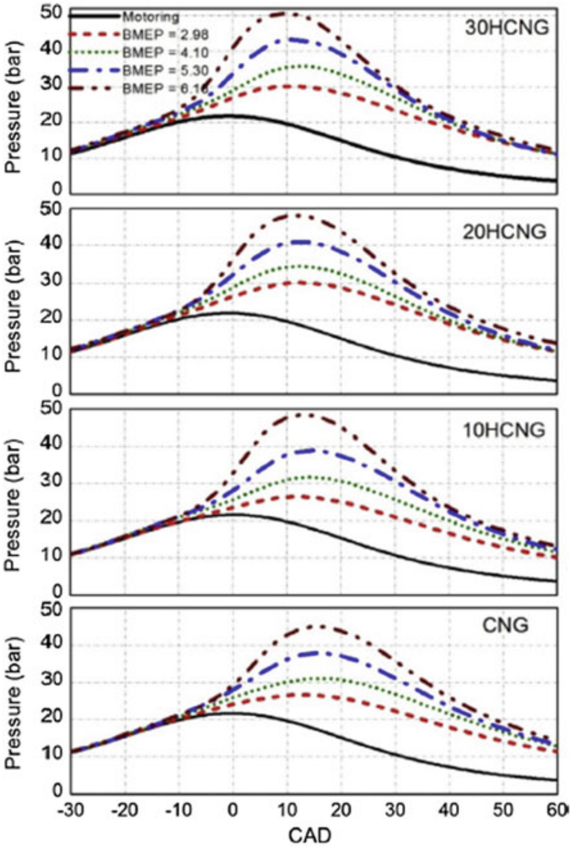
6.2.1.2 Combustion Characteristics of HCNG Engine

Figure 6.6 shows the in-cylinder pressure variations observed at different BMEP for baseline CNG and various HCNG mixtures. Peak cylinder pressure increased with increasing load due to higher fuel quantity requirement. For a given fuel, crank angle position corresponding to peak cylinder pressure shifted towards TDC side due to reduced combustion duration with increasing BMEP. This improved the fuel utilization; therefore, BTE also increased. At a given BMEP, peak cylinder pressure shifted towards TDC with increasing hydrogen fraction in HCNG due to higher flame speed. HCNG delivered higher peak cylinder pressure at the same BMEP. The tendency of knocking would enhance, if the hydrogen fraction in the HCNG mixture increased since the rate of burning would also proportionally increase. However, optimum hydrogen content in the fuel–air mixture would result in higher BTE compared to CNG.

Figure 6.7 shows variations in rate of pressure rise (RoPR) and heat release rate (HRR) of HCNG mixtures at different BMEP. RoPR and HRR increased with increasing engine load for a given fuel. This was primarily due to relatively earlier start of combustion (SoC) observed at higher BMEP and high fuel quantity at higher BMEP. Additionally, at a constant BMEP, RoPR was relatively higher for HCNG mixtures.

Maximum RoPR was obtained for 30HCNG due to its highest hydrogen fraction amongst all test fuels. Hydrogen has relatively higher flame speed, which increases the HRR and RoPR. Crank position for maximum RoPR and HRR shifted towards

Fig. 6.6 In-cylinder pressure-crank angle diagrams of HCNG mixtures (Hora and Agarwal 2015)



TDC, similar to peak cylinder pressure. HRR was higher for HCNG mixtures due to higher flame speeds because of hydrogen addition.

Figure 6.8 shows variations in cumulative/total heat release (CHR), mass burn fraction (MBF) and combustion duration with BMEP for different HCNG mixtures. CHR increased with increasing engine load due to higher fuel consumption. At a given BMEP, CHR was higher for HCNG mixtures due to their higher HRR. High HRR and CHR were the reasons for improved fuel economy of HCNG.

Combustion in SI engines has three distinct combustion stages namely flame development, flame propagation and after-burning. Flame development phase is considered to be over at crank angle position for 10% MBF. Combustion duration is considered as the crank position duration between 10 and 90% MBF. Period after 90% MBF till the end of combustion is considered as after-burning phase, which is considered as the least significant. Figure 6.8 shows the variations in 10, 50, 90% MBF and combustion duration for all test fuels. Flame development phase shortened with increasing hydrogen fraction in the test fuels due to significantly lower ignition energy requirement of hydrogen, which also led to rapid formation of

