

Using Hythane as a Fuel in a 6-Cylinder Stoichiometric Natural-gas Engine

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ABSTRACT

Combination of right EGR rates with turbocharging has been identified as a promising way to increase the maximum load and efficiency of heavy duty spark-ignited natural gas engines. With stoichiometric conditions a three way catalyst can be used which means that regulated emissions can be kept at very low levels. However dilution limit is limited in these types of engines because of the lower burnings rate of natural gas with higher EGR rates. One way to extend the dilution limit of a natural gas engine is to run the engine with Hythane (natural gas + some percentage hydrogen). Previously benefits of hydrogen addition to a Lean Burn natural-gas fueled engine was investigated [1] however a complete study for stoichiometric operation was not performed.

This paper presents measurements made on a heavy duty 6-cylinder natural gas engine. Three different experiments were designed and tested to investigate first of all if the engine encounters too severe knocking problems, second how and why, Hythane affect the running and finally how lean limit and dilution limit will be improved. The experiments were performed successfully and the results showed no significant differences between natural gas and Hythane in terms of efficiency and emissions when engine operates stoichiometric.

INTRODUCTION

Recently, environmental improvement and energy issues have become more and more important as worldwide concerns. Road transport is one of the biggest energy consuming sectors which has a great impact on environment. The fuels mainly used in internal combustion engines are petroleum products namely gasoline and diesel. One way for reducing these impacts

is to use alternative fuels. Natural gas consisting highly of methane (~90%) is a good alternative fuel to improve environmental problems because of its plentiful availability and clean burning characteristics. Natural gas generates less emission than Diesel engines and the efficiency can be increased compared to spark ignited gasoline engines due to higher compression-ratio tolerance.

Adding some hydrogen to the Natural gas can increase the efficiency and decrease the environmental impacts even further. Hythane is a mixture of natural gas and hydrogen, 7-10 percent hydrogen by energy. Hydrogen and methane are complimentary fuels in some ways. Methane has a relatively narrow flammability range which is especially a problem with lean burn operation. This limit can be extended by adding some hydrogen which has a wide flammability range. Methane has a slow laminar flame speed, especially in lean operation, while hydrogen has a much faster laminar flame speed [2], [3]. Methane is a fairly stable molecule that can be difficult to ignite, but hydrogen has an ignition energy requirement much lower than methane. In [4], [5] and [6] some benefits of using Hythane are also established.

Heavy duty SI NG-engines can be operated either lean or stoichiometric. In [1] benefits of hydrogen addition to a Lean Burn natural-gas fueled engine was investigated however a complete study for stoichiometric operation was not performed. Recent work at the department of energy sciences at Lund University has shown better results with stoichiometric operation [7], since stoichiometric operation with a three way catalyst results in very low emissions while keeping efficiency at a reasonable level. Exhaust Gas Recirculation (EGR) is also used to improve engine fuel economy at low loads and decreasing knock tendency.

The objective of this work is to investigate the engine behavior and possible benefits of running the engine with Hythane (Natural gas + 10% Hydrogen¹) when the engine operates stoichiometric. It is also desired to investigate the extension of the lean and dilution limit.

EXPERIMENTAL APARATUS

This section covers the information about the experimental engine and the modifications, the engine control system, measurement system and gas data.

THE ENGINE

The experimental engine was originally a diesel engine from Volvo which has been converted to a natural gas engine, see Table 1 for specification. The engine is equipped with a short route cooled EGR system and also turbocharger with wastegate.

Table 1: Specification of the engine

Number of Cylinder	6
Displacement	9,4 Liter
Bore	120 mm
Stroke	138 mm
Compression ratio	10,5 :1
Injection System	Single-Port

ENGINE CONTROL SYSTEM

A master PC based on GNU/Linux operating system is used as a control system. It communicates with three cylinder-control-modules (CCM) for cylinder-individual control of ignition and fuel injection via CAN communication, see Figure 1. Crank and cam information are used to synchronize the CCMs with the crank rotation.

Flexible controller implementation is achieved using Simulink and C-code is generated using the automatic code generation tool of Real Time Workshop. The C-code is then compiled to an executable program which communicates with the main control program. The controllers used for this experiment are lambda, load and EGR controller which determine the offset amount of fuel, air and EGR. The controllers can be activated from the Graphical User Interface (GUI).

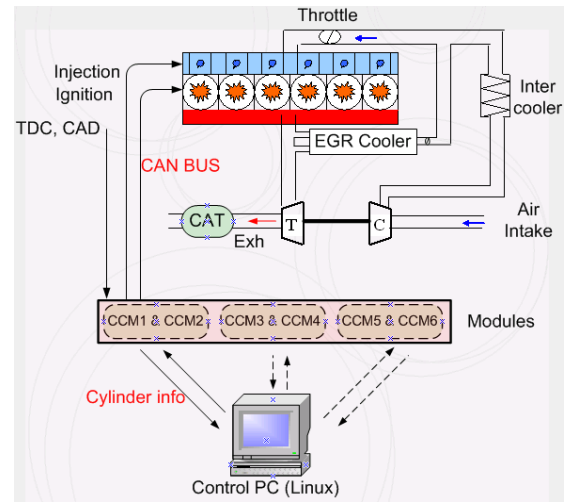


Figure 1: The Engine and its control system

MEASUREMENT SYSTEMS

Each cylinder head is equipped with a piezo electric pressure transducer of type Kistler 7061B to monitor cylinder pressures for heat release calculations. Cylinder pressure is sampled by a Microstar 5400A data acquisition processor. EGR was calculated by measuring CO₂ at inlet and exhaust. Emissions (HC, CO, NO, NO₂, NO_x, CO₂, O₂) are measured before and after catalyst. The emission system consists of a Heated Flame Ionization Detector (HFID) for measuring HC, a Heated Chemiluminescence Detector (HCLD) for measuring NO_x, two Non Dispersive Infrared Detector (NDIR) for measuring CO and CO₂ and a Para-Magnetic Detector (PMD) for measuring O₂.

