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Hydrogen-enriched compressed natural gas as a fuel for engines

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1. Introduction

Natural gas is often thought of as the most promising alternative fuels for vehicles. Natural gas is a much more abundant fuel than petroleum and is often described as the cleanest of the fossil fuels, producing significantly less carbon monoxide, carbon dioxide, and non-methane hydrocarbon emissions than gasoline; and when compared to diesel it nearly eliminates the particulate matter. Other advantages of natural gas include a high H/C ratio and a high research octane number (RON) causing the exhaust to be clean and allowing for high anti-knocking properties. Hydrogen is the most abundant element on earth, and is often thought of as the ideal alternative fuel. However, the current infrastructure does not support hydrogen as a wide-spread fuel. In order to expand the role of hydrogen in the near term, one option is to use hydrogen for transportation by mixing it with natural gas and use it for use in ICE engines. This new blended fuel is known as HCNG, or hythane, for which the use will create a basic infrastructure for the use of hydrogen in the future.

2. History

Natural gas-hydrogen mixtures have been used in test engines dating back to as early as 1983 (Nagalim et al, 1983). Nagalingam et al. (1983) conducted experiments with an AVL engine fueled with 100/0, 80/20, 50/50, 0/100. In 1989, HCI (Hydrogen components Inc.) began blending various ratios of hydrogen and natural gas and testing them at Colorado State University (Hythane Company, LLC, 2007). Hythane is a patented mixture of hydrogen and CNG, created by Hydrogen Components, Inc. in Littleton, Colorado. According to US Patient #5,139,002 (Lynch & Marmaro, 1992), Hythane® was invented by Frank Lynch and Roger Marmaro and was granted a US patient in 1992. In this patient, hythane is defined a blend of hydrogen and natural gas provided for burning in an engine without the need for modifications to engine parameters, and is defined as roughly a 15% blend of Hydrogen in CNG fuel. In 1992, the first Hythane® station was built and opened. Since then, there have been engines created specifically for the fuel, and many fleets on the road testing the fuel to further understand the HCNG fuel. There has also been much

research relating to the optimization of the in the areas of excess air ratio, hydrogen ratio, and spark timing.

The author of this paper, Dr. Fanhua Ma and his research group at Tsinghua University have been conducting research and development of HCNG (Hydrogen-enriched Compressed Natural Gas) engine and vehicle since 2000. Dr. Ma has published many works, many of which are cited in this chapter and has also succeeded in acquiring several Chinese patients relating to HCNG.

3. Advantages

Enriching natural gas with hydrogen for use in an internal combustion engine is an effective method to improve the burn velocity, with a laminar burning velocity of 2.9 m/s for hydrogen verses a laminar burning velocity of 0.38 m/s for methane. This can improve the cycle-by-cycle variations caused by relatively poor lean-burn capabilities of the natural gas engine. Hydrogen is characterized by a rapid combustion speed, a wider combustion limit and low ignition energy. These characteristics can reduce the exhaust emissions of the fuel, especially the methane and carbon monoxide emissions. The fuel economy and thermal efficiency can also be increased by the addition of hydrogen. The thermal efficiency of hydrogen enriched natural gas is covered in more detail in Ma et al. (2007).

HCNG allows for an initial use of hydrogen while taking advantage of the current CNG infrastructure. This allows for the hydrogen infrastructure to slowly become established until the production and efficiency demands can be met for the hydrogen economy. The research completed for the HCNG engine can be directly applied to a hydrogen engine. The addition of hydrogen to natural gas also greatly reduces the carbon monoxide and carbon dioxide emissions. The HCNG fuel can also help to avoid problems associated with evaporative emissions and cold start enrichment seen in gasoline engines, and the high anti-knock properties of CNG due to the high activation energy helps resists self-ignition.

4. Challenges

There are some challenges when it comes to using the hydrogen-natural gas mixture as a fuel. One of the biggest challenges using HCNG as a fuel for engines is determining the most suitable hydrogen/natural gas ratio. When the hydrogen fraction increases above certain extent, abnormal combustion such as pre-ignition, knock and back-fire, will occur unless the spark timing and air-fuel ratio are adequately adjusted. This is due to the low quench distance and higher burning velocity of hydrogen which causes the combustion chamber walls to become hotter, which causes more heat loss to the cooling water. With the increase of hydrogen addition, the lean operation limit extends and the maximum brake torque (MBT) decreases, which means that there are interactions among hydrogen fraction, ignition timing and excess air ratio. Therefore finding the optimal combination of hydrogen fraction, ignition timing and excess air ratio along with other parameters that can be optimized is certainly a large hurdle.

The emissions levels of fuels are probably the most important factor in determining whether or not the fuel is suitable as an alternative. Although the NOx emissions for CNG are already extremely low compared to traditional fuels, the addition of hydrogen causes increased NOx emissions. The addition of hydrogen has the opposite effect on the hydrocarbon emissions, so it is necessary to compromise at a hydrogen ratio for which the NOx and hydrocarbon emissions are equally low.

Probably most evident challenge for wide-spread use of the new fuel is the current lack of infrastructure. In many countries, however, the infrastructure for natural gas is well developed, which can be further adapted to carry hydrogen for the new fuel. Similar to other gaseous fuels, natural gas and hydrogen are both lighter than air, therefore if there is a leak it will quickly disperse into air with adequate ventilation. Lastly, the currently cost of hydrogen is more expensive than the cost of natural gas resulting in HCNG being more expensive than CNG. Although the cost is likely decrease as the use of hydrogen increases, it will be of great concern to consumers in the near-term.

5. Experimental Apparatus

Unless otherwise stated, the tests in this chapter are all completed using a six-cylinder, single point injection, SI natural gas engine, with the engine specifications shown in table 1.

Displacement	6.234 L
Stroke	120 mm
Bore	105 mm
Compression Ratio	10.0
Rated Power	169 kW / 2800 rpm
Rated Torque	620Nm / 1600 rpm

Table 1. Dongfeng EQD230N engine parameters

The engine is coupled to an eddy-current dynamometer for the measurement and control of speed and load. The exhaust concentration of HC, NO_x, CO, H_2 and the air/fuel ratio are monitored using a HORIBA-MEXA-7100DEGR emission monitoring system and a HORIBA wide-range lambda analyzer, respectively. A high speed YOKOGAWA ScopeCorde is used to record the cylinder pressure from a Kistler 6117B piezoelectric high pressure transducer. Corresponding crankshaft positions were measured by a Kistler 2613B crank angle encoder with a resolution of 1 degree CA.

An online mixing system is used to blend desired amount of hydrogen with natural gas in a pressure stabilizing tank just before entering the engine. The tank is divided into two chambers with a damping line used to improve the mixture uniformity. A schematic of the fuel supply system is shown in figure 1. The flow rate of natural gas and hydrogen are measured using a Micro Motion flow meter that uses the principle of Coriolis force for a direct measure of mass flow and an ALICAT flow control valve is used to adjust the flow rate of the hydrogen according to the flow rate of CNG and obtain the target hydrogen fraction.

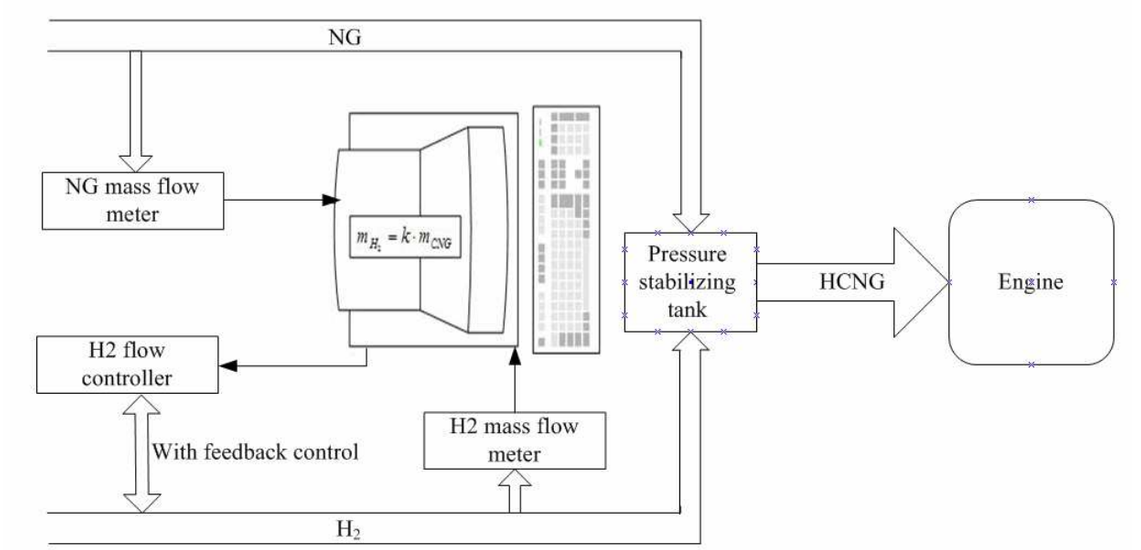


Fig. 1. Control logic of the on-line hydrogen/natural gas mixing system

6. Fundamental Equations

The chemical reactions of the fuel are essential in determining the amount of emissions the fuel will produce. This section will introduce some fundamental equations related to HCNG. Because CNG is made up of primarily methane, the following chemical equations are assumed:

$$CH_4 + 2O_2 \rightarrow (1 - x)CO_2 + 2H_2O \tag{1}$$

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \tag{2}$$

The fraction of hydrogen is x , and by assuming the molar mass of methane is 16 kg/mol and the molar mass of H_2 is 2 kg/mol, the mass fraction becomes

$$q = \frac{xM_{H_2}}{xM_{H_2} + (1-x)M_{CH_4}} = \frac{2x}{2x + 16(1-x)} = \frac{x}{8 - 7x} \tag{3}$$