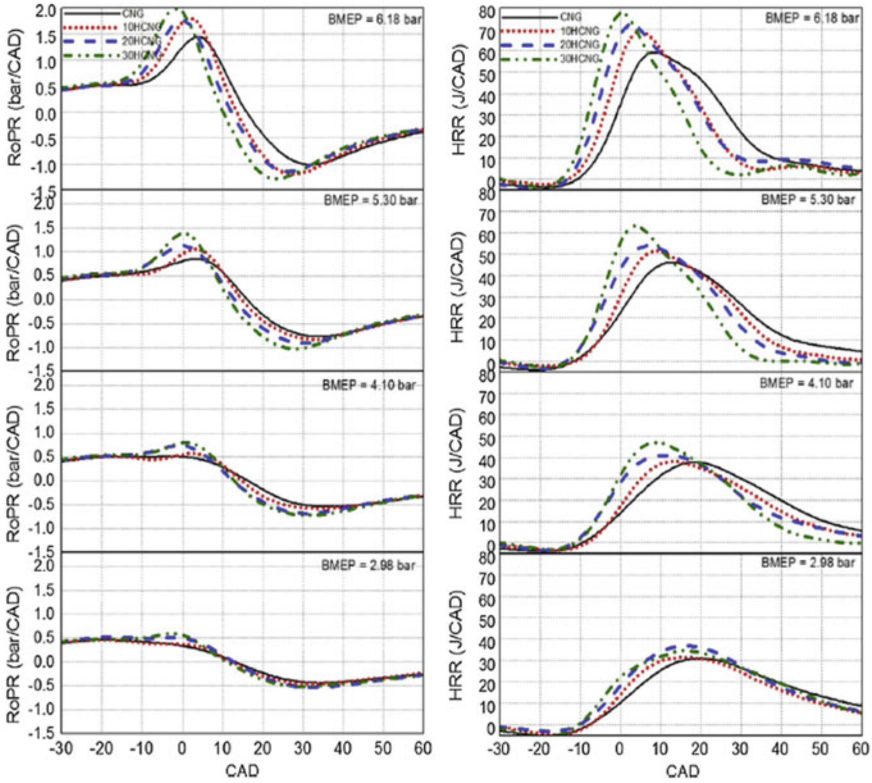


Fig. 6.7 Rate of pressure rise and heat release rates of HCNG mixtures (Hora and Agrawal 2015)

OH radicals during combustion. Similarly, crank angle position for 50% MBF also retarded towards TDC for HCNG mixtures, primarily due to higher flame speed due to hydrogen. As the fuel burns, oxygen available for combustion reduces, thus slowing down the propagation of flames leading to after-burning. Crank angle for 90% MBF was relatively earlier for HCNG compared to CNG. Combustion duration for 10HCNG, 20HCNG and 30HCNG was shorter than CNG.

6.2.1.3 Emission Characteristics of HCNG Engine

Figure 6.9 shows raw exhaust emissions and brake-specific mass emissions of regulated gaseous pollutant species from a HCNG engine at different BMEP. Thermal NO_x formation depends on peak combustion temperature and oxygen content, which was relatively higher in case of HCNG mixtures. NO_x emissions were higher due to relatively higher in-cylinder temperatures because of hydrogen addition to the CNG, which favoured NO_x formation. Flame front temperature increased with increasing hydrogen fraction in HCNG mixtures. At lower

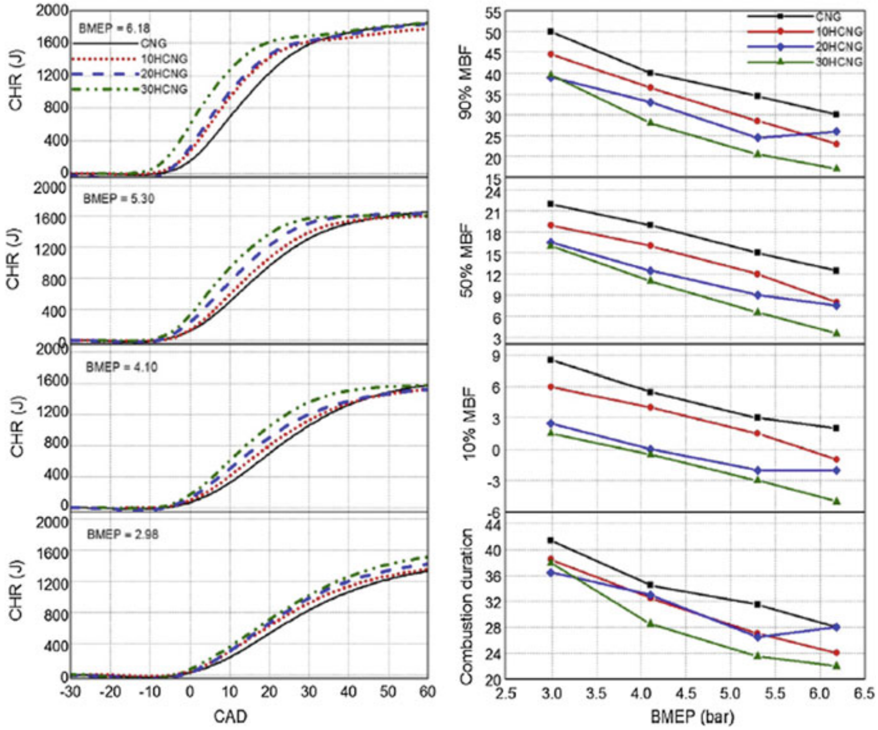


Fig. 6.8 Cumulative heat release and mass burn fractions of HCNG mixtures (Hora and Agrawal 2015)

BMEP of 2.98 bar, negligible difference in NO_x formation was observed amongst all test fuels. This was due to leaner fuel–air mixtures and relatively lower peak cylinder temperatures, which were outside the NO_x formation window. This, however, changed at higher loads, and higher NO_x emissions were observed. Both the raw emissions and brake-specific NO_x emissions increased with increasing BMEP and increasing hydrogen fraction in HCNG mixtures.

Formation of CO_2 in the engine exhaust is an indicator of degree of completion of combustion of hydrocarbon fuel. Higher CO_2 and lower CO emissions indicate superior combustion quality and effective fuel utilization. CO_2 emissions were relatively lower for HCNG mixtures due to reduction in C/H ratio with increasing hydrogen content in the HCNG mixtures. This was in addition to higher BTE observed for HCNG mixtures. HC emissions were formed because of inefficient combustion of hydrocarbon fuel, wherein exhaust contained some unburnt fuel fractions, which remains trapped in the crevice volume at the time of combustion, essentially unaffected by combustion.

