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CIMAC Guideline

H_2 in stationary gas engines for power generation

The first edition of this CIMAC Guideline was approved by the members of the CIMAC WG17 'gas engine' at its meeting on October 1st 2021.

Content

1 Introduction

This CIMAC guideline describes influence on gas engine operation, controls and hardware during operation on hydrogen/natural gas blends up to pure hydrogen. This usage of hydrogen as fuel is becoming increasingly important as energy is stored in chemical form as hydrogen when renewable energy is in oversupply. Furthermore, using hydrogen blends up to pure hydrogen in reciprocating engines is seen as a key enabler of energy decarbonization.

Important properties of mixtures of natural gas and hydrogen, such as heating value and Wobbe Index (WI) are discussed below. Combustion behavior, knocking characteristics, and allowable rate of change of gas composition with time are different depending on the amount of hydrogen in the natural gas.

Composition of pipeline quality gas is changing due to increased blending of biogases, synthetic gases, hydrogen, new sources of natural gas, and liquefied natural gas. It is therefore becoming ever more important to have a good understanding of the knock resistance of the gaseous fuel that is fed to a given engine. If hydrogen content is increased beyond a limit, different on each engine type, changes to basic engine hardware are needed.

Dedicated hydrogen engines will look different than natural gas engines. Changes in hydrogen admission, turbocharging and other engine components are expected. A fully flexible dual-gas engine able to run from 0 to 100 % vol hydrogen requires complex compromises and in the long-term, dedicated hydrogen engines will likely be favored.

This guideline focuses on land-based stationary power generation gas engines. Marine applications, gas compression, and other non-road mobile machinery are out of the present scope.

2 Basic Statement on impact of blending rates

Current discussions include various levels of hydrogen blended into natural gas. This can be reduced to 3 scenarios:

- Up to 5% vol: Could typically be handled in engines without changes. But for the existing fleet individual engines need to be checked for compatibility with “new” fuel specification.
- Up to 25% vol: Typically, different engine settings or hardware changes are required. For example, a hydrogen sensor or design change in the engine hardware. Consultation with the engine OEM is needed to understand the extent of change required.
- Up to 100%: A dedicated hydrogen engine design is required.

The most challenging application is a dual-gas engine able to run from 0 to 100% hydrogen. This will require a complex compromise and needs to be discussed with the OEM.

Rate of change of gas composition must be limited, especially for an engine designed for natural gas, and able to be operated with some vol % of hydrogen; hydrogen plug flow needs to be avoided completely.

Plant specific components are not considered.

3 Impact on performance and emissions with H_2 blending

Impact on performance and emissions is described here in a qualitive way and will be different for various OEMs and engine models. Performance changes are driven by the different fuel properties of hydrogen, compared to natural gas.

3.1 Properties of H_2

In Table 1 are shown some important properties for natural gas (NG), synthetic natural gas (SNG) and hydrogen. There is a large difference in lower heating value (LHV). Hydrogen has a very low minimum ignition energy and a very high laminar flame speed. These properties provide challenges in development of the combustion process, driven by the high knock tendency of hydrogen (indicated by a low Methane Number (MN); per definition, MN=0 for hydrogen). An advantage of hydrogen and hydrogen blends is the ability to ignite very lean mixtures, but this leads to high boost pressure demands to reach high power levels.

		NG (example)	SNG (CH_4)	H_2
CH_4	Vol-%	97,6	100	0
C_xH_y	Vol-%	2,4	0	0
H_2	Vol-%	0	0	100
LHV	kJ/Nm³	36 730	35 784	10 800
LHV	kJ/kg	49000	50 013	120 000
LHV	kWh/Nm³	10,2	9,94	3
Minimum ignition energy	mJ		0,29	0,017
MN	-	92	100	0
WI	MJ/Nm³	49	50	~47
Lam. Flame speed	cm/s	38	38	350

Table 1: Properties of different fuel gases (Source: INNIO Jenbacher)

3.2 Performance

Impact on engine performance with different hydrogen content is dependent on engine layout and will differ for different OEMs. Figure 1 shows qualitative impact on engine performance.