Assuming that the air is 23.2% oxygen, the stoichiometric air-fuel ratio for the hydrogen/methane mixture is

$$l_0 = 34.48\frac{4 - 3x}{8 - 7x} \tag{4}$$

In order to calculate the lower heating value, the following equation is used

$$H_u = H_{H_2} q + H_{CH_4}(1 - q) \tag{5}$$

By substituting equation (3) and the relative heating values for hydrogen and methane (assuming the lower heating value of methane is 120 MJ/kg and the lower heating value of hydrogen is 50 MJ/kg), the following equation is formed with the units of MJ/kg.

$$H_u = \frac{120x + 50(8 - 8x)}{8 - 7x} \tag{6}$$

7. Performance Characteristics

Performance plays an important role in the choice of a fuel. HCNG has many advantages when it comes to performance because of the high octane number of hydrogen, the engine performance generally increases with the addition of hydrogen. The transient performance is also very important because in most cases the car will be running in transient conditions, this is covered in more detail by Ma et al. (2009b).

The thermal efficiency of both natural gas and HCNG increases with increasing load, which makes it an ideal fuel for high load applications and heavy-duty vehicles, this relationship can be seen in figure 2. It is also clearly seen in figure 2 that in nearly every case, the HCNG fuel has a higher thermal efficiency than pure natural gas. The results show that the brake effective thermal efficiency increases with an increased percentage of hydrogen at low and medium loads. The increase in thermal efficiency with the hydrogen addition is due to the reduction in the equivalence ratio. The hydrogen addition allows the lean burn limit to be extended because of the fast burn rate of hydrogen. The fast burn rate of hydrogen causes the combustion duration to decreases while the heat release rate and exhaust NOx increase with an increased percentage of hydrogen.

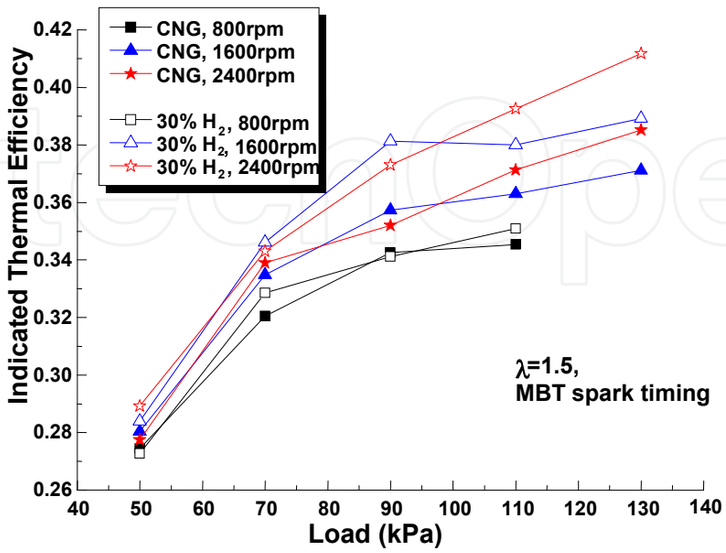


Fig. 2. Indicated thermal efficiency at the maximum brake torque spark timing

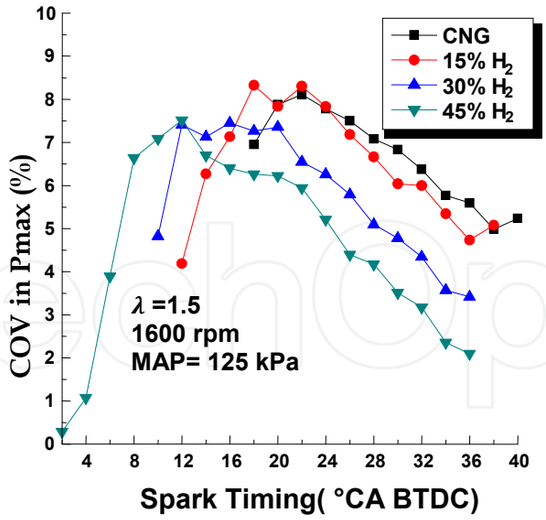


Fig. 3. Variation in the maximum pressure for various spark timings

The cycle-by cycle variations are also reduced with the addition of hydrogen, figures 3 and 4 show graphs of the coefficient of variation in the maximum pressure and indicated mean effective pressure respectively, for different hydrogen ratios. It can be seen that the coefficient of variation is reduced with an increased percentage of hydrogen at lean burn operation. The torque drop caused by retarded spark timing is relatively smaller in the case of HCNG fueling compared to that of CNG fueling, which can be seen in figure 5. This makes it possible to further retard the spark timing in an HCNG engine which results in lower NOx emissions. A higher torque also has other advantages such as resulting in a lower brake specific fuel consumption which is shown in figure 6.

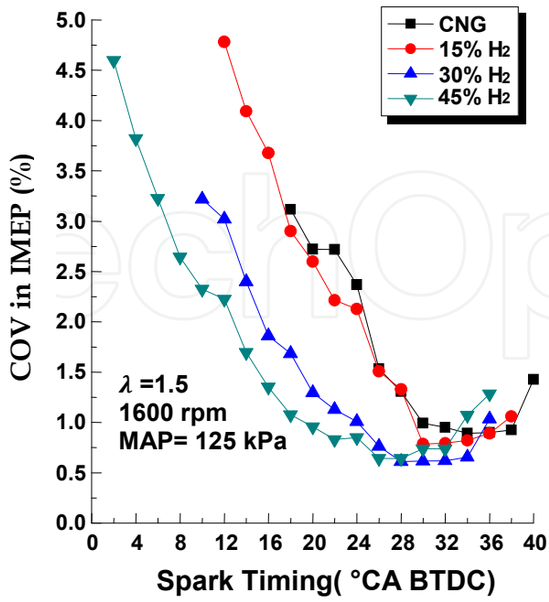


Fig. 4. Variation in the indicated mean effective pressure for various spark timings

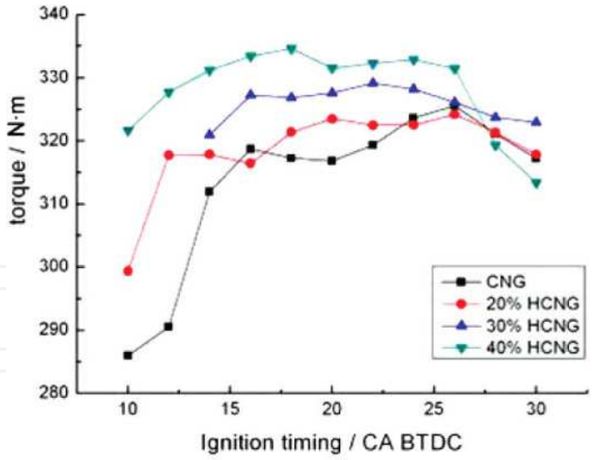


Fig. 5. Torque output for various H/CNG ratios (1200 $rpm, \lambda = 1.3$) (Ma et al., 2009a)

When two fuels with identical lower heating values are used, the fuel with the higher torque output will have lower brake specific fuel consumption (BSFC). According to the rules of lower heating value equivalent transformation, the mass of hydrogen in the HCNG fuel can be converted to a CNG mass with an equal lower heating value; this mass can then be added to the mass of CNG in the HCNG blend, therefore calculating an equivalent CNG mass. Using this equivalent data, the BSFC of HCNG and CNG can be compared and is shown in figure 6. (Ma et al., 2009a) It can be seen that the BSFC of the HCNG fuel is lower than the BSFC of pure CNG in nearly every case.

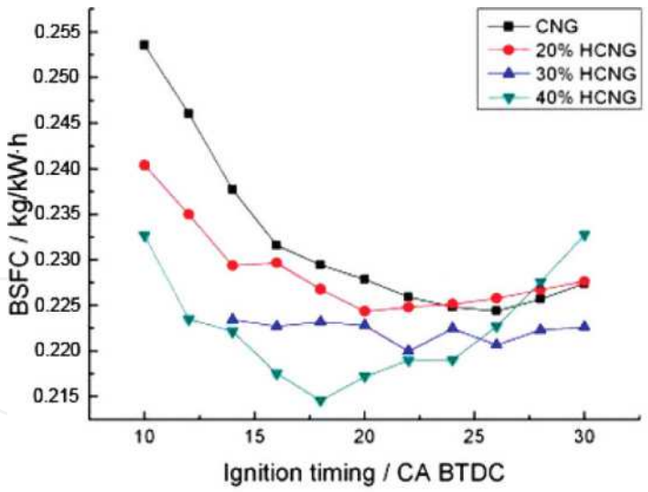


Fig. 6. Brake Specific Fuel Consumption for various H/CNG ratios (1200 $rpm, \lambda = 1.3$) (Ma et al., 2009a)

8. Emission Characteristics

When it comes to alternative fuels, arguably the most important factor in determining the feasibility of the fuel is the exhaust emissions. Because of the strictly controlled emissions

regulations, it is not only necessary to find a fuel that has optimum performance, but it is also very important to find a fuel that can meet the respective emissions standards.