Both raw and mass HC emissions reduced with increasing BMEP because at higher BMEP, higher peak cylinder temperatures favoured the oxidation and

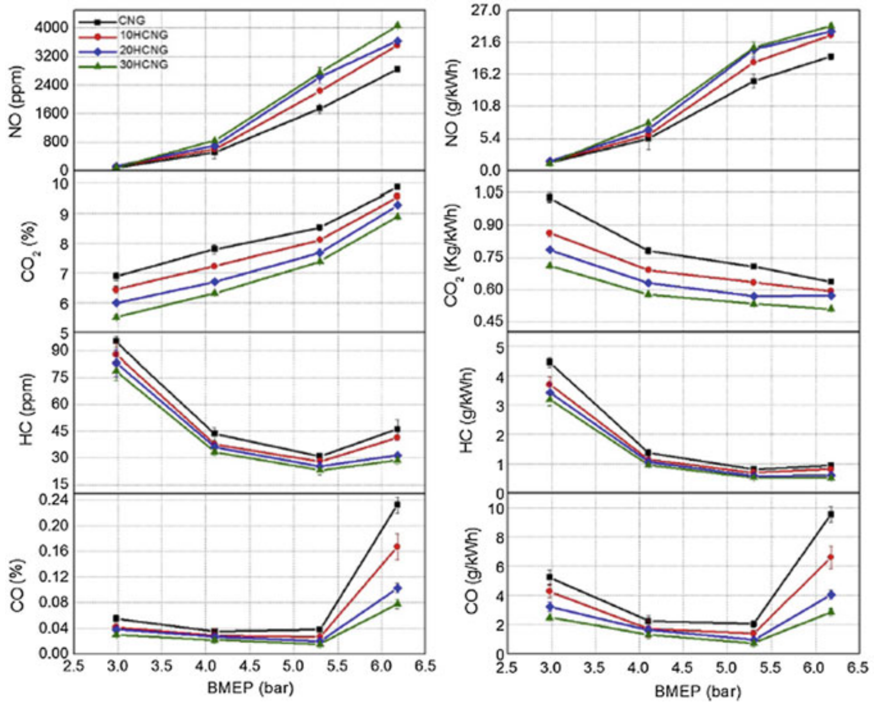


Fig. 6.9 Exhaust tailpipe emission from HCNG mixtures (Hora and Agrawal 2015)

combustion of unburnt fuel/hydrocarbons. For HCNG mixtures, HC emissions were relatively lower because of improved combustion efficiency and relatively lower quenching gap. CO is formed due to incomplete combustion and it reduced with increasing BMEP because higher peak cylinder temperature at higher BMEP favours oxidation of CO into CO_2. HCNG mixtures showed lower CO emission than baseline CNG due to higher peak cylinder temperatures and lower C/H ratio of HCNG mixtures.

6.2.2 Nanoparticle Emissions from HCNG Engine

6.2.2.1 Particle Size-Number Distribution of HCNG Engine

Figure 6.10 shows particle size-number distribution from HCNG engine at various loads. It can be observed that number of nanoparticles (nucleation mode particles Dp > 50 nm) were high from all test fuels, while accumulation mode particles (0.1–0.3 µm) were relatively lower in number. 30HCNG showed emission of higher number of particulate amongst the test fuels. Abrupt change of particle

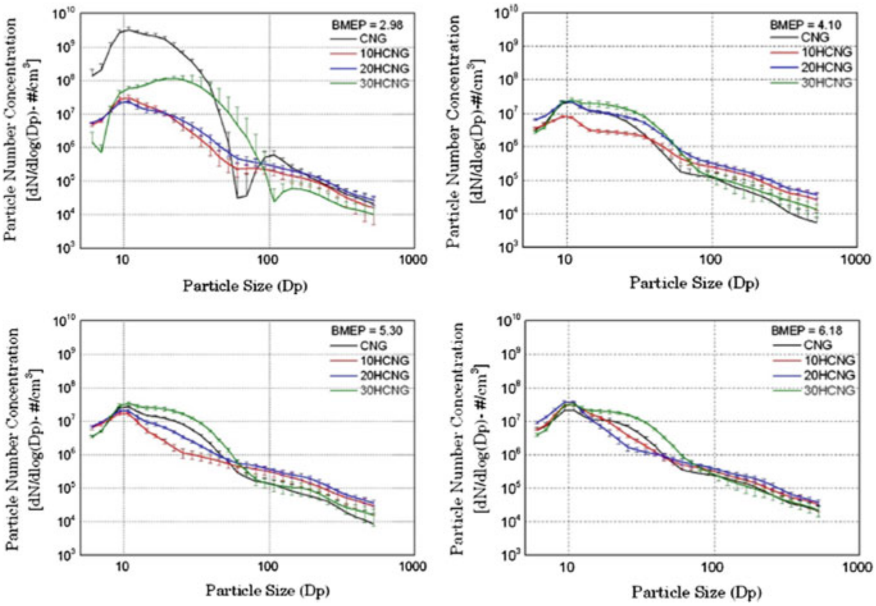


Fig. 6.10 Particle number versus size distribution from HCNG mixtures (Hora and Agrawal 2016)

numbers for CNG at BMEP = 2.98 bar was due to poor engine stability, because of poor lean-burn capability of CNG. When hydrogen was mixed with CNG, the flame speed and combustion speed increased, resulting in lower particulate emissions of all sizes. Same behaviour of particle emissions was observed for all HCNG mixtures as well. CNG- and HCNG-fuelled engines emit negligible particulate emissions, which originate from the fuel. The main source of particulate emissions is unburnt lubricating oil, which is consumed during combustion.