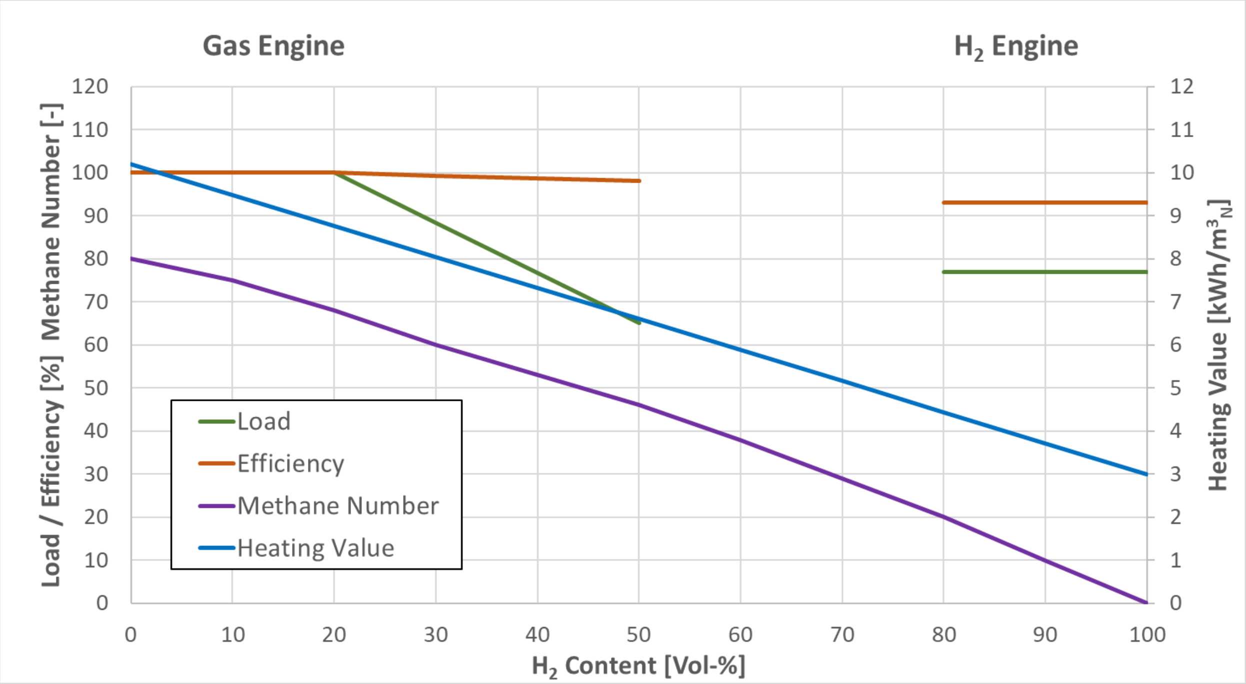

Figure 1: Engine performance (Load and eff.) with different H_2 % vol. content (Source: Caterpillar)

Dependent on engine layout and quality of the natural gas, there will be a drop in maximum engine load starting at a certain hydrogen content. The drop is driven by reduction in MN and the engine control system's response in reducing power to avoid knocking. This drop will start typically in a range of 10 to 30% hydrogen in natural gas, all dependent on the engine settings and natural gas quality. Also, engine efficiency will have a similar behaviour with a less drastic drop. At about 50% hydrogen the maximum amount is reached with a natural gas configuration.

Engines designed for dedicated hydrogen use (100% H_2) have slightly reduced maximum power output compared to a natural gas engine of the same displacement and can be operated down to about 80% hydrogen. Hydrogen has a very high laminar flame speed, and this accelerates combustion. If a dedicated hydrogen engine is operated with natural gas, or a low amount of hydrogen, combustion duration will be too long and thermal load on components will be excessive. Check with the OEM before running a dedicated hydrogen engine on natural gas at full load for an extended period.

All these constraints lead to a gap in the operating range where neither a dedicated natural gas engine nor a dedicated hydrogen engine is an optimum solution (in figure 1 in the range from about 50 to 80% H_2). Engines able to be operated in this range are available and are, up to now, typically used to burn syngas. Characteristics and designs of syngas engines are not the focus of this guideline.

