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HCNG – A Dead End or a Bridge to the Future?

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1 Introduction

HCNG is a vehicle fuel which is a blend of natural gas and hydrogen in various proportions, typically 8-50 vol% hydrogen. Mixtures below 20% are often referred to as Hythane™. HCNG is can bridge the gap between traditional liquid fuels and hydrogen. By using HCNG as a transition fuel and taking advantage of the CNG existing infrastructure, it is possible to start building a hydrogen infrastructure at a minimum cost, even though dedicated hydrogen vehicles, on a large scale, are 15-30 years away, many critical aspects of the whole hydrogen chain as a vehicle fuel can be investigated right away in commercial HCNG operation. Besides this benefit as a transition fuel, HCNG has its own specific advantages in terms of noxious emissions and, if in addition, the hydrogen is produced from renewable resources, HCNG could also contribute to reduced GHG emissions.

2 History

Since the filing of the original Hythane® patent [1] in 1990, several demonstrations have been carried out in North America, often with limited commercial operation, (Denver, 1992, Montreal, 1995-1996, Thousand Palms, 1999 and on, Las Vegas, Phoenix, …) and more lately in Europe (Sweden, Italy) and Asia (India and China). HCNG was observed to have benefits in terms of the usual emissions (CO, NO_x, unburned hydrocarbons), although the performances differ for every specific situation, type of engine and operation mode. In the last decade, HCNG has been viewed also as a transition vehicle fuel towards hydrogen and renewables if the added hydrogen is “green”.

3 Fuel Properties

By adding hydrogen to CNG, the properties of the fuel changes in several ways. The most important factors are:

- Lower ignition energy and fast burning rate of HCNG makes it less resistant to knocks than CNG at constant λ.
- Lower heating value – higher consumption in terms of Nm^3 per km.
- Lower compressibility factor – fewer Nm^3 in a tank at 200 bar compared to CNG.
- Higher flame speed – faster combustion. higher engine efficiency.

Table 1 gives a few figures concerning the energy loss in the storage tanks at constant pressure.

Table 1: LHV and compressibility factor for different HCNG mixes at 200 bar (Danish natural gas).

H_2 content	0 %	8 %	20 %	25 %	30 %
LHV (MJ/Nm^3)	43,8	41,3	37,6	36	34,5
Change compared to CNG	0%	-6%	-14%	-18%	-21%
Compressibility Z @ 200 bar	0,75	0,80	0,87	0,90	0,93
Change compared to CNG	0%	-7%	-16%	-19%	-23%
Total energy compared with CNG	0%	-12%	-28%	-34%	-39%

The upper limit of the range loss is 12-15 % when using 8-10 % hydrogen and 30-40 % when using HCNG with 20-30 vol-% hydrogen. A potential higher engine efficiency when burning HCNG can compensate in part the negative changes in gas properties when comparing CNG and HCNG. As buses may be fitted with additional storage capacity without too much difficulty, HCNG appears more suited to public bus fleets than to passenger cars.

4 GHG Balance

A Well-To-Wheel (WTW) analysis of HCNG and CNG (EU-mix) has been performed and three ways of supplying hydrogen has been investigated: reforming of natural gas (EU-mix), electrolysis (EU-mix electricity) and electrolysis (renewable electricity).

Table 2: WTW CO_2 emissions (g/MJ) for HCNG produced through different routes and with different hydrogen content.

H_2 content	0 %	8 %	20 %	25 %	30 %
Electrolysis green electricity	66	64	62	60	59
CO_2 change	0 %	-2,4 %	-6,4 %	-8,3 %	-10 %
Electrolysis EU-mix electricity	66	70	77	80	84
CO_2 change	0 %	6,1 %	17 %	22 %	27 %
Reforming natural gas	66	68	72	74	76
CO_2 change	0 %	3,5 %	9,7 %	13 %	16 %

In terms of GHG reductions, the CO_2 emissions associated from production of hydrogen through reforming of natural gas or electrolysis of “grid” electricity can never be compensated through increased efficiency as that would require unrealistic improvements (10-15 % at 20 % H_2). Reforming of biogas has been suggested as a way for supplying green hydrogen but for that case it would be better to use the biogas as vehicle fuel directly. If the existing vehicles have problems with high emissions of methane, the introduction of HCNG could still reduce overall GHG emissions as methane is a very potent GHG and adding hydrogen to the CNG would improve the combustion efficiency and stability.

A cost-benefit analysis of HCNG versus CNG mixed with biogas to give the same CO_2-reduction as HCNG shows that biogas upgraded to vehicle quality (>97 % methane) can be produced for 2-2.5 €c/MJ. Hydrogen from grid electrolysis can be produced for 3.5-5 €c/MJ, clearly giving a cost-benefit advantage in favor of biogas.