Lubricating oil enters the combustion chamber through the piston and liner interactions. Pyrolysis of this lubricating oil leads to formation of unburnt hydrocarbons and particulates. Lubricating oil contains high molecular weight hydrocarbon compounds, which remain unburnt, resulting in formation of nanoparticles. The engine was operated at constant speed (1500 rpm) at all loads; therefore, contribution of lubricating oil in the particulate formation essentially remains similar at all loads.

6.2.2.2 Particle Size-Mass Distribution of HCNG Engine

Figure 6.11 shows the particle size-mass distribution for the test fuels at different BMEPs. It was observed that majority of particulate mass was composed of accumulation mode particles, while contribution of nanoparticles was significantly

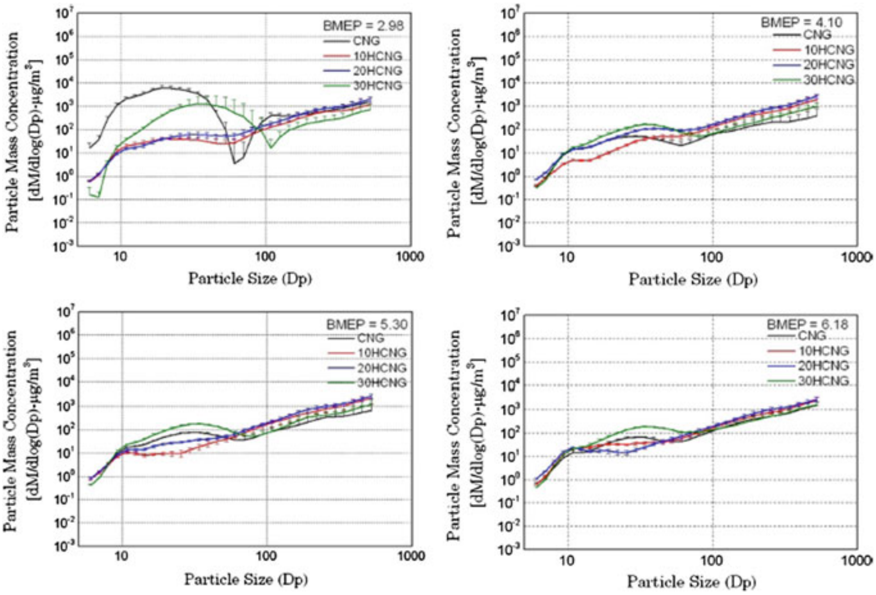


Fig. 6.11 Particle size versus mass distribution (Hora and Agrawal 2016)

lower. Particle size-mass distribution showed that CNG/HCNG mixtures were prone to generate very high number of nanoparticles, which have very low contribution to the particulate mass emissions. Nanoparticles can easily enter human body during inhalation and can cause significant risk because of their toxicity, while larger particles have tendency to settle down due to their weight. Nanoparticles pose greater risk due to their higher atmosphere retention time. Euro-6 emission regulations restrict the particle numbers emitted by the engine; therefore, it is important to emphasize on reducing the emission of number of particles from CNG/HCNG-fuelled engines.

6.2.2.3 Particle Size-Surface Area Distribution of HCNG Engine

Particle size-surface area distribution was studied for CNG and HCNG mixtures (Fig. 6.12). Particle surface area is calculated by assuming particles as spherical. Particle surface area provides the quantification of active sites available for adsorption of high boiling point organic compounds present in the exhaust gas. Particulate surface area distribution was slightly higher for 30HCNG compared to other test fuels. Both nanoparticles and accumulation mode particles contribute significantly to higher surface area, while larger particles have relatively smaller contribution to surface area per unit mass of particles.

Practically, particles emitted are mostly in fractals or branched shapes, which provide far greater surface area than assumed spherical shapes.

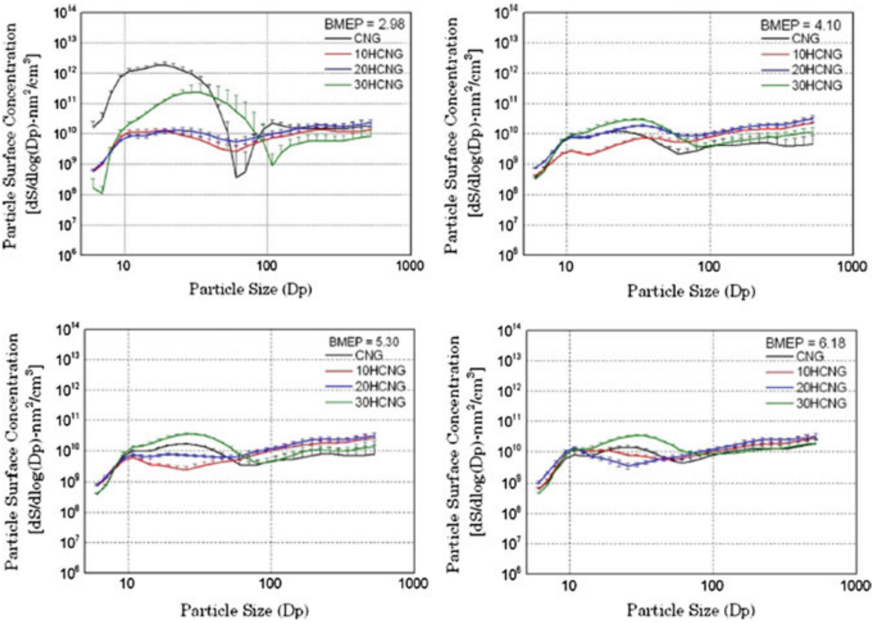


Fig. 6.12 Particle size versus surface area distribution from HCNG mixtures (Hora and Agrawal 2016)

6.3 HCNG Vehicle Development

Growing concerns of environmental and health issues originating from fossil fuels have led to implementation of gaseous fuels such as CNG/HCNG across Asia, Europe and America. Though the conversion requirements of conventional gasoline/diesel engines to CNG/HCNG are minimal, however, engine needs hardware changes, especially in the fuel injection system. Technologies available for gaseous fuels include direct injection combustion, dual-fuel combustion or bi-fuel combustion. Both these techniques are depicted in Fig. 6.12. Next subsection discusses additional components required to manufacture a CNG/HCNG engine. In a direct injection technology, CNG/HCNG is injected directly into the combustion chamber, and while in bi-fuel/dual-fuel engine, CNG is injected in the intake manifold. Direct injection technology is not widely implemented though for gaseous fuels due to the challenges arising because of high injection pressure (Fig. 6.13).