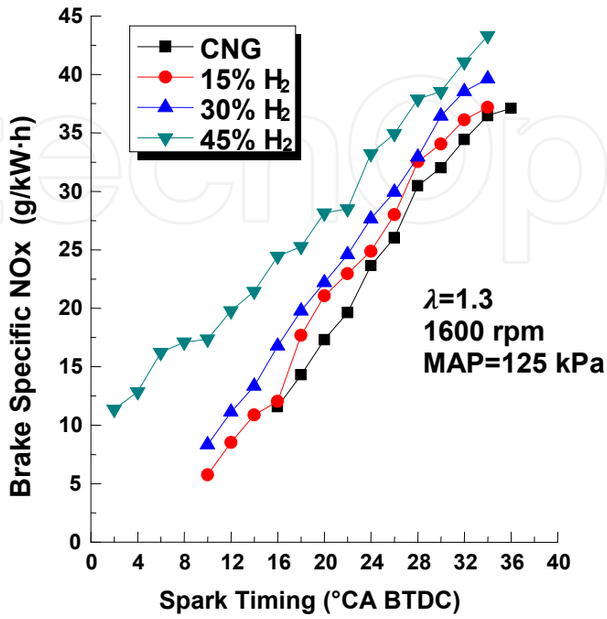


Fig. 7. Brake specific NOx emissions for different hydrogen fractions

Considering emissions, when HCNG fuel is compared with gasoline and diesel it appears to be a very appealing alternative fuel. When compared to gasoline, it produces significantly less nitrous oxide, carbon monoxide, carbon dioxide and non-methane emissions. And when compared with diesel, it nearly eliminates the particulate matter which is often of great concern. Compared to pure natural gas, it has been concluded that the addition of hydrogen increases the NOx emissions while reducing the HC emissions. The combustion stability is also improved by the addition of hydrogen which plays a part in reducing the un-burnt hydrocarbon emissions.

NOx emissions versus ignition timing were plotted in figure 7. As can be seen from the figure, the NOx emissions for the HCNG fuel are greater than the emissions of pure CNG. This is because of the elevated flame temperature due to the hydrogen. However, the NOx emissions of the HCNG are still considered relatively low compared to other fuels, and can be adjusted with further optimization.

Figure 8 indicates the variation of specific brake hydrocarbon emission versus spark timing for HCNG fuel at different ratios of hydrogen. As can be seen from the figure, the hydrocarbon emissions for HCNG fueling are greatly reduced compared to natural gas. The main reason for the decrease in hydrocarbon emissions is that the addition of hydrogen increases the laminar flame speed which decreases the amount of unburned hydrocarbons in the exhaust. Also, methane has a relatively stable chemical structure, therefore making it difficult to reduce emissions by after treatment. For this reason, the engine fueled with

HCNG has a large advantage regarding the hydrocarbon emissions than that of CNG fueling.

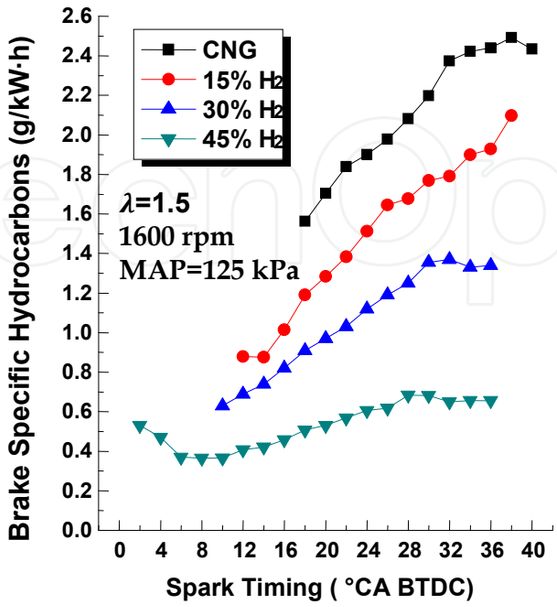


Fig. 8. Brake specific hydrocarbons at different hydrogen fractions

9. Optimization

There are many methods to optimize the engine for performance and emissions based on the properties of the fuel. Although the exhaust emissions from hydrogen-enriched natural gas are already very low, further refinement must be done in order to further reduce emissions and to achieve Enhanced Environmentally Friendly Vehicle (EEV) standards. There are many methods to improve the emission output as well as improving the performance of the engine.

9.1 Lean Burn

Lean burn characteristics are ideal in a fuel, because by running a fuel with a larger excess air ratio can not only reduce the emissions, especially NOx, but can also offers advantages in other areas such as reducing the brake specific fuel consumption. The lean burn limit is increased by the addition of hydrogen because of the faster burn speed as well as the improved laminar burn properties of hydrogen which makes it an ideal fuel to be run on lean-burn conditions. Ma et al. (2008d) specifically investigates the lean burn limit of HCNG.

Probably the largest advantage to running the engine on lean burn, is that it has the ability to greatly reduce the NOx emissions. The reduction in NOx emissions are due to the increased airflow which causes the engine to run at a lower temperature, therefore reducing the NOx emissions. Figure 9 shows how the NOx emissions are reduced at different excess air-ratios. It is very clear from this figure that as the excess air ratio is increased the NOx emissions drop considerably.

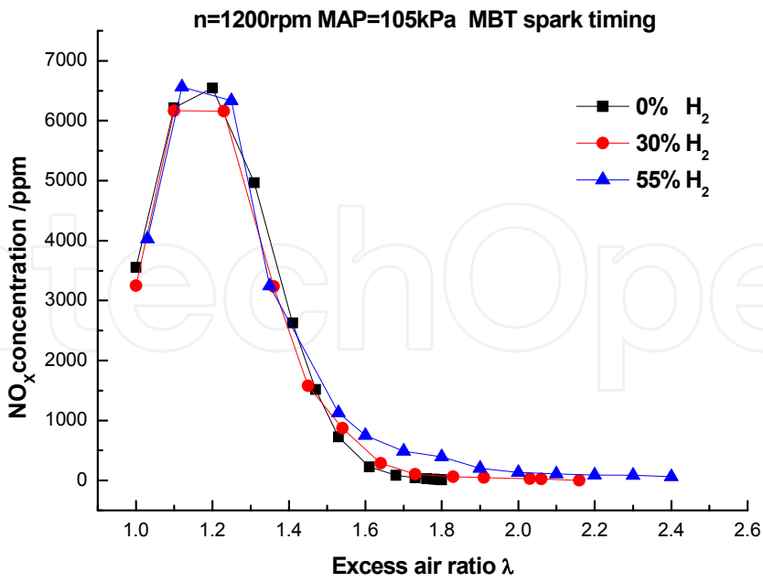


Fig. 9. The effect of excess air ratio vs NOx at MBT spark timing

The effect of the excess air ratio on hydrocarbon emissions can be seen in figure 10. It can be seen from the figure that there is a small reduction at an air-fuel ratio of roughly 1.25, but as the excess air ratio increases even further, the hydrocarbon emissions also increase. The reduction in hydrocarbon emissions at an excess air ratio of around 1.25 is not as evident in the hydrocarbon emissions as it was in the nitrous oxide emissions because as more air is added it can also contribute to unstable combustion which can also contribute to more unburned hydrocarbons. An increased excess air ratio can also increase the cycle-by-cycle variations which causes poor running conditions.

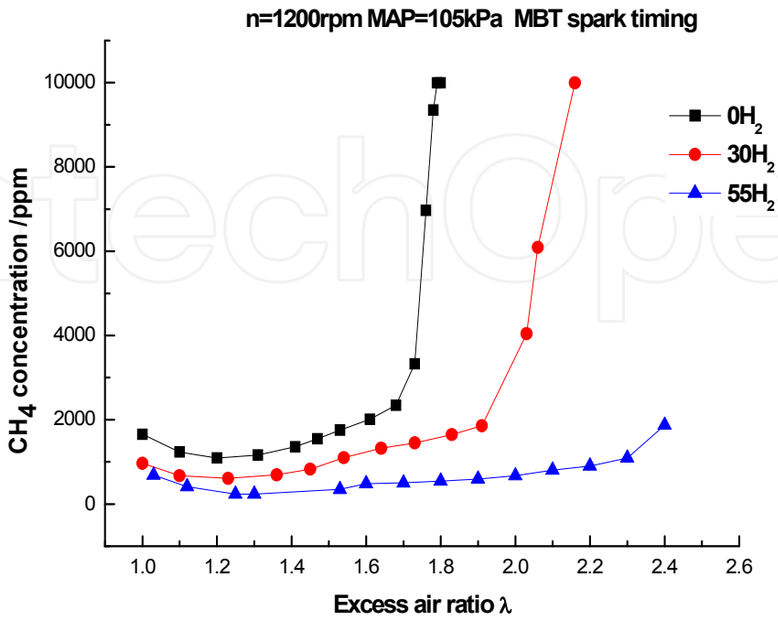


Fig. 10. Hydrocarbon Emissions for different hydrogen fractions and excess air ratios

Carbon monoxide emissions should also be considered when selecting the ideal excess air ratio. As seen in figure 11, by increasing the excess air ratio the carbon monoxide emissions drop dramatically. This occurs because the formation of carbon monoxide is mainly caused by incomplete combustion. However, as the excess air ratio becomes too large the combustion conditions are reduced and the carbon monoxide emissions begin to increase.