3.3 Emissions

Impact on engine emissions with different hydrogen content is dependent on engine layout and will differ for various OEMs and engine models. Figure 2 shows a qualitative impact on engine emissions. Notice that CO_2 emissions are not reduced linearly with increasing hydrogen. With respect to NO_x emissions, without a closed loop NO_x control strategy, NO_x emission will rise with an increase of hydrogen content in the fuel gas and can exceed limits. This effect is driven by increased combustion speed of the hydrogen containing mixture. The increased combustion speed can be used to an advantage with an optimized engine control system and NO_x emissions can be reduced significantly with similar engine performance.

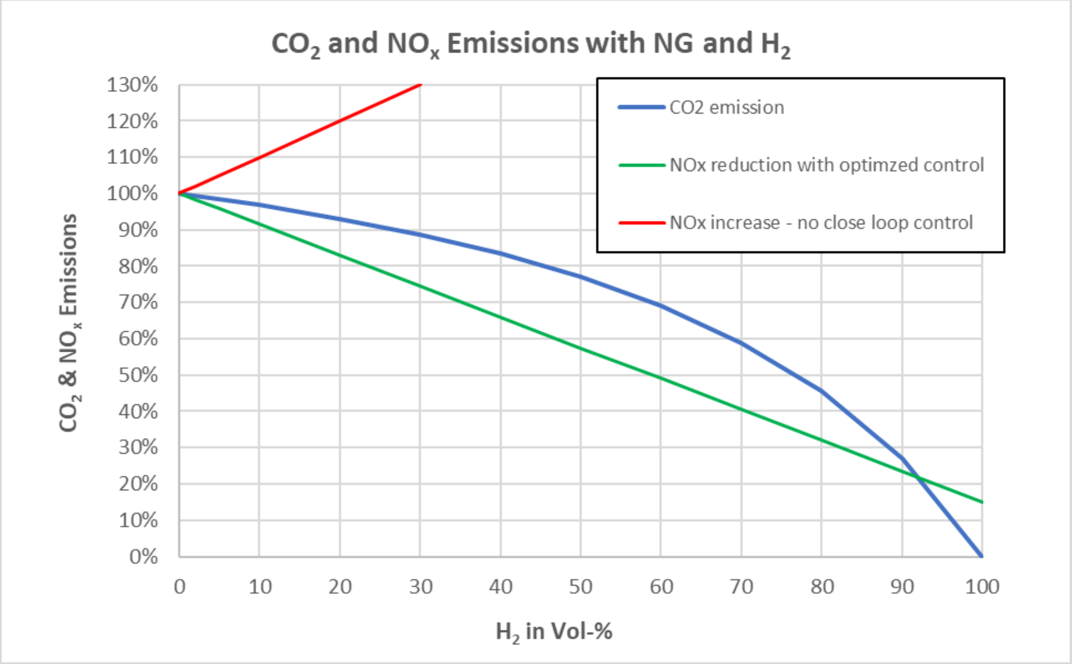

Figure 2: Change of engine emissions with different H_2 % vol. content (Source: INNIO Jenbacher)

4 Engine Hardware and Controls Changes

Special focus on gas admission, turbo charging, material selection, and lube oil quality is required when operating on hydrogen or hydrogen mixtures.

4.1 Fuel supply system

There are 3 different ways to supply hydrogen into the engine. Premixed, port injection and direct injection.

4.1.1 Premixed combustion

In a premixed combustion engine, gas is mixed with the incoming air in a mixing device at low pressure in the air inlet of the engine. Typically, there is one device on an inline engine or two for a V-Engine. Air/fuel ratio controlled by the opening or closing of a gap or an orifice in the fuel system. Premixed combustion is most commonly used for high speed and smaller medium speed gas engines. Air/fuel ratio in each cylinder is constant with the global control at the mixing device.