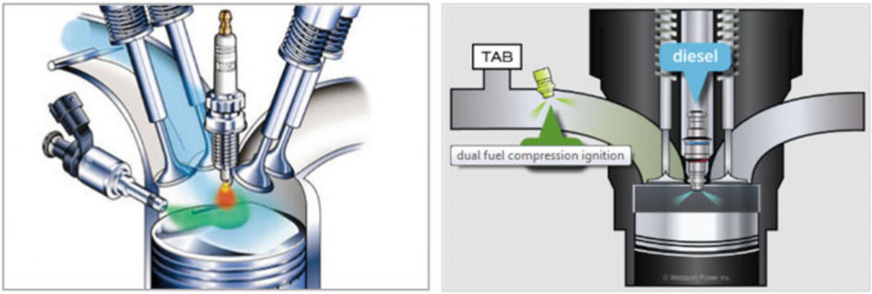


Fig. 6.13 Direct injection and dual-fuel techniques (http://www.full-race.com/articles/inside-the-ecoboost-f-150.html; http://www.westport.com/is/core-technologies/combustion/dual-fuel)

6.3.1 Technology Requirements

Major modifications in the gas engines compared to conventional engines include changes in fuel injection systems. Depending on the fuel injection technology used, requirements of fuel injection components vary. Commonly, CNG/HCNG engines require components such as gas injectors, fuel lines, pressure regulator, fuel tank, CNG sensors, shut-off valves, CNG rail in order to induct high-pressure fuel gas to the engine combustion chamber. The technology of direct injection of CNG is commonly known as high-pressure direct injection (HPDI) technology. Figure 6.14 shows the direct injection CNG injectors and port fuel CNG injector from one of the OEMs. CNG injectors can also be utilized for HCNG injection. Direct injection CNG engines are capable of generating equivalent power and performance as that of equivalent petrol/diesel engines with superior fuel economy. However, direct injection CNG engines are rare. Most CNG/HCNG engines commercially available are manifold injected engines. These engines are capable of meeting stringent

Fig. 6.14 Direct injection and port fuel injection CNG injectors (http://www.delphi.com/manufacturers/auto/powertrain/alternative-fuel-systems/multec-cng-injector)

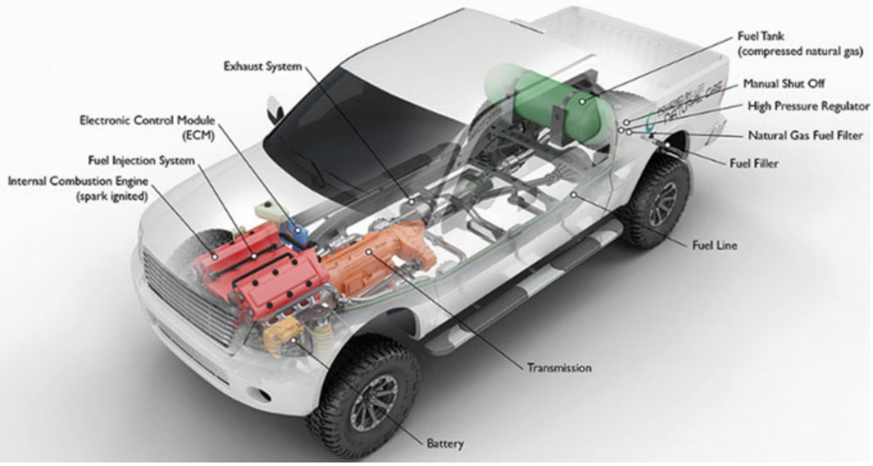


Fig. 6.15 CNG/HCNG configuration of a pickup (LCV) (Central U.P. Gas limited)

emission norms such as EU-6/BS-6. CNG/HCNG engines produce nearly zero particulate emissions; hence, the effort of engine calibration is significantly lower than that of diesel engines. Port injection technology is commonly used in bi-fuel and dual-fuel engines.

A bi-fuel engine can operate in two modes, either on 100% fossil fuel or on 100% CNG/HCNG; while a dual-fuel engine can operate on either 100% diesel or a mixture of diesel and CNG/HCNG. In a dual-fuel engine, diesel is directly injected into the combustion chamber, while a definite amount of CNG/HCNG is injected into intake manifold, which is drawn in along with the intake air. Bi-fuel engine requires a spark plug to initiate the combustion, and while in a dual-fuel engine, diesel pilot initiates the combustion of CNG/HCNG. Dual-fuel engines have improved fuel economy and reduced emissions. Bi-fuel technology is suitable for light-duty engines typically used in passenger vehicles, while HPDI/dual mode is suitable for heavy-duty engines typically used in commercial applications. Bi-fuel engines operate with petrol and CNG since they require a spark-plug, while dual-fuel engines do not require a spark plug.