Another advantage to lean burn is that as the excess air ratio is increased, the brake specific fuel consumption decreases. This is because as the air-fuel ratio is increased, it usually leaves less unburned fuel. That is true until the excess air ratio reaches a certain limit when the cycle-by-cycle variations begin to increase because of the lack of fuel. Lean operation also reduces the likelihood of knocking, which allows the use of a higher compression ratio. However, there are some difficulties with lean-burn operation including cycle-by-cycle variations. Cycle-by-cycle variations, which increase as the engine is leaned-out, are generally recognized as a limiting factor for the engine's stable operation, fuel efficiency and emissions. Lean operation can decrease the CO and NOx emissions while simultaneously improving engine efficiency. A compromise must be made so that significant reduction in emissions can be made without sacrificing the burn quality of the fuel which may include slow flame propagation, increased cycle by cycle variations and incomplete combustion which may be more clearly explained in Ma et al. (2008a), Ma et al. (2008e) and Ma et al. (2008f).

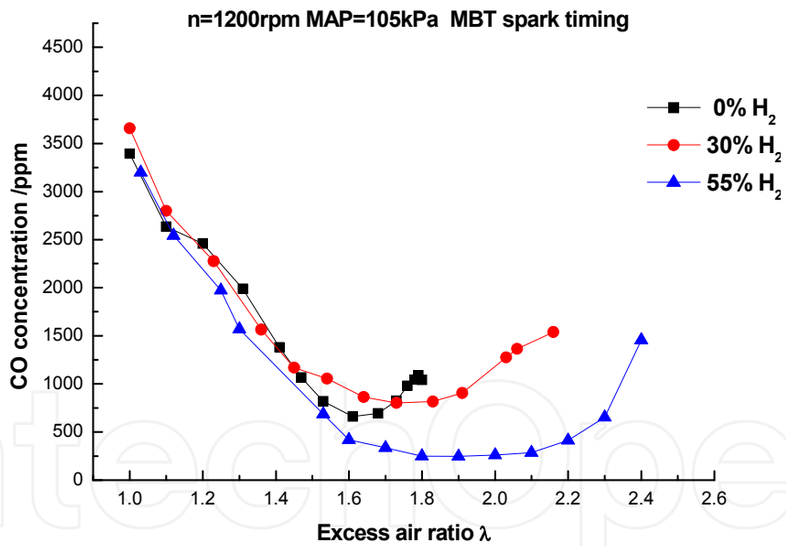


Fig. 11. Carbon Monoxide emissions vs excess air ratio

9.2 Hydrogen Ratio

The addition of hydrogen can greatly improve the performance and emissions of the fuel. There have been many studies completed in efforts to obtain the ideal hydrogen ratio, and the general consensus is that hydrogen/natural gas blends around 20%, results in the best overall combination of emissions and engine performance. According to Wang (2009a), the role of hydrogen in the flame will change from an intermediate species to a reactant when hydrogen fraction in the blends exceeds 20%. (Wang et al., 2009a) Consequently the most

suitable hydrogen fraction is significantly related to ignition timing and excess air ratio. According to Akansu et al. (2004) who completed tests on a single cylinder AVL engine at hydrogen/natural gas ratio ranging from 0% to 100%, a 20–30% hydrogen enrichment of natural gas gives the most favorable engine operation. Higher hydrogen contents undermine the knock resistance characteristics of natural gas, lower power output of the engine and increase the fuel cost. Akansu et al. also concludes that, Hydrogen content lower than 20–30% does not make enough use of the performance enhancement potential of hydrogen. (Akansu et al., 2004)

The thermal efficiency of fuel can be improved as seen in figure 2 from a previous section and figure 12 of this section. Also seen in figure 12, the thermal efficiency begins to drop rapidly after reaching a certain excess air ratio, for which this decline in thermal efficiency can be reduced as the hydrogen ratio is increased. This is due to the improvements in burning velocity and improvements in the combustion characteristics which can help extend the lean burn limit and also improve the fuel efficiency. It can be seen in figure 6 that the BSFC of the HCNG fuel can be reduced by increasing the ratio of hydrogen. The minimum BSFC was attained using 40% HCNG, which results in a 5.07% lower BSFC than that of CNG fueling at the same conditions.

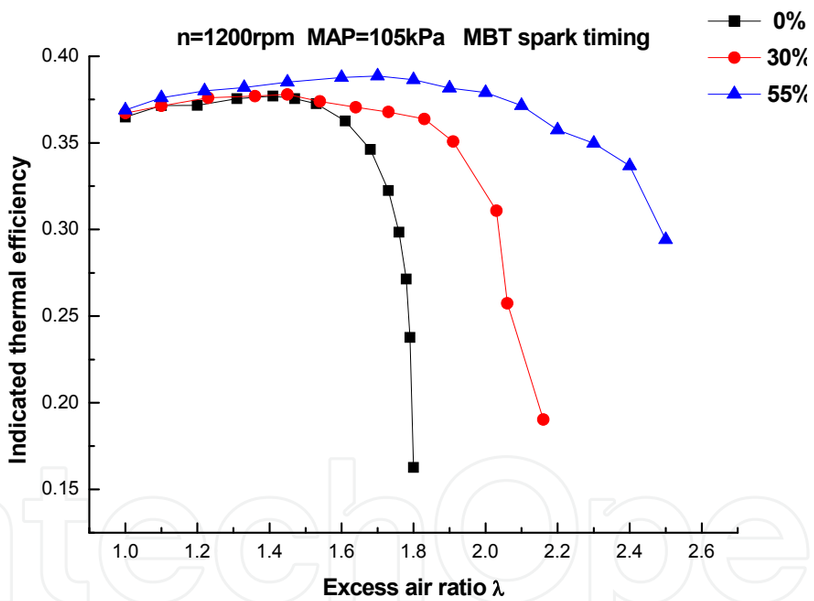


Fig. 12. Indicated thermal efficiency versus excess air ratio

Under idle operation conditions, hydrogen addition is an effective method for improving the power output of the engine and reducing both exhaust emissions and fuel consumption. Furthermore, these results improve as the ratio of hydrogen is increased; however, studies show that under ideal conditions there is not significant improvement when increasing the hydrogen ratio in the HCNG fuel. Under normal operation conditions, the addition of hydrogen is effective at improving the power output of the engine and reducing fuel consumption. The hydrogen-enriched fuel can help improve the burning velocity and improve the incomplete combustion and is seen to increase with the hydrogen ratio. Even

though the volumetric calorific value of the HCNG mixture is slightly lower than the calorific value of pure CNG, after the fuel is enriched with hydrogen the combustion efficiency and thermal power conversion efficiency are enhanced resulting in a higher power performance as can be seen in figure 13.

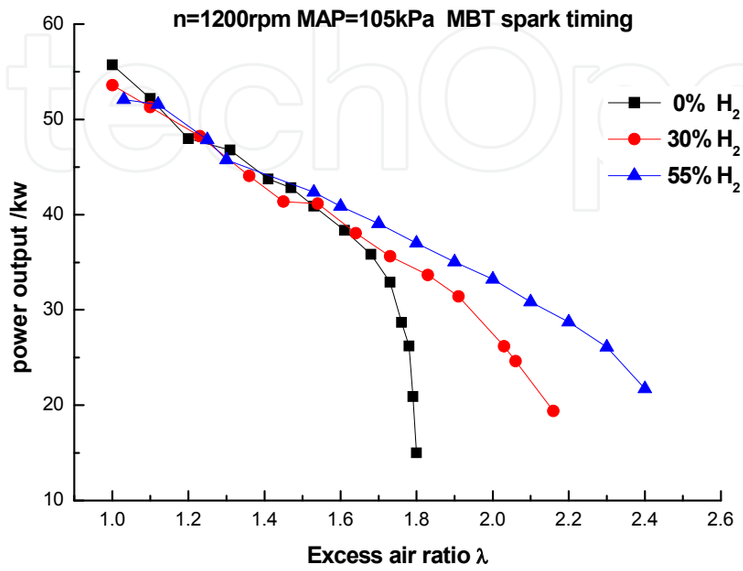


Fig. 13. Engine's power performance versus excess air ratio

Figure 3 and figure 4 from a previous section show that the hydrogen addition can also be an effective method to reduce the as coefficient of variation decreases. Cycle by cycle variations are caused by poor burn quality and have many adverse effects such increasing the emissions and reducing the performance. As the hydrogen fraction is increased, the output torque also increases which can be seen in figure 5. According to Ma, et al. (2009a) this is true at high engine speeds, but for low engine speeds the variation in torque is negligible. Figure 14 shows the coefficient of variation of the indicated mean effective pressure for different hydrogen ratios at different excess air ratios. As can be seen, hydrogen addition can reduce COV_{imep} especially when compared at high excess air ratios due to hydrogen's broader burn limit and its' fast burn speed.