Temperatures at inlet/exhaust, pressures at inlet/exhaust, fuel and air flow, lambda, torque and engine speed are also measured.

GAS DATA

Two different gases are used in this investigation viz. *natural gas* and *Hythane*. The composition of the *natural gas* is shown in Table 2. The lower heating value is 48,4 MJ/kg corresponding to 11 kWh/Nm³. Normal density of the natural gas is 0.82 Kg/Nm³ and H/C ratio is equal to 3,7.

Table 2: The natural gas composition

COMPOSITION	%	STRUCTURE
METHANE	89,84	CH ₄
ETHANE	5,82	C ₂ H ₆
PROPANE	2,33	C ₃ H ₈
I-BUTANE	0,38	C ₄ H ₁₀
N-BUTANE	0,52	C ₄ H ₁₀
I-PENTANE	0,11	C ₅ H ₁₂
N-PENTANE	0,07	C ₅ H ₁₂
HEXANE	0,05	C ₆ H ₁₄
NITROGEN	0,27	N ₂
CO ₂	0,6	CO ₂

¹ This percentage is volume based and not energy based

The composition of the **Hythane** is shown in Table 3. The lower heating value is 48,96 MJ/kg corresponding to 10,2 kWh/Nm³. Normal density of the Hythane is 0.75 Kg/Nm³ and H/C ratio is equal to 4,29.

Table 3: The Hythane composition

COMPOSITIONS	%	STRUCTURE
METHANE	79	CH ₄
ETHAN	6	C ₂ H ₆
PROPANE	2	C ₃ H ₈
BUTANE	1	C ₄ H ₁₀
INERT	2	-
HYDROGEN	10	H ₂

EXPERIMENTS

The main objective of this study was to investigate if running the engine with Hythane operating under stoichiometric condition is feasible i.e. it does not encounter too severe knocking problems. Investigating the possible benefits is also desired. Three different experiments were designed and performed as follow:

1. **European Stationary Cycles (ESC):** The engine operated according to the ESC to see if knock limits the engine and also how efficiencies and emissions change with Hythane. Lambda was kept equal to one, Injection timing was fixed for all cases but ignition timing varied in order to get Maximum Brake Torque (MBT) for each case. CA50 was used for adjusting ignition timing. CA50 is an engine crank position in Crank Angle Degree (CAD) at 50% heat release. Previous experiments from the engine show that when CA50 is around 12 CAD After Top Dead Center (ATDC), MBT is achieved.
2. **Lambda Sweep:** It was performed by keeping the air flow constant and changing the fuel flow. The engine speed was 1000 RPM in this experiment, throttle position was kept at 40% opening and the fuel injection duration was adjusted to get different lambda. The lambda was varied from 0.9 to roughly 1.5 which is the lean limit for the engine. Ignition timing was adjusted to obtain MBT timing with the different lambda. This variation in lambda resulted in a load variation in a range of roughly 8,6 to 5,2 bar BMEP. The combustion duration and efficiencies are investigated. The combustion duration is defined as the difference between CA10 and CA90. CA10 is an engine crank position in CAD at 10% heat release and same for CA90.
3. **EGR Sweep:** EGR rate was increased from 0 to roughly 13 percent at 1000 RPM to investigate combustion duration. The dilution limit was also investigated.

These experiments were performed twice, once with Natural gas and once with Hythane and the results were

compared afterwards. Start of Injection is set to a fixed point during all experiments.

EXPERIMENTAL RESULTS

The results are divided into three parts as they are experimented and evaluated in form of different efficiencies, emissions and combustion duration.

EUROPEAN STATIONARY DRIVING CYCLES

The engine was operated according to Table 4 with both natural gas and Hythane. As Table 4 shows the engine was operatable with both fuels, and except for one point MBT timing was achieved for all cases. The reason for not achieving MBT in that point was that the ignition timing was retarded some degree to avoid knock. This behavior was the same for both fuels.

Table 4: European Stationary Driving Cycles

SPEED (RPM)	LOAD (%)	MBT (NATURAL GAS)	MBT (HYTHANE)
1000	25	*	*
	50	*	*
	75	*	*
	100	*	*
1250	25	*	*
	50	*	*
	75	*	*
	100	O	O
1500	25	*	*
	50	*	*
	75	*	*
* MBT ACHIEVED			
O MBT NOT ACHIEVED			

Efficiencies Vs. Load

Brake Efficiency is a product of different efficiencies as follows:

$$\eta_b = \eta_{GI} \times \eta_{GE} \times \eta_m \quad \text{Where}$$

η_b = Brake efficiency

η_{GI} = Gross-Indicated efficiency

η_{GE} = Gas-Exchange efficiency

η_m = Mechanical efficiency

Gross Indicated efficiency is the product of thermodynamic and combustion efficiencies and it can be calculated as follows