Figure 6.15 shows a typical layout of a CNG pickup vehicle and Fig. 6.16 shows a similar typical layout of a heavy-duty vehicle.

For an optimized engine, combustion bowl and piston should be designed as per CNG fuelling, injection and combustion characteristics. Heavy-duty HCV engines require fuel system capable of withstanding high pressure, typical to CNG (200–225 bars). Number of CNG storage cylinders for this type of application is more in order to provide it a long range. One of the major concerns is to accommodate large number of CNG cylinders in the limited space available on-board. Hence, most commonly, these cylinders are packaged behind the cabin vertically or beneath the chassis horizontally.

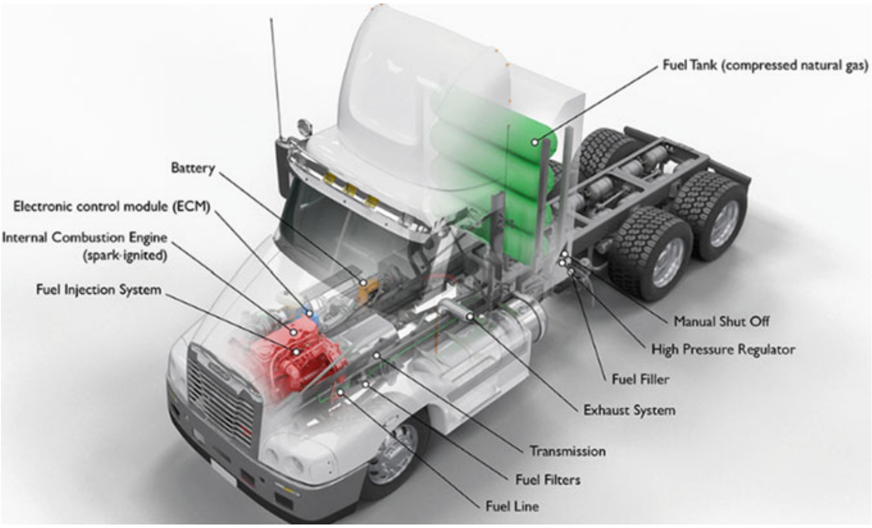


Fig. 6.16 CNG/HCNG configuration of a heavy-duty truck (HCV) (https://www.afdc.energy.gov/vehicles/natural_gas.html)

Some of the major components required for a CNG vehicle development are described below. These components have to be specifically designed for CNG/HCNG application.

1. **Fuel tank, Pressure gauge and High-pressure lines**: CNG is lighter than air and to accommodate high volume of gas, CNG is compressed and stored in high-pressure cylinders. The typical pressure of a CNG cylinder is 200–225 bars. These cylinders are designed to withstand jerks during vehicle operations as well as mishandling. Hydraulic testing of cylinder is performed to verify the cylinder quality. A pressure gauge is installed on each cylinder to show the gas pressure. High-pressure lines which can withstand 200–225 bar pressure (with some factor of safety) are fitted for CNG transport from storage cylinder to the engine cylinder.
2. **High pressure shut-off valve**: To address the safety concerns, an electronic shut-off valve is installed in the CNG passage lines. A CNG sensor is installed in the vicinity of cylinder bank, which can detect CNG leakages and can give command to the shut-off valve to close. This communication can be initiated through the engine ECU, which can take inputs from gas sensors and command the electronic shut-off valve. Shut-off valve is usually a solenoid valve, which remains in normally shut-off state and delivers the gas only when the ignition is ‘on’ from the driver’s cabin. The location of shut-off valve should be close to the gas storage cylinders in order to minimize the plumbing requirement. Figure 6.17 shows a typical electronic shut-off valve.

Fig. 6.17 Typical electronic shut-off valve

3. **High-pressure fuel filters**: In order to prevent the foreign particles from entering the combustion chamber, a pre-filter is installed in the cylinders and a main filter is installed in the CNG/HCNG passage to the injectors. Function of the filters is to prevent fuel contamination by arresting any debris from reaching the high-pressure regulator and the injectors, thus avoiding possible serious damages. Pre-filter is located between the cylinders and the fill connection. The filters showed are designed such that pressure drop/restriction is rather minimal. The maximum pressure drop in fuel system from the outlet of the high-pressure regulator to the engine inlet must not be more than 25 psi. These filters have a life cycle in terms of vehicle kilometres and have to be replaced after regular intervals.
4. **High-pressure regulators**: The function of a pressure regulator is to expand high-pressure CNG from the cylinders to a nominal working pressure (approx. 4–10 bar), depending on application. This regulator reduces vehicle fuel tank pressure to required engine pressure levels. Cummins recommends regulator settings to be at 6–8 bars. During reduction of gas pressure, these regulators can be frozen to very low temperature as the gas expands to lower pressures. To ensure proper functioning of these regulators and to prevent ice-lock in the gas pressure, these regulators require warm coolant from the engine to prevent freezing of regulators. Figure 6.18 shows a typical CNG regulator.
5. **Low fuel pressure lamp**: To provide comfort to the drivers and to ensure vehicle is running safe and within emission limits, legislation provides inclusion of on-board diagnostics (OBD). To comply with OBD, vehicle manufacturer has to provide various messages to the vehicle dashboard. One of the requirements is the vehicle fuel level, thus vehicle manufacturers have to provide fuel level indicator on the vehicle dashboard. Functioning of the low fuel pressure lamp is controlled by the inputs from the fuel pressure sensor. In case of low fuel pressure, drop in vehicle power and performance can be observed.