NOx emissions versus ignition timing were plotted in figure 7 of a previous section. As can be seen from the figure, the NOx emissions increase as the hydrogen ratio increase. This is caused by the elevated flame temperature in the cylinder which rises as the hydrogen is added. Carbon monoxide emissions can also be greatly reduced with the addition of hydrogen. Table 2 shows different hydrogen fractions while holding the power constant, it is clearly seen in this table that as the hydrogen fraction is increased the carbon monoxide and unburned hydrocarbon emissions are greatly reduced while the NOx remains at acceptable levels. The reduction in hydrocarbon and carbon monoxide emissions can be attributed to hydrogen's ability to strengthen combustion, especially for lean fuel-air mixtures.

Regarding emissions, the largest advantage to using a higher hydrogen ratio is the reduction in hydrocarbon emissions which can be seen in figure 10 of a previous section. The reduction of hydrocarbon emissions can be explained by the fact that hydrogen can speed up flame propagation and reduce quenching distance, thus decreasing the possibilities of incomplete combustion, and because of the fact that the carbon concentration of the fuel blends is decreased due to hydrogen addition. Hydrogen's ability to strengthen combustion has a large effect on the hydrocarbon emissions, which can be especially evident in lean fuel-air mixtures.

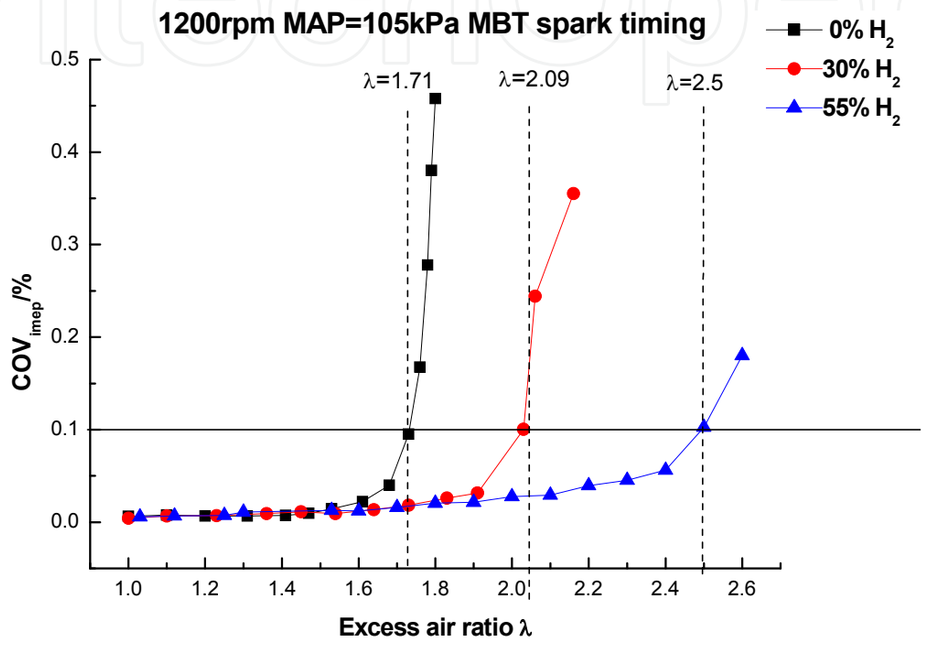


Fig. 14. COV_{imep} versus excess air ratio

Hydrogen fraction (%)	NOx (%)	CH_4 (%)	CO (%)	Economy (%)	Power (%)
0	100	100	100	100	100
10	67.2	84.3	90.4	97	100
20	50.4	71.1	82.7	92	100
30	64.3	65.3	76.5	93	100
40	88.6	60.1	71.3	94	100
50	105	57.3	67.3	94	100

Table 2. The overall performance of different hydrogen fraction at full load 1600r/min

Figures 15 confirms the improvements in flame development speed (characterized as the duration between the spark and 10% mass fraction burned) and propagation speed (characterized as the duration between 10% and 90% mass fraction burned). Fundamentally, the addition of hydrogen provides a large pool of H and OH radicals whose increase makes the combustion reaction much easier and faster, thus leading to shorter burn duration. Engine performance and emissions at different hydrogen ratios are looked at in more detail in Ma et al. (2008h) and Ma et al. (2010).

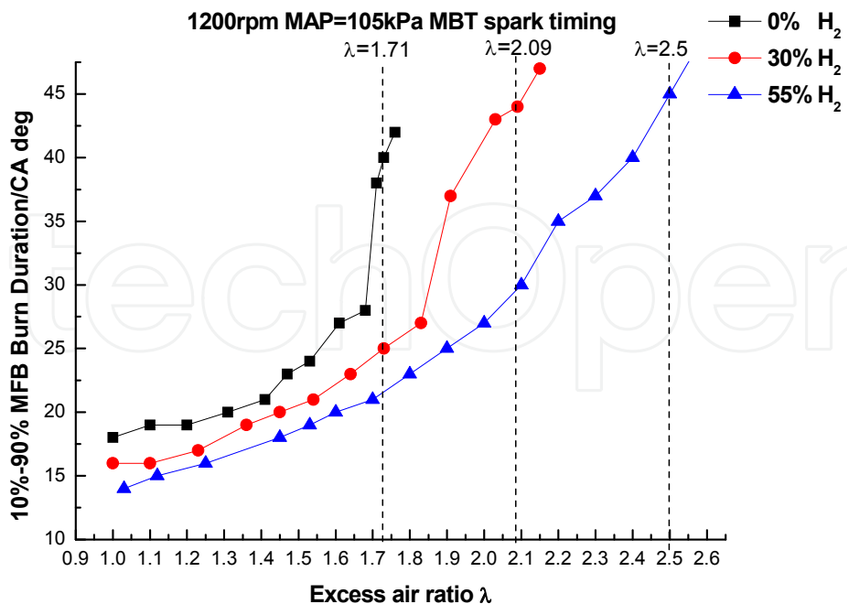


Fig. 15. 10% to 90% MFB burn duration versus excess air ratio

9.3 Spark Timing

Optimizing spark timing can be used as a strategy to avoid knocking and to avoid exceeding the limit of maximum cylinder pressure when operating under lean burn conditions. An effective way to reduce NOx emission is to retard the spark timing which can be seen in figure 7 in a previous section. This is due to the combustion stability and the elevated flame temperature in the cylinder. This figure shows an engine speed of 1600rpm, but at a lower engine speed such as 800 rpm it is found that the NOx emissions also increase slightly when the spark timing becomes closer to TDC beginning around 5 degrees CA BTDC. This is because of the increased engine power loss when the ignition timing is set too close to TDC because the fuel cannot burn completely and the combustion process mainly takes place in the expansion stroke with a relatively low-pressure environment.

The thermal efficiency, shown in figure 16, is also greatly affected by the spark timing. As can be seen in the figure, the thermal efficiency rises as the spark timing is advanced. This is due to the decrease in temperature due to the early ignition timing. The performance and emissions characteristics at different spark timings are more clearly explained in Ma et al. (2008c).

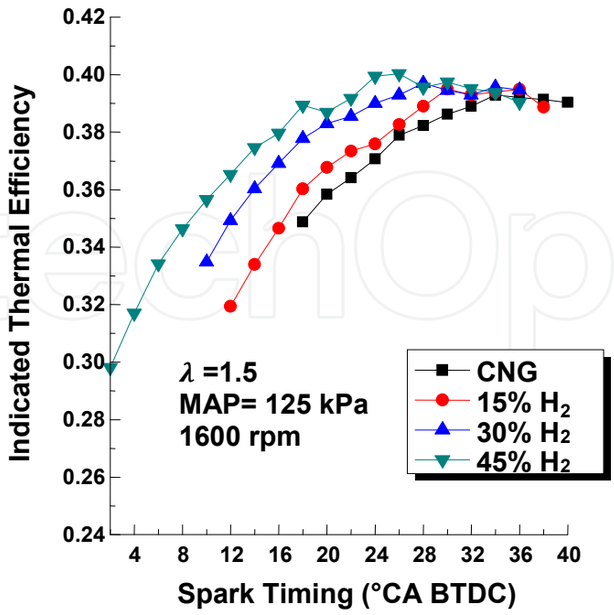


Fig. 16. Indicated thermal efficiency at different spark timings

Maximum brake torque (MBT) spark timing is dependent on flame speed, namely faster flame speed will result in a decrease in the crank angle before TDC at which the spark for maximum torque is applied. With identical fuel energy and equivalent excess air ratios, as the MBT approaches TDC, the torque output increases. This can be explained by the fact that hydrogen addition increases the burning speed of the flame causing the real engine cycle to be similar to the ideal constant volume cycle, thus improving the thermal efficiency of the engine. This relationship can be seen in figure 17. The spark timing also has influence on the coefficient of variation; in general, as hydrogen is added the optimal spark timing should be a few crank angle degrees closer to top dead center. The excess air ratio also has a relatively large effect on the ideal spark timing. In order to degrease the coefficient of variation, the spark timing should be advanced as the excess air ratio is increased.

Figures 7 and 8 from a previous section show the relationship between spark timing and NOx and hydrocarbon emissions, respectively. It is very clear from these figures, that in order to reduce emissions, the spark timing should move closer to top dead center. It can also be observed that as the hydrogen content increases the spark timing should move closer to top dead center. Although there are many other factors that affect the emissions (particularly the air fuel ratio) the spark timing also has a dramatic influence on the emissions.