4.1.2 Port fuel injection

Port fuel injection uses a gas injector, which is typically actuated by a solenoid and admits gas at a precise time into the inlet port close to the intake valve(s). There is one injector on each cylinder, which can be controlled individually. In order to inject gas in a short time during intake stroke, gas supply pressure is higher than for premixed combustion. For larger medium speed gas engines port fuel injection is most common. This requires a more sophisticated individual-cylinder air/ fuel ratio control. With ignition limits of hydrogen being much wider and flame speed much higher, port fuel injection commonly is used for all pure hydrogen engines as a safety precaution. This technology also increases complexity of the control system for the engine because it requires a solenoid driver to control injection timing for each cylinder.

4.1.3 Direct injection

In a direct injected (DI) engine, gas will be brought directly into the cylinder like in a diesel engine, during the compression stroke after the intake valve is closed. This method requires a much higher gas pressure depending on mixing requirements and combustion strategy. DI provides more flexibility for changing speed and load conditions and can also increase specific power output. In stationary engines, the pressure level of gas supply is typically too low to use a DI system without a compressor.

4.1.4 Technical readiness level

State of the art is a gas mixer, which is simple, robust, and fully mature in the market. Due to wider ignition limits, gases which contain hydrogen in higher concentration require specific safety measures to avoid left over hydrogen in the air manifold after engine shut down. Special starting procedures are also required.

For port injection systems, many injectors are available for natural gas, but only a very limited number of port injectors are approved for hydrogen. Most components have limitations on lifetime and are only used for pilot installations and field tests. Because of the small size of hydrogen molecules, leakage is a concern and wear of sealing features of the injector is an issue for pure (dry) hydrogen operation.

Direct injection is new technology for hydrogen engines and has only been implemented in research. For small hydrogen engines, there have been reports of product development, but for larger engines there are no injectors and related components available in the market.

4.2 Influence of hydrogen properties on turbocharger matching

Physical properties of hydrogen that are important for turbocharger matching differ in certain aspects from natural gas (see Table 2). Due to the performance and emissions effects discussed in section 3, lean operating conditions are required. This together with the low density of the fuel lead to the requirement for between 1 and 1.5 times higher in-cylinder pressure compared to a state-of-the-art natural gas engine. In order to operate the engine, charge air pressure needs to be increased by this same proportion.

Fuel	Stoichiometric air-to-fuel ratio [kg/kg]	Lower Heating Value (LHV) [MJ/kg]	Density at 100kPa / 25°C [kg/m^3]
Natural gas (methane)	17.2	50	0.66
Hydrogen	34.3	120	0.09

Table 2: Physical properties related to turbocharging

Compressor matching is also dependent on the fuel admission concept (described in section 4.1). For port-fuel and direct injection, compressor matching only needs to consider the level of charge air pressure resulting from power density and excess air ratio. In the case of premixed fuel admission, capacity of the compressor stage also needs to be scaled up with the additional space required by the hydrogen fraction (i.e. an enlargement by up to 1.5 times).

On the turbine side, component matching is mainly influenced by boundary conditions from the engine. The usually faster combustion and very lean operation with hydrogen leads to lower exhaust gas temperatures, hence less enthalpy in the working gas. The temperature drop is further increased by the higher specific heat of the exhaust gas due to substitution of carbon dioxide by steam in the combustion products. This effect, however, has no influence on turbine size. The typically higher excess air ratio requires an increased power transfer to the compressor. Both the reduced enthalpy and the increased power extraction requirement lead to a relatively smaller turbine area than for natural gas engines.

For mixtures of natural gas with hydrogen the described effects apply linearly to the mixing ratio.

4.3 Materials

With the introduction of hydrogen gas, two major challenges arise for metallic materials. One is premature failure due to hydrogen embrittlement and the other is severe wear due to friction and tribocorrosion. Hydrogen embrittlement is the change in brittleness affected by the diffusion and incorporation of hydrogen into a metal making the component “weaker”. All engine components that are directly exposed to hydrogen gas, such as valves, piston or cylinder liner, are potentially affected. There are internal and external sources of hydrogen. The focus in the following is on the external hydrogen input from hydrogen as a fuel.