Fig. 6.18 Electronically controlled CNG pressure regulator (http://www.landiusa.com/)

6. **CNG common rail**: For a multi-cylinder engine, a common rail is required to deliver gas into each cylinder manifold, at a constant pressure. The timing of injection depends on engine calibration and opening of injector. Injection timing is controlled by the engine ECU. An optimized injection timing is decided based on requirement of better fuel economy, performance and emissions.
7. **Electronic control unit and wiring harness**: Most advanced engines electronically regulate fuel quantity as per driver's demand and load condition. Engine's electronic control unit (ECU) precisely controls the fuel requirement. An engine-mounted electric shut-off valve is provided in the fuel system to cut-off the fuel supply in case of emergency such as over-speed and stopped engine (no speed detected). This valve is controlled by the engine ECU. Engine complying with EU-4 and beyond norms are electronically controlled. The actuators and throttle are controlled based on sensor inputs and ECU control strategy. A dual-fuel CNG engine requires two ECUs. One ECU is used for mono-mode, i.e. only diesel operation, while the other ECU is used for CNG and diesel dual-mode operation. During dual-mode functioning, CNG ECU is master and engine is governed based on the calibration of dual-mode, while in case of mono-mode, diesel ECU is master and base diesel calibration governs the engine speed and load demand.

Figure 6.19 shows the layout of various components of a CNG/HCNG fuel system in a typical vehicular setting.

With the evolution of CNG as established engine fuel and advancement in technology, instead of injecting CNG in the intake manifold, it is mixed with the intake air before the turbocharger to ensure complete mixing. This method of CNG induction provides higher power output from the engine. A typical fuel injection layout for a bi-fuel turbocharged engine is shown in Fig. 6.20.

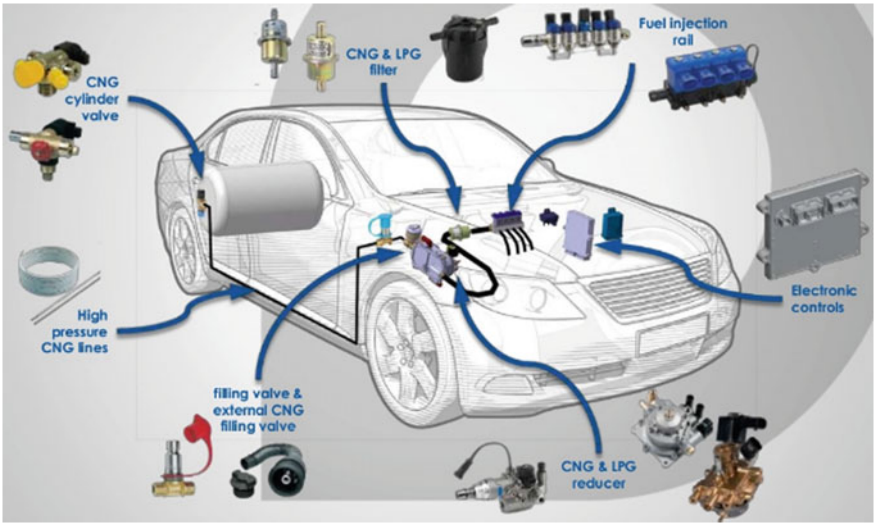


Fig. 6.19 CNG/HCNG fuel system components and layout in a vehicle (www.westport.com)

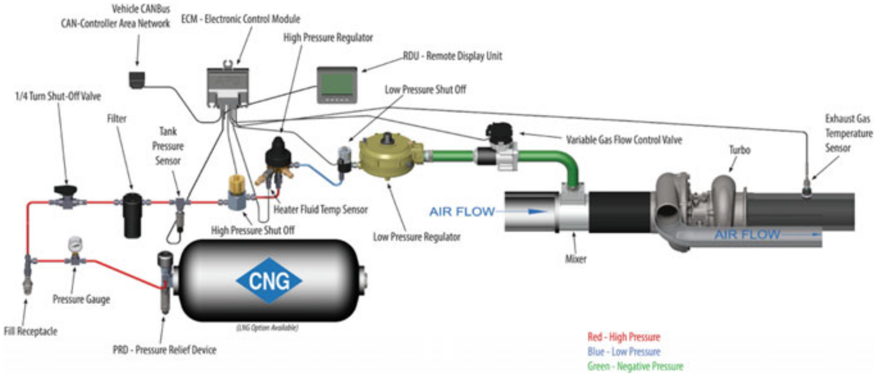


Fig. 6.20 Typical CNG induction system layout for a turbocharged bi-fuel engine (http://www.americanpowergroupinc.com/apg-technology.html)

6.3.2 Global Experience of HCNG Vehicles

Benefits of HCNG have been realized by industries, scientists and researchers but most of studies of HCNG engines were limited to laboratories and restricted in practical implementation on road. HCNG vehicles are not commercially available in market in most countries. Major restrictions of HCNG are due to lack of infrastructure for distribution. Most countries have scarcity in CNG fuelling stations and are required to increase the proximity between CNG refilling stations just like gasoline/diesel fuelling stations. Countries such as Italy, Korea and China, where sufficient CNG stations are commercially viable, are shifting gradually from CNG to HCNG, while other countries have this technology developed only as pilot projects. Another major concern related to commercial availability of HCNG vehicles is the safety concerns that come with hydrogen and its cost. OEMs are not interested in manufacturing HCNG vehicles due to lack of infrastructure, investments and government policies.