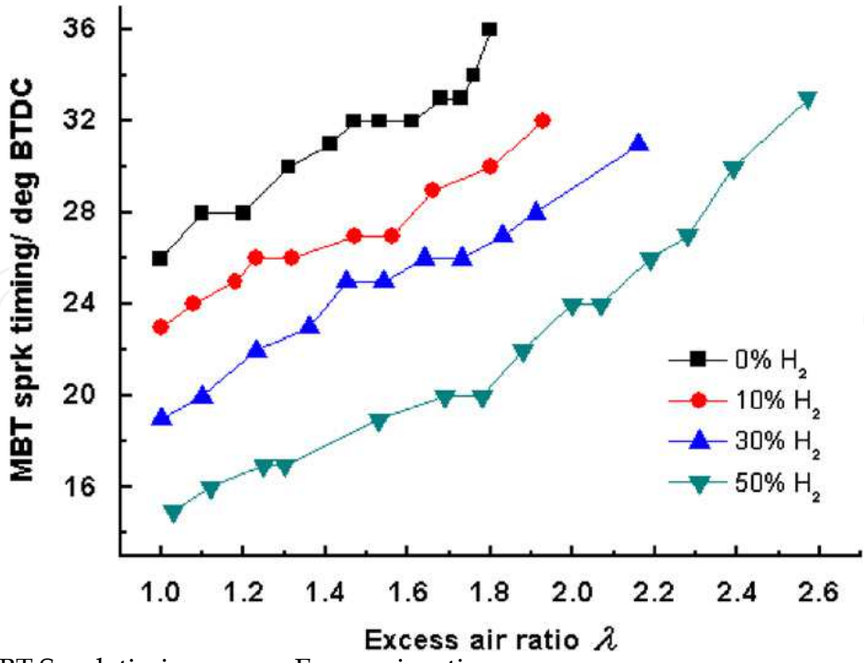


Fig. 17. MBT Spark timing versus Excess air ratio

9.4 Catalytic Converter and European Transient Cycle (ETC) Performance

Although there has not been extensive research completed in this area, a catalytic converter is a common and effective method to reduce the engine emissions, and has also been proven as a suitable method for reducing the emissions in an HCNG engine. ETC performance is a test cycle that has been introduced in the year 2000, in order to receive an emission certification of heavy-duty diesel engines in Europe.

The ETC performance data of the Dongfeng EQD230N engines fuelled with CNG and 20% HCNG without a catalytic converter are shown in figures 18 and 19, and the comparison of CNG and 20%HCNG engine's ETC performance data are listed in table 3. It should be indicated that both the CNG and 20% HCNG engines have been carefully optimized and calibrated. From table 3 it is found that at a 20% hydrogen to natural gas ratio, the engine's NOx emission based on the European transient cycle (ETC) are reduced by nearly 50% compared with CNG engine, which resulted from the addition of 20% HCNG, the engine's larger excess air ratio and increased ignition delay. It can also be found that the engine running on 20% HCNG has about 40% CO reduction, 60% NMHC reduction, 47% CH_4 reduction and 7% BSFC (brake specific fuel consumption) reduction compared with CNG engine, and the peak power maintains unchanged.

A comparison of the ETC performance data for the three different oxidation catalysts running on 20% hydrogen/natural gas are shown in table 4. All three catalysts can obtain enhanced environmentally friendly vehicle (EEV) standards, which are listed in table 5. By implementing a proper oxidation catalyst on a HCNG engine, it allows EEV standards to be more easily achieved. However, by increasing catalytic efficiency, exhaust resistance is increased, engine power is reduced and the brake specific fuel consumption is increased.

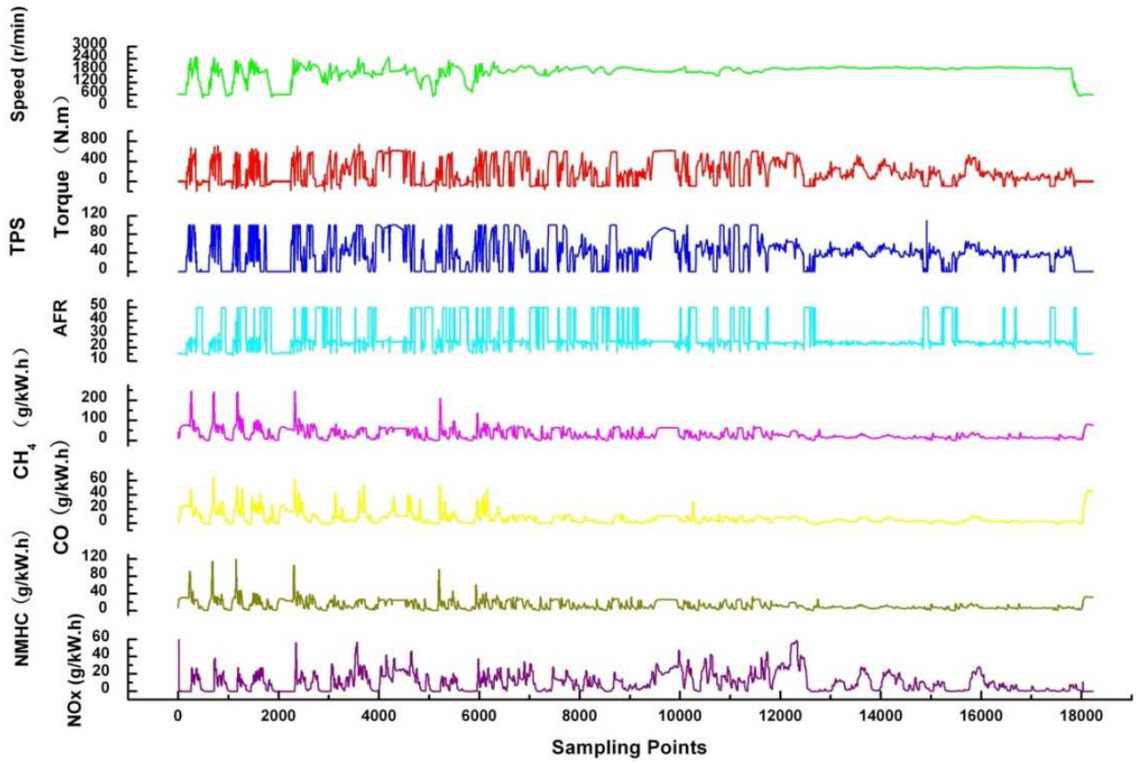


Fig. 18. The ETC performance data for Dongfeng EQD230N CNG engine

A three-way catalyst can be used to reduce the hydrocarbon emissions by oxidizing unburned hydrocarbon, as well as reducing NOx emissions. However, because of the three-way catalyst requires stoichiometric operation, a three-way catalyst may not be the best alternative to reduce emissions in an HCNG or natural gas engine. As the air-fuel ratio approaches the stoichiometric air-fuel ratio, the temperature of the HCNG engine will be elevated resulting in durability problems as well as increasing the emissions and reduces the engine's thermal efficiency.

Fuel type	NOx (g/kW.h)	CO (g/kW.h)	NMHC (g/kW.h)	CH_4 (g/kW.h)	BSFC (g/kW.h)	Peak power (kW)
CNG	4.76	2.45	0.52	4	254	154
20%HCNG	2.31	1.54	0.21	2.1	236	154

Table 3. The comparison of CNG and 20% HCNG engine's ETC performance data

Catalyst type	Nox (g/kW.h)	CO (g/kW.h)	NMHC (g/kW.h)	CH4 (g/kW.h)	BSFC (g/kW.h)	Peak power (kW)
A	1.34	0.25	0.05	0.45	260	150
B	1.42	0.13	0.03	0.42	263	149
C	1.51	0.07	0.02	0.20	272	145

Table 4. The ETC peformance data comparison of three different oxidation catalysts on 20% HCNG engine

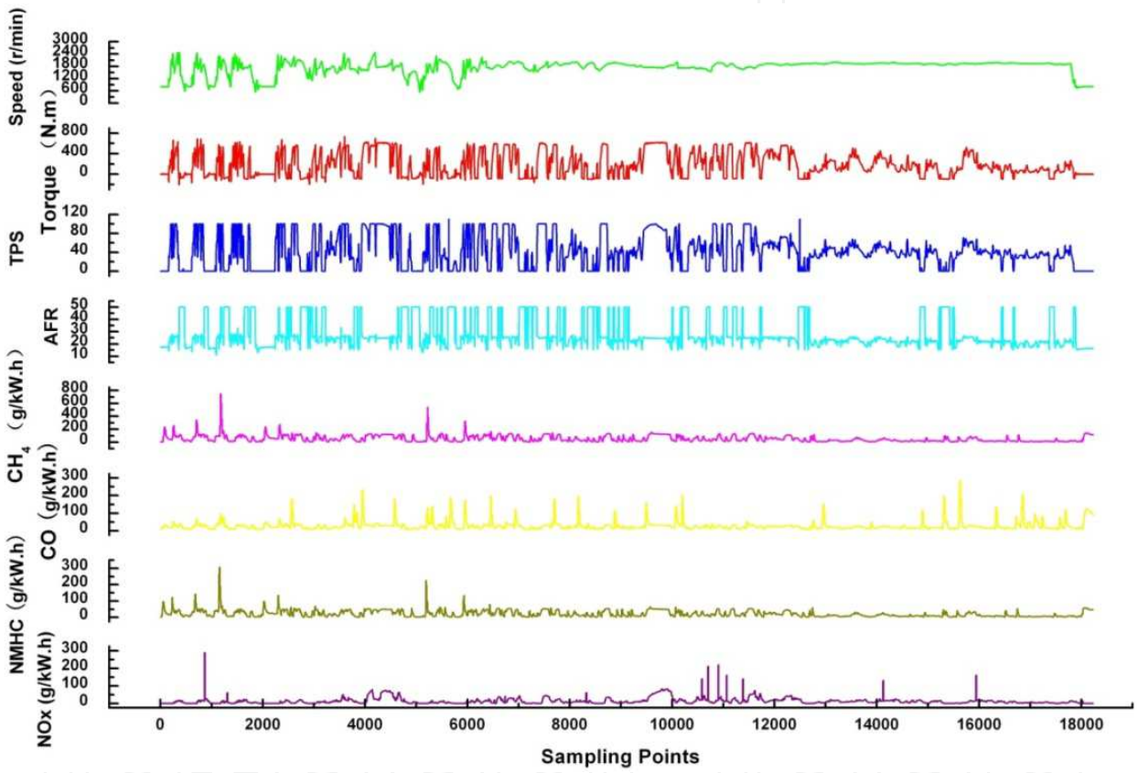


Fig. 19. The ETC performance data for Dongfeng EQD230N engine fuelled with 20% HCNG