Hydrogen as the lightest element has the smallest atomic radius of 25 picometres [9], so hydrogen can easily penetrate metallic materials and move freely. Regardless of the type of metallic material, hydrogen embrittlement can only occur during hydrogen-fueled operation when the following three conditions are simultaneously met, the presence of hydrogen gas, tensile stresses within the component and the use of high-strength alloys, typically with an ultimate tensile strength above 800 MPa [18]. In addition temperature, pressure and microstructure determine the absorption behavior of hydrogen into the alloy and will determine the rate of degradation [17]. Hydrogen-assisted damage, especially in steel materials, is a widespread and undesirable phenomenon in high-strength steels [19]. For current materials in gas engines, the two damage mechanisms, hydrogen-induced stress corrosion cracking (HSCC) and hydrogen-induced cracking (HIC) have to be considered. To prevent hydrogen embrittlement, consultation with the component suppliers is needed to understand the extent of change required. It will be necessary to optimise engine components for increasing hydrogen admixing in conjunction with higher power output.

In terms of tribology, two aspects are relevant in hydrogen operation, on the one hand the drier character of hydrogen gas compared to natural gas (higher friction) and the other hand the higher amount of the combustion product water vapor (higher tribocorrosion). Tribosystems such as valve/seat are critical in terms of severe wear because of hydrogen embrittlement, chemical reactions to hybrids and the loss of wear-protective tribofilms, which form during operation. These films consist mainly of oxide layers which cannot be rebuilt in a hydrogen environment. Thus, there is a greater chance of fretting wear occurring [12]. Diffusible hydrogen content in metal-to-metal contact has an impact on premature surface failure caused by white etching cracks (WEC) [16]. Furthermore, liquid lubricants or increasing their feed rates are often not applicable due to the higher risk of autoignition in hydrogen operation. Commercial hydrogen gas contains impurities of water and oxygen. For many components in hydrogen technology, solid lubrication is an effective method to counteract the dry property of hydrogen as a fuel. PTFE, graphite, DLC, MoS_2 or wear-resistant coatings such as WC, Cr_2O_3, TiN or Tribaloy™ alloys, applied as functional layers, can improve friction and wear in gaseous as well as in liquid hydrogen environments [10, 15]. However, it should be noted, that information about their long-term hydrogen resistance is very limited. MoS_2-based coatings offer low friction but a short lifetime in a hydrogen environment [14]. Carbon coatings have a higher friction compared to MoS_2 but a much longer lifetime in hydrogen environment. In humid hydrogen environment these coatings fail rapidly. PTFE-coatings provide low friction; however, the type of gas (pure hydrogen gas, air, liquid hydrogen) affects their frictional behavior, regardless of humidity [11]. To assess the hydrogen impact on component wear, component/engine testing and consultation with the component supplier is required to understand the modifications required.

4.4 Gas Engine Oils and Lubrication Needs

Lubrication needs of stationary natural gas fired engines for power generation vary considerably based on designs, applications, operating conditions, and fuel quality used to fire these engines. As far as selecting lubricants for gas engines is concerned, there are no industry standards or widely accepted specifications to define performance requirements. Engines operating on gaseous fuels require lubricating oils designed and formulated to meet unique requirements of the gas engine. Most gas engine OEMs have their own lubrication specifications. Both base stocks and additive combinations are critical in balancing the performance needs of these engines [1]. A guideline for lubrication of reciprocating gas engines was published recently by CIMAC WG 8.

Gas engine lubricants have to carry out a number of tasks, the main ones being separating moving surfaces and reducing friction. This is primarily a function of viscosity, although antiwear additives are used to provide protection in areas of marginal lubrication, such as cams and piston rings [2]. The low lubricity of hydrogen has to be considered for the lubricant; suitable valve seat materials have to be chosen [3] and design of the fuel injection system should take this into account. The oil then has to keep the engine clean, preventing deposit formation that leads to ring sticking, bore polishing and other problems. It must also protect against corrosion, through application of protective films or neutralization of acidic components. Finally, it must help remove heat from the engine [2]. For hydrogen fired engines an engine lubrication oil compatible with increased water concentration in the crankcase has to be chosen [5]. Combustion chamber deposit formation needs to be controlled to avoid abnormal combustion [6]. Measurement of the composition of gases in the crankcase [8] showed significant hydrogen concentration arising from blowby caused by hydrogen’s high flame speed and thus fast burn rate. Among others lubricant requirements are depending on fuel gas quality and need to be adjusted for hydrogen fired engines accordingly.