Section below shows some of the successful HCNG vehicle projects implemented across the world:

City of Malmo, Sweden introduced few hythane buses in its transport fleet. Malmo has abundant CNG filling stations and CNG buses are widely used for local transport. Since 2003, 8% hythane blend was introduced in few buses and CNG filling stations were upgraded to deliver pure hydrogen and hythane blends along with CNG. These hythane buses covered 1,60,000 km and proved superior in performance and emission compared to conventional gasoline/diesel vehicles. Also, HCNG bus resulted in better fuel economy. Other parts of Europe such as Germany, Italy, France are also promoting use of HCNG, CNG and LNG as transport fuel to displace diesel/petrol. Germany in collaboration with Solbus, a Polish bus manufacturer, demonstrated LNG bus for public commute. France started a project called ALT-HY-TUDE with support from French agency ADEME and GDF SUEZ. ALT-HY-TUDE means alternate hydrogen in urban transport in Dunkerque. The project was aimed to initiate application of hydrogen in vehicles, performance measurement and technical and economic analysis. The engine was operated with 6 and 20% HCNG mixture (ALT-HY-TUDE project 2009) (Fig. 6.21).

Italy which has more than 80 years of experience in using CNG has 6,00,000 CNG vehicles on the roads. CNG infrastructure is fairly matured and normalized in Italy and slowly Italy is shifting towards using HCNG. Italy has tested HCNG buses on the roads and observed significant reduction in emissions. These buses were operated for different hydrogen fractions ranging from 5 to 25% over urban and suburban duty-cycles (Fig. 6.22).

In Asia, India, Korea and China are investigating HCNG as transport fuel. In India, CNG network is limited and not widespread; therefore, HCNG is limited to laboratory experiments only. India has more than 200,000 CNG vehicles. IOCL and SIAM collaborated to demonstrate HCNG vehicles and fifty HCNG vehicles are to be manufactured and implemented for a pilot study before introducing HCNG in the mainstream. IOCL investigated 18% HCNG and claimed maximum reduction in emissions amongst other HCNG mixtures. MNRE and Eden energy are collaborating to introduce HCNG vehicles in India by 2020. Automotive OEMs such as TATA Motors, Ashok Leyland, Eicher Motors, Mahindra & Mahindra have already developed HCNG engines for demonstration projects. Indian government is taking major steps to increase the number and density of CNG station across the country.

Fig. 6.21 HCNG projects in Germany and France (http://busnews.blogspot.in/2012)

Fig. 6.22 HCNG project in Italy (http://www.eltis.org/discover/case-studies/testing-hydromethane-buses-emilia-romagna-italy)

Korean researchers have demonstrated pilot project of HCNG buses. Moreover, Korean researchers have developed a HCNG engine compliant with Euro-6 emission norms. They appreciated the levels of reduction in nitrogen oxides and greenhouse gases from these vehicles. China is also promoting switching to LNG and CNG vehicles. Figure 6.23 shows the emissions from a HCNG bus compared to Euro-6 legislative requirements. HCNG meets the emission requirements with sufficient margins.

In USA, Hythane® a subsidiary of Eden energy has initiated many projects to convert the buses, pickups and trucks to HCNG. HCNG demonstration projects started as early as in 1900–93 with hythane pickup trucks. Denver project operated 5% (w/w) hydrogen blended with methane. In 2002–04, a HCNG bus pilot project was started in California (Fig. 6.24).

In 2007, Eden energy received tender to convert shuttle fleet of San Francisco International Airport to HCNG. Twenty-seven buses were converted to hythane. A Ford 6.8L V10 engine was calibrated for hythane and certified by California Air Resource Board (CARB). This engine resulted in reduction of 10% CO_2, 40%

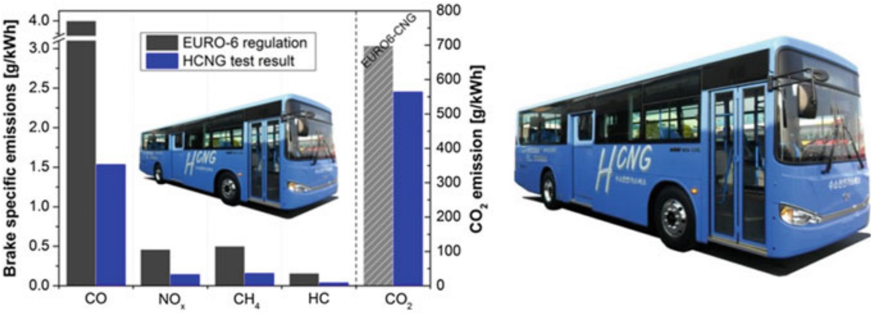


Fig. 6.23 Euro-6 HCNG bus project in Korea (http://www.businesskorea.co.kr/english/news/sciencetech/1420)

Fig. 6.24 HCNG bus project in USA (http://edeninnovations.com/)

NMHC, 49% methane and 70% particulate matter compared to similar natural gas engine (ASX Quarterly report 2009). Volvo has also developed a vehicle, which can be operated on five fuels, including hythane and CNG.

6.4 Conclusions

Based on the research studies and field trials of HCNG engines, the following conclusions can be drawn:

1. HCNG reduces GHG emissions and has good potential to slow down climate change.
2. HCNG is superior alternative to fossil fuels delivering superior power and reduced emission.
3. Hydrogen addition in CNG improves engine performance and reduces emissions; however, nanoparticles need to be controlled.

4. Hydrogen addition in CNG improves lean-burn limit of CNG and results in superior fuel economy.
5. HCNG engines are capable to successfully meeting Euro-6 emission legislations, which will be implemented in India by 2020.
6. Existing CNG networks can be improvised to dispense HCNG into vehicles.
7. Usage of HCNG vehicle is to be encouraged by the government.

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