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Study on the extension of lean operation limit through hydrogen enrichment in a natural gas spark-ignition engine

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ABSTRACT

An experimental study aimed at investigating the extension of lean operation limit through hydrogen addition in a SI engine was conducted on a six-cylinder throttle body injection natural gas engine. Four levels of hydrogen enhancement were used for comparison purposes: 0%, 10%, 30% and 50% by volume. The effects of various engine operating conditions on engine's lean burn capability were also examined. Test results were then analyzed from a combustion point of view. The results show that engine's lean operation limit could be extended through adding hydrogen and increasing load level (intake manifold pressure). Effect of engine speed on lean operation limit is smaller. At low load level increase in engine speed is beneficial to extending lean operation limit but this is not true at high load level. The effects of engine speed are even weaker when the engine is switched to hydrogen enriched fuelling. Spark timing also influences on lean operation limit and both over-retarded and over-advanced spark timing are not advisable. It is also observed there existed a limiting value imposed on spark-90% MFB burn duration if lean operation limit is not to be exceeded and interestingly, this limiting value was independent on hydrogen enhancement level and engine operating conditions examined in this study.

1. Introduction

The operation of SI engine on fuel lean mixtures has many positive features [1–4]. One advantage manifests itself in the reduction of exhaust emissions: excess oxygen would not only result in lower CO and HC engine-out emissions but also provide for subsequent oxidation of CO and HC in the exhaust systems; NO_x emissions would also be reduced as a result of decreased cylinder temperature arising from increased air dilution. On the other hand, lean burn also helps to improve engine thermal efficiency. This is because improvements in combustion efficiency, reduction in heat transfer loss, increase in the ratio of specific heats and permission of employing higher compression ratio, all of which help to improve thermal efficiency could be simultaneously achieved by excess air and/or the resulting reduced combustion temperature.

However, there are also several difficulties associated with lean burn operation including slower flame propagation speed, increased cycle-by-cycle variations and undermined combustion completeness. These shortcomings which may lead to poor engine performance are even more evident in natural gas (NG) fuelled engines because NG has slower laminar burning velocity and higher ignition energy, both of which have negative effects on the engine's lean burn capability. So generally, NG engines' lean burn capability is

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Nomenclature

ATDC	after top dead center
BTDC	before top dead center
CA	crank angle
COV	coefficient of variation
COV_{IMEP}	coefficient of variation of IMEP
EGR	exhaust gas recirculation
HC	hydrocarbons
HNG	hydrogen enriched natural gas
IMEP	indicated mean effective pressure
lambda (λ)	excess air ratio
LOL	lean operation limit
MAP	manifold absolute pressure
MBT	maximum brake torque
MFB	mass fraction burned
NG	natural gas
NO_x	nitrogen oxides

always not ideal enough to solve the problem of untreated NO_x emissions (NO_x is quite difficult to get deoxidized in the presence of much oxygen—cases in lean burn engines where three-way catalyst cannot be used). Conventional ways of addressing these shortcomings include intensifying cylinder turbulence and increasing either spark energy or numbers of spark plug, but unfortunately, their effects are always limited and they may sometimes bring certain penalties. For example, increasing ignition energy will shorten the life of the spark plug and heavy turbulence is detrimental to volumetric efficiency. Therefore, there is a need to enhance the combustion of NG without bringing about those drawbacks. An effective way is to mix NG with fuels that possess faster burning velocity and smaller ignition energy. Hydrogen is regarded as the best gaseous candidate for addition into NG because it has some unique and highly desirable properties for application in SI engines. Some thermal and chemical properties of hydrogen and methane, which is the main component of NG are compared in Table 1. As can be seen, compared to NG hydrogen has a wider flammable mixture range, lower ignition energy and faster flame propagation rates, all of which are helpful to improve engine's lean burn capability [5,6,9]. This paper specifically deals with the improvement of NG engine's lean burn capability through hydrogen addition. Since lean operation limit is an indicator of lean burn ability which can be quantitatively assessed and that it is not only dependent on hydrogen enhancement level but on engine operating conditions, a parametric study on the engine's lean operation limit was conducted. The authors hope this study could give some practical guidance to the development and calibration of hydrogen enriched NG ultra-lean burn engines.

Table 1 – Fuel properties of methane and hydrogen [9]

Properties	Methane	Hydrogen
Density at NTP (kg/m^3)	0.65119	0.083764
Lean ignition limit (λ) in NTP air	1.887	10
Volumetric lower heating value at NTP (kJ/m^3)	32,573	10,046
Volumetric lower heating value in air ($\lambda = 1$)	3,088	2913
Laminar burning speed in NTP air (cm/s)	37–45	265–325
Quenching distance in NTP air (cm)	0.203	0.064
Adiabatic flame temperature in air (K)	2148	2318
Minimum ignition energy in NTP air (mJ)	0.29	0.02

2. Previous work

Many researches related to hydrogen enriched fuels have been conducted during the last 10 years and earlier. Some of them focused on the effects of hydrogen addition on engine's overall performance and emission characteristics, such as those performed by Collier et al. [7], Swain et al. [8], Bauer and Forest [9], Sierens and Rossel [10], Huang et al. [11] and Ma et al. [12]. These studies generally showed that HC and CO concentrations could be decreased by hydrogen addition. However, NO_x emissions may increase for natural gas-hydrogen combustion because of the elevated combustion temperature. But no worry is needed since hydrogen could enhance the lean burn capability thereby solving the problem of NO_x through allowing ultra-lean operation. There are still some of the literatures centering on the influences on combustion characteristics including those performed by Karim [6], Tully and Heywood [13], Goldwitz and Heywood [14] and Huang et al. [15]. The results of these researches showed with consistency that both the flame development and propagation duration can be reduced through introducing hydrogen.

It appears that the most obvious and important advantage NG engines could benefit from hydrogen addition is the improvement in lean burn capability which is manifested as the extension of lean operation limit (LOL). The authors mention the extension of LOL as the most obvious benefit because nearly all of the above-mentioned studies have observed this, while conclusions regarding the changes in thermal efficiency have some inconsistency. Furthermore, exhaust emissions of NO_x, which is the most problematic issue associated with the combustion of lean NG/air mixtures can be solved by the extension of LOL through hydrogen enhancement. Also as it is known, without the expensive lean burn deoxidization catalyst NG engines are hard to be run on such dilute mixtures that NO_x emission level can be kept down below the level the emission regulations require. And it is in this sense that the authors deem the extension of LOL as the most important benefit.

There is also a lot of published information related to the lean limit of fuels, both in constant pressure combustors and real SI engines. Wierzba et al. investigated experimentally the lean flammability limits of $H_2-CO-CH_4$ mixtures in a