Nox (g/kW.h)	CO (g/kW.h)	NMHC (g/kW.h)	CH4 (g/kW.h)
2.0	3.0	0.40	0.65

Table 5. Enhanced environmentally friendly vehicle (EEV) standards

9.5 Exhaust Gas Recycle

Exhaust gas recycle (EGR) is used to reducing emissions in both gasoline and diesels engines. This is another area in which there has not been extensive research in regarding the

use of HCNG engines. However, it has been shown in CNG engines to be an effective method in reducing the emissions, especially the NOx emissions.

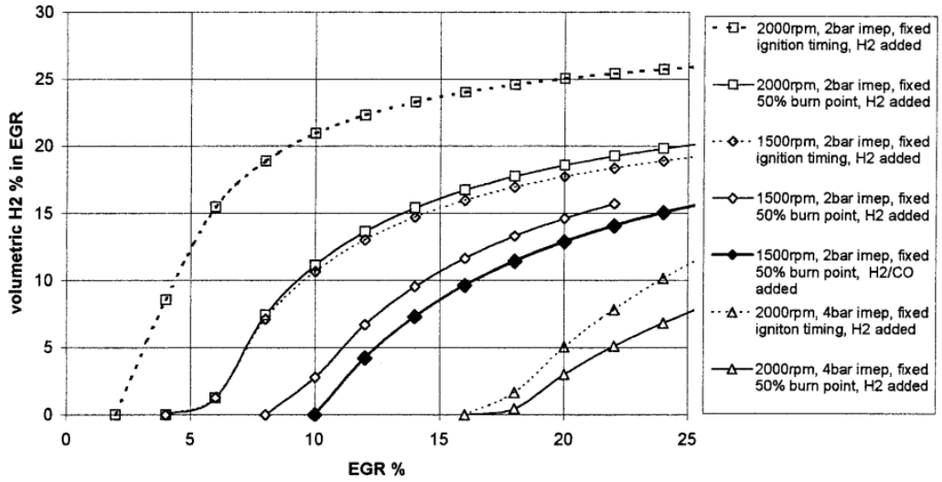


Fig. 20. The percentage hydrogen required in a reformed EGR stream to maintain a COV of iMEP of 5 percent or lower (Allenby et al., 2001)

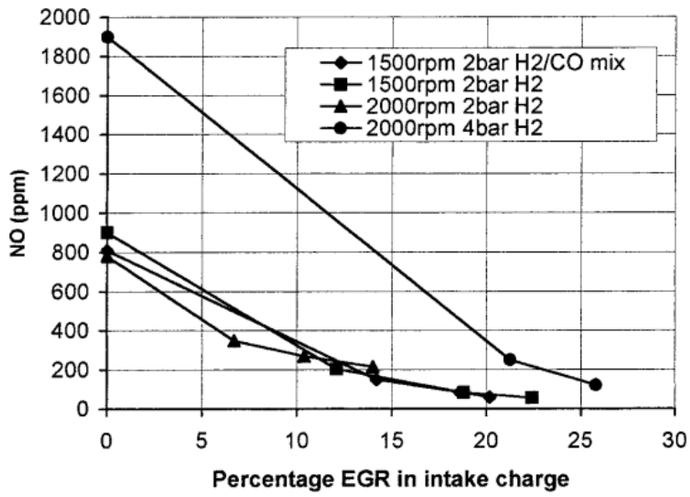


Fig. 21. Dry base engine-out NO emissions versus percentage EGR for four test cases (Allenby et al., 2001)

Research completed by Allenby et al. (2001) on a single cylinder SI engine shows that by adding hydrogen to the EGR of a natural gas engine through a catalyst, the percentage of exhaust gas to be recalculated through this system can be increased; this relationship can be seen in figure 20. In this study, as can be seen in figure 21 the NOx emissions decrease as the percentage of EGR is increased. This study shows that with the addition of hydrogen in the EGR, the engine can tolerate up to 25 percent EGR while maintaining a indicated mean effective pressure, coefficient of variability below 5%, and at this level of EGR, the reduction of NOx emission is greater than 80 percent. (Allenby et al., 2001)

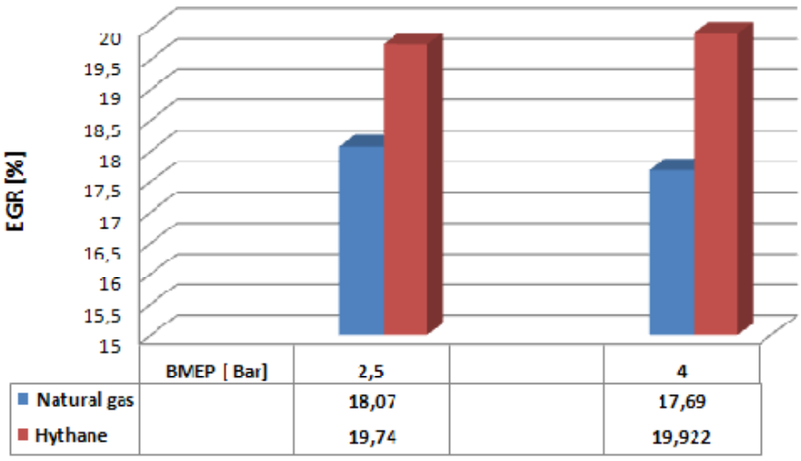


Fig. 22. Engine EGR tolerance for different fuels (Kaiadi et al., 2009)

Another study investigating the use of an EGR system was completed by Kaiadi et al. (2009) using a natural gas engine operated a stoichiometric conditions shows that by using an HCNG mixture of 15% as a fuel, the limit for exhaust gas recirculation can be increased as shown in figure 22. This figure shows that by using hydrogen enriched natural gas rather than natural gas alone, the amount of gas that can be recycled is increased by nearly 20%.(Kaiadi et al., 2009)

9.6 Compression Ratio

Because both natural gas and hydrogen are gaseous fuels, they are able to with-stand a higher compression ratio which allows for increased efficiency. Although the studies on the effect of an increased compression ratio on the performance and emission of the fuel are not plentiful, it has been proven to be an effective method to increase performance. According to NRG Tech (2002), by completing tests on an HCNG engine with compression ratio ranged from 9.1 to 15.0 , it was concluded that a desirable compression ratio ranges between 12 and 15. However, care must be taken to avoid engine knock. This can require non-optimal designs for emissions, but will allow knock-free operation. (NRG Tech, 2002)

10. Optimizing the Control System

As can be seen from the previous section, there are many factors that contribute to the performance and emissions of the HCNG fuel. In order to optimize such parameters, there must be the relative software and hardware developed to support this. Simulation can also be useful in determining the ideal parameters. A quasi-dimensional model developed by the author and his research group is presented in Ma et al. (2008b) and Ma et al. (2008g).

There are eight areas of hardware that should be optimized for the HCNG fuel which include: the main chip circuit design, the power management circuit design, the input signal conditioning circuit design, the actuator drive circuit design, the communication circuit design, thermal design, EMI design and access socket design. There are three aspects to the software design, the first is the measurement and modeling of the engine operating

parameters. The second is to judge the engine operating conditions and calculation of the state. The third is the implementation of the module results.

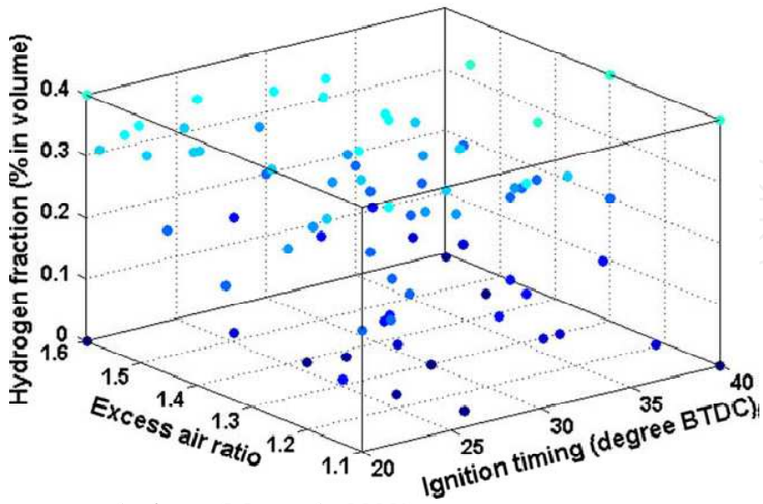


Fig. 23. Control system platform (Ma et al., 2008i)

Finally, the HCNG control unit must with-stand system verification of functionality, reliability and stability. There have already been advances in the electronic control system hardware and software design, additional optimization is necessary to obtain the best combination of parameters. Figure 23 shows an example of data points which were taken in efforts to optimize a control system. The control strategy used by the author is presented in Ma et al. (2008i).