5 Lund Laboratory Tests [2, 3]

The Division of Combustion Engines at Lund University, Faculty of Engineering has performed several tests using HCNG. Tests on a one-cylinder 1.6 liter engine back in 2002 showed that HCNG would improve combustion stability on low loads, the combustion time is reduced, NO_x at very lean operation is reduced and that the effects of HCNG are reduced when using a piston that creates high turbulence. Full engine tests in 2003 on a 10 liter gas lean burn engine showed: approximately 2 % points higher efficiency and this is more noticeable when reaching lean limits, increased NO_x emissions and reduced HC emissions, better combustion stability (lower COV). Tests with 25 % hydrogen on the same engine gave more or less the same results but it was necessary to change the engine mapping in order to run on 25 % hydrogen.

In 2008, they performed test of using 10 % hydrogen in a 9.4 liter Volvo G9 (λ=1) gas engine and the main conclusions are:

- The engine operated stoichiometric with CNG and HCNG according to the European Stationary Cycle and no significant changes in knock margins, efficiency and emissions were captured.
- Combustion quality is good when engine operates stoichiometric on CNG and the combustion duration is short enough which means using HCNG does not show benefits over CNG in terms of efficiency and emissions.
- Dilution limits (EGR levels) can be extended by approximately 10 %.

Additional tests on 25 % hydrogen where carried out late 2009. Since 2008, the engine had been fitted with new pistons with geometries designed to generate high turbulence which might have reduced some of the effects of HCNG. The results suggest that HCNG may not offer significant advantages over CNG in terms of emissions in vehicles equipped with modern stoichiometric engines with three way catalysts.

- Dilution limits (EGR) can be extended by 15 %.
- No significant changes are observed in efficiencies or knocking margins.
- Pre-catalyst emissions of NO_x increase, while emissions of HC and CO decrease, most significant decrease is observed for HC because of the high H/C ratio of HCNG.

6 Sweden [4]

Two city buses were run in Malmö for about 160.000 km during 2003-2005. These were Volvo buses from 1996 with lean-burn engines. It was not necessary to modify the buses for running 8 % HCNG but for 20 % a new engine mapping was used. The fuel consumption was reduced for the HCNG case compared to CNG but there was no significant difference between using 8 % or 25 % hydrogen. On road emissions tests with 25 % hydrogen showed:

- Running uphill: 50 % reduction of HC, no change of CO and 200 %.NO_x increase

- Constant speed: 30-50 % reduction of HC, slight increase of CO, fuel consumption down about 3 % and about 100 % increase of NO_x
- Acceleration from 0 km/h measured during 24 seconds: HC reduced by 50 %, NO_x increase about 50 %, CO reduced by 30 % and 10 % lower fuel consumption.

The lower fuel consumption during the acceleration phase is interesting as many city buses do not run steady state for long times and most of the time it is brake, idle or acceleration.

7 Norway [5]

In Bergen, HCNG was demonstrated during late 2008. Early emissions tests show no reduction of HC and CO, a slight increase of NO_x and a CO_2 reduction of 5 %, about half of that is due to increased efficiency and half due to lower carbon content in the fuel. The buses used lean-burn technology.

8 Italy [6]

Italy has almost 600.000 CNG cars on the road and more than 80 years of CNG experience. In 2008, Italy created a 10 M€ Hydrogen Platform Fund which includes development of HCNG applications. The plan is to build a network of stations out of lighthouse projects. HCNG is considered a bridge to future hydrogen technology and a few Agip stations can supply HCNG, such as the most recent one which opened in Milan in February 2010. Laboratory tests have showed promising results for HCNG which will be followed by road tests. Fiat has also showed the concept car Panda Aria which can run on HCNG with 30 % hydrogen.

9 Asia [7]

India has been pursuing CNG for reducing local pollutions and among the actions taken has been a mandate for public transport in New Delhi to use CNG. Due to the increasing number of vehicles, pollution levels have been steadily rising. HCNG has been introduced as an option to make CNG vehicles even cleaner and the Society of Indian Automobile Manufacturers together with Indian Oil Company has been investigating this issue. Their research shows that HCNG with 18 % hydrogen gives the greatest reduction of NO_x and the lowest power reduction. The next step is to convert 50 vehicles, test them and then introduce HCNG as a mainstream fuel.