4.5 Engine Controls

To reach optimum engine performance a sophisticated controls system, compared to natural gas, is needed. For hydrogen content beyond about 10%, information on hydrogen content is needed. If this is missing, emissions can increase significantly. A hydrogen sensor would be beneficial or a closed loop NO_x control system with a NO_x sensor in the exhaust system.

Engines close to 100% hydrogen are operated typically as hydrogen port- or in future as direct-injected engines (in development). Compared to natural gas engines with gas premixed, cylinder to cylinder variation in combustion characteristics will be greater. A control loop needs to be implemented to balance all cylinders for optimum engine performance. Balancing can be done via temperature sensors or with in-cylinder pressure sensors.

As hydrogen blending increases, requirements for engine control increase, especially at high load. In addition to combustion control by in-cylinder pressure or in-cylinder temperature sensors, additional sensors may be required to detect fuel quality. Fluctuating hydrogen mixtures present a special challenge for control of gas engines. Additional information is required for safe operation in accordance with expectations of customers. In addition, a review of the limit values of the engine control is required when the hydrogen content in the fuel gas is increased.

4.6 Safety

With use of Hydrogen in a natural gas engine, new requirements may arise with regard to compliance with safety regulations. The requirements may affect the engine or the engine operating room. The classification of safety requirements depends on the level of hydrogen percentage in the fuel, with mixtures above 25% requiring special attention.

The following areas must be taken into account with regard to safety-relevant requirements:

- Gas engine safety concept
  - Additional control algorithms
  - Additional sensors
- Engine room ventilation concept
- Fire, gas, H_2 alarm system
- H_2 leakage detection
- Engine room access control
- Operational instructions
- Material Evaluation Certificates

5 Conclusion

Gas engines have proven robust capability to successfully operate on a wide range of fuel types including Syngas, wood-gas and industrial gases with varying concentrations and qualities of hydrogen. There is a long history and good experience of operating reciprocating gas engines using hydrogen up to 70% vol. The development of spark ignited gas engines to operate of 100% hydrogen does require some engineering effort however this is now at a stage where there is technical feasibility.

Reciprocating gas engines offer long term durability and stability with little to no performance degradation over engine life-times. The technology is readily available and is a good match against the EUGINE definition. Retrofit packages from the OEMs to enable conversion of stationary gas engines to operate on hydrogen can also be provided to the end user. All these factors mean that the use of stationary reciprocating gas engines represents a more sustainable technology package for future zero carbon energy supply.

6 References

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20) The knock characteristics of a gaseous fuel can be calculated for a given composition and the calculated Methane Number (MN) indicates the resistance of the given fuel to end gas knock. Information on the following topics can be found in other CIMAC Working Group 17 position papers.

7 Additional CIMAC papers

CIMAC GHG Strategy Group | White Paper 3 and 4

CIMAC WG 17 | Impact of Gas Quality on Gas Engine Performance (July 2015)

CIMAC WG 17 | Information concerning the application of gas engines in the marine industry (December 2013)

CIMAC WG 17 | Transient response behavior of gas engines (April 2011)

CIMAC WG 17 | The influence of ambient conditions on the performance of gas engines. (March 2009)

CIMAC WG 17 | Information about the influence of ammonia in the fuel gas on NOx emissions (December 2008)

CIMAC WG 17 | Information about the use of liquefied natural gas as an engine fuel (December 2008)

CIMAC WG 8 | Guideline on the Lubrication of Reciprocating Gas Engines (March 2021)

8 Abbreviation

DI	Direct Injection
HIC	Hydrogen-induced cracking
HSCC	Hydrogen-induced stress corrosion cracking
LHV	Lower heating value
MN	Methane Number
NG	Natural Gas
OEM	Original Equipment Manufacturer
SNG	Synthetic Natural Gas
WEC	White etching cracks
WI	Wobbe Index
%vol	percent volume

Imprint

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