11. Online-Mixing

Another of the many challenges that come with the development and implementation a mixed fuel such as hydrogen-enriched compressed natural gas is the method of mixing the two fuels. In many testing facilities the two fuels are pre-mixed and bottled in high-pressure cylinders, which can be costly, unsafe and constrains the blend ratio; however the use of an online mixing system can not only increase safety and decreases cost, but also allows for a variable blend ratio which can increase efficiency and reduce costs while testing.

The use of premixed, bottled hydrogen/natural gas mixtures restricts the ability to fluctuate the hydrogen ratio, and is especially limiting when doing lab tests. One alternative to having pre-bottled hydrogen-natural gas used for dispensing is by implementing an online mixing system. The relative pressures can be used to control the blend ratio which is described by Dalton's law of additive pressures which states that the pressure of a gas mixture is equal to the sum of the pressure of each gas if it existed alone at the mixture temperature and volume. This can be written to solve for the hydrogen fraction x_1 as follows:

$$x_1 = \frac{P_{H2,1}}{P_1} \tag{8}$$

Where $P_{H2,1}$ is the pressure after the initial charge of hydrogen, and P_1 is the total cylinder pressure at the end of the first charging. After some time, when the cylinders should be recharged, the following equation is used to calculate the hydrogen fraction.

$$x_i = \frac{P_{H2,i} - (1 - x_{1-i})P'_{i-1}}{P_i} \tag{9}$$

In this equation, $P_{H2,i}$ is the hydrogen pressure, x_i is the hydrogen fraction, and P_i is the cylinder pressure after the ith recharge where P_{i-1} represents the pressure before the ith refuel.

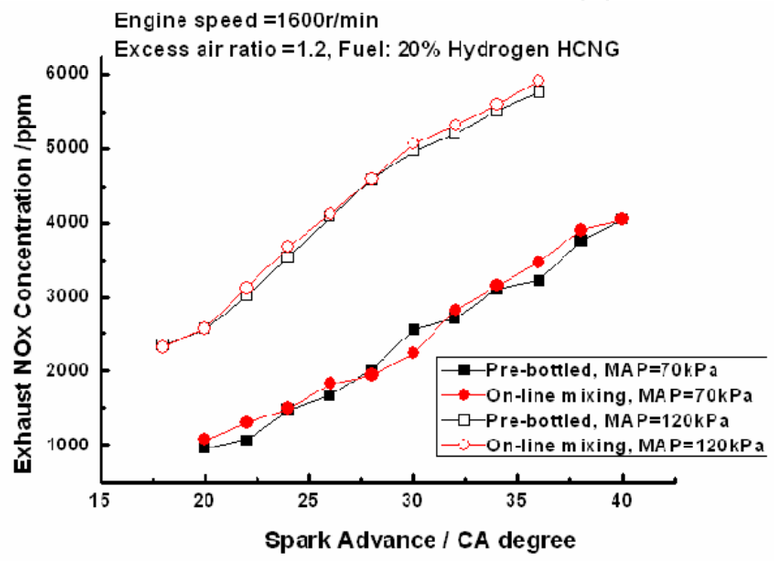


Fig. 24. Online mixing system compared with pre-bottled mixing (Ma et al., 2008j)

Figure 1 from a previous section shows a schematic of an online mixing system that can be used to implement the HCNG fuel. An HCNG dispenser is generally combined with a CNG dispenser for natural gas vehicles as both use the same feed stream from the compressed natural gas grid. In addition the Hydrogen production method differs per station, some stations use on-site generation where other stations use on-site delivery of hydrogen to feed the HCNG dispensers. By using the online mixing system, the power and emissions are nearly identical to those of the pre-bottled HCNG. A comparison of the nitrous oxide emissions can be seen in figure 24. (Ma et al., 2008j)

12. Infrastructure

An established infrastructure is critical for the wide-spread use of any alternative fuel. Currently the infrastructure of natural gas is already well-established and growing in many places, this existing infrastructure could potentially be used as a base for the establishment of infrastructure for the HCNG as a fuel. Furthermore, the HCNG infrastructure can be a good start point to move in the right direction as the world moves closer to a hydrogen economy. According to (Fuel Cells 2000, 2009), There are currently 14 public and R&D

fueling stations around the world including fueling centers in Phoenix, Arizona, Thousand Palms California, Fort Collins Colorado, Las Vegas Nevada, Hempsted New York, University Park Pennsylvania, Montreal Canada, Surrey Canada, Dunkerrque Frace, Toulouse Frace, Faridabad India, Montova Italy, Stavanger Norway and Malmo Sweden. There are also fueling stations planned for Barstow California, Delhi India, Goteborg Sweden, Shanxi Province in China and possibly Grenoble France.

13. Future Research

Future research of the hydrogen enriched compressed natural gas fuel include continuous improvement on performance and emissions, especially to reduce the hydrocarbon emissions (including methane if necessary) which are currently not heavily regulated but will probably be more closely regulated in the future. Additional optimization is also necessary for the HCNG fuel in order to obtain the ideal combination of excess air ratio, hydrogen ratio and spark timing. This should be further followed by the implementation of an adequate control system. Other potential improvements include the reduction of emissions which can be transpire with the addition of a catalytic converter or by implementing an exhaust gas recycle system, lastly there is potential for performance improvements with an increase in the compression ratio.

14. Conclusion

Compared with natural gas, HCNG has many advantages when it comes to performance. Research has shown that the brake effective thermal efficiency increases with an increased percentage of hydrogen. Another effect of the addition of hydrogen is that the brake specific fuel consumption is reduced, the cycle by cycle variations are also reduced, and the thermal efficiency is increased.

Emissions can also be improved with the addition of hydrogen. Compared to pure natural gas, HCNG reduces the HC emissions, which is in part due to the increased combustion stability that comes with the addition of hydrogen. However, due to the increased temperature and combustion duration that accompanies the hydrogen addition, an increase in NOx emissions is observed.

There are many optimization parameters that can be modified to adjust to the HCNG fuel. With the increase of hydrogen addition, the lean operation limit extends which is often used to maximize the thermal efficiency and reduce the nitrous oxide emissions, although due to the increased air running through the engine, at high excess air ratios the combustion becomes more unstable leaving unburned hydrocarbons in the exhaust. Therefore, the excess air ratio should be positioned by finding the best combination of nitrous oxide and the hydrocarbon emissions. Another method to reduce emissions, is to move the spark timing closer to top dead center, however this is greatly dependent on the excess air ratio. The hydrogen ratio can also be increased to extend the lean limit, improve the combustion and reduce the hydrocarbon emissions.

Although the exhaust emissions from hydrogen-enriched natural gas are already very low, further refinement must be done in order to further reduce emissions and to achieve Enhanced Environmentally Friendly Vehicle (EEV) standards. Therefore finding the optimal combination of hydrogen fraction, ignition timing and excess air ratio along with other parameters that can be optimized is certainly a large hurdle. It is not only a challenge to locate the ideal combination of hydrogen fraction, ignition timing, and excess air ratio, but it can also be a large challenge to control these parameters. This requires sufficient control system to be developed for the HCNG engine to maximize the performance simultaneously minimizing the exhaust emissions.

Probably the biggest challenge with the implementation of the fuel comes with developing an infrastructure to support this promising alternative fuel. There HCNG allows for an initial use of hydrogen while taking advantage of the current CNG infrastructure. This allows for the hydrogen infrastructure to slowly become established until the production and efficiency demands can be met for the hydrogen economy. Although there is currently a large amount of research taking place regarding the HCNG fuel, there are certainly many steps to take before wide-spread implementation can occur.

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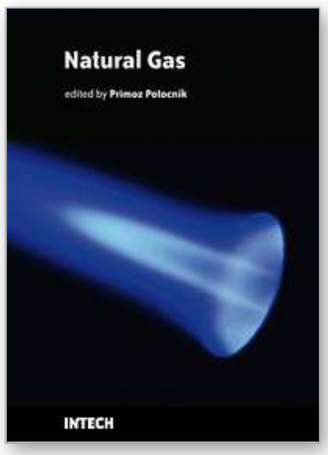
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The contributions in this book present an overview of cutting edge research on natural gas which is a vital component of world's supply of energy. Natural gas is a combustible mixture of hydrocarbon gases, primarily methane but also heavier gaseous hydrocarbons such as ethane, propane and butane. Unlike other fossil fuels, natural gas is clean burning and emits lower levels of potentially harmful by-products into the air. Therefore, it is considered as one of the cleanest, safest, and most useful of all energy sources applied in variety of residential, commercial and industrial fields. The book is organized in 25 chapters that cover various aspects of natural gas research: technology, applications, forecasting, numerical simulations, transport and risk assessment.

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