10 Current US Status [8, 9, 10]

The arguably largest breakthrough favoring the use of HCNG in the US came in August in 2009 as the California Air Resources Board (CARB) granted certification for the Ford 6.8L V10 engines used in the Ford model E-450. The vehicles are converted by BAF Technologies (US) in cooperation with the Hythane Company LLC (a US subsidiary of Eden Energy, Australia). The use of HCNG in this engine has been reported to reduce the non-methane hydrocarbons by 40%, the methane emissions by approximately 50% and a 70% reduction of particulate emissions compared to the natural gas version of the engine. The certification indicates that commercial sale of HCNG vehicles can commence, not limiting the use of the fuel to controlled demonstration projects. Then engine calibration was performed for the inclusion of the vehicle in a HCNG project at the San Francisco airport. In the project, 27 Ford E-450 will be converted to HCNG and a refilling station will be constructed at the airport by the Hythane Company LLC.

Additional activities include a 4 year DOE program in Las Vegas, where nine compressed natural gas vehicles were converted and driven between 5 500 km and 60 000 km with varying results. In general there were low to zero maintenance issues after the first conversion bugs were sorted out. The fuel consumption varied between the different vehicles, some vehicles had a 20% reduction while some had a 30% increase in fuel consumption. Operating experience also include poor performance (lack of power and misfiring) when the hydrogen level in the natural gas was low and knocking with the possibility of serious engine damage at high hydrogen concentrations. Most of the vehicles showed zero NO_x emissions after conversion. Even though the program has been terminated, the cars are still being operated.

11 Safety

Safety related problems that could be associated with HCNG are essentially material compatibility, leakage and hydrogen embrittlement. In conjunction with the Malmö field tests, safety studies were performed on two bus models and these showed no major obstacle for using HCNG in terms of material and component compatibility. Worst case scenario, i.e. exposure to pure hydrogen was used when examining material compatibility. Of course, these results cannot be generalized to all vehicle models but it is an indication that there are no major showstoppers in the vehicles. A second safety study on newer buses also indicated that most high-pressure parts are compatible with 100 % hydrogen.

Another issue affecting the possibilities to introduce HCNG is the lack of standards. Since HCNG covers a range of mixtures and since none is a specified fuel, there are no standards, codes, test procedures etc. covering HCNG. Because of that, no vehicles are certified for HCNG operation, making it very difficult to introduce HCNG in any larger scale than small demo projects. New vehicles cannot be certified for HCNG as there are no regulations and if they cannot be certified, they cannot be sold, in Europe at least. In the US, there is some ongoing work within NFPA to include HCNG in NFPA 52, which, when in place, could clearly be beneficial for introducing HCNG vehicles.

12 Discussion

In cities where local pollution is a major issue, HCNG can reduce emissions of NO_x, CO and HC and help improve air quality. However, a few conflicting observations have been reported in that respect. This is not so surprising in view of the fine engine tuning required to reduce overall emissions and the sensitivity of the emissions to the mode of vehicle operation. Therefore, the benefits of HCNG must be appreciated on the basis of the statistics built on the numerous observations obtained over the years rather than on isolated results obtained in conditions not fully described. In lean burn vehicles, HCNG offers clear advantages over CNG:

- Emissions of CO and HC will likely be reduced without the need for engine optimization or tuning.

- Significant NO_x reductions can be obtained with leaner operation, but at the expense of efficiency
- Efficiency gains are possible but these will be modest, especially if low NO_x emissions are targeted (trade off).

For stoichiometric engines, the environmental and technological issues are different. Today, the majority of the new CNG vehicles are using λ=1 engines with TWCs and have very low emissions. For heavy-duty vehicles, the HCNG specific technological role could exist at the EGR level but considering the levels of the regulated pollutants for the coming years, HCNG does not offer a significant advantage compared to CNG in this respect.

Considering the reduction of CO_2 emissions which is one of the priorities today HCNG may have an edge over CNG from a Well-To-Wheel perspective if the added hydrogen is green. That hydrogen may originate from biomass gasification or from water electrolysis using excess renewable electricity in order to achieve a reduction of GHG emissions. However, if only a CO_2 reduction is targeted, HCNG maybe not the right tool as 30 % of hydrogen gives only a CO_2 reduction of 10 %. In many area of the world, this can be achieved more easily by adding 10 % of biogas which would be available at a much lower cost and does not lead to any range reductions.

Given all the aspects discussed previously, HCNG must be considered best suited for markets where lean-burn vehicle engines are in use and the number one issue is local pollution, not CO_2 reduction. This represents a huge market in emerging economy countries. In the smaller markets where optimized CNG technology is in use, the main benefit of HCNG is its value as a transition fuel permitting a hydrogen distribution infrastructure to be set up at a realistic pace and acceptable costs. That benefit, combined with the energy issue awareness impact in public transportation, cannot be overestimated.

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