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Experimental study on thermal efficiency and emission characteristics of a lean burn hydrogen enriched natural gas engine

Fanhua Ma*, Yu Wang, Haiquan Liu, Yong Li, Junjun Wang, Shuli Zhao

State Key Laboratory of Automobile Safety and Energy, Tsinghua University, Beijing 100084, PR China

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Abstract

In order to analyze the effect of hydrogen addition on natural gas (NG) engine's thermal efficiency and emission, an experimental research was conducted on a spark ignition NG engine using variable composition hydrogen/CNG mixtures (HCNG). The results showed that hydrogen enrichment could significantly extend the lean operation limit, improve the engine's lean burn ability, and decrease burn duration. However, nitrogen oxides (NO_x) were found to increase with hydrogen addition if spark timing was not optimized according to hydrogen's high burn speed. Also found when spark timing was set at constant was that hydrogen addition actually increases heat transfer out of the cylinder due to smaller quenching distance and higher combustion temperature, thus is not good to improve thermal efficiency if combined with the effect of non-ideal spark timing. But if spark timing was retarded to MBT, taking advantage of hydrogen's high burn speed, NO_x emissions exhibited no obvious increase after hydrogen addition and engine thermal efficiency increased with the increase of hydrogen fraction. Unburned hydrocarbon always decreased with the increase of hydrogen fraction.

Keywords: Hydrogen enrichment natural gas; Lean burn; Lean operation limit; Indicated thermal efficiency; Emission

1. Introduction

Concerns about pollution of the environment and lack of fossil fuels have become increasingly greater these days, especially in the field of transportation. Natural gas (NG) is thought to be a good alternative to traditional vehicle fuels since it has cleaner combustion characteristics and plentiful reserves. Engines fuelled with NG emit less carbon-monoxide and non-methane hydrocarbons compared to a gasoline engine, but the NO_x emission may not be low enough to meet the increasingly more stringent emission requirements [1].

As we know, the problem of high NO_x emission could be alleviated by lean burn, which means operating the engine on a lean fuel mixture. Apart from the reduction of NO_x emission, lean operation has some other advantages. Firstly, excess air could increase the ratio of specific heats ($\kappa = C_p/C_v$) of the burned gas and improve combustion efficiency, both of which are beneficial to the engine's thermal efficiency [2]; secondly, possibilities of knock become smaller since cylinder temperature decreases, thus higher compression ratio which is also good to thermal efficiency could be employed; thirdly, excess air can decrease the emission of carbon monoxide and unburned hydrocarbon.

However, the advantages mentioned above may be compromised by the reduced burn rate and increased ignition energy of the dilute fuel–air mixtures. These two drawbacks would make the engine exhibit high cyclic variation, poor hydrocarbon emission as well as low thermal efficiency at lean operation. So, certain approaches must be taken to compensate for these drawbacks. Hydrogen addition seems to be a good choice since hydrogen, by its nature, has relatively fast laminar burning velocity and low ignition energy. Therefore, it is quite natural to think of blending hydrogen with NG to make it more suitable for lean operation, and this fuel blends is called HCNG or hythane.

This paper focuses on the effect of hydrogen addition on NG engine's thermal efficiency and emission, some other features such as combustion stability, and lean operation limit

* Corresponding author. Tel.: +86 10 62782352; fax: +86 10 62796002.
E-mail address: mafh@tsinghua.edu.cn (F. Ma).

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Nomenclature

κ	ratio of specific heats
C_v	constant volume specific heat
HCNG	hydrogen enriched compressed natural gas
BTDC	before top dead center
λ	excess air rato
COV	coefficient of variation
MAP	manifold absolute pressure
C_p	constant pressure specific heat
NG	natural gas
CA	crank angle
TDC	top dead center
MBT	maximum brake torque
IMEP	indicated mean effective pressure
ITE	indicated thermal efficiency
THC	total hydrocarbon

are also briefly investigated. Tests were conducted on a six-cylinder spark ignition NG engine using variable composition hydrogen–NG mixtures.

2. Prior research

The idea of adding hydrogen into conventional vehicle fuels to improve thermal efficiency and inhibit cyclic variation could date back to several decades ago. A relatively early research (not first) was conducted by Varde [3]. Varde investigated the combustion characteristics of a single-cylinder spark ignition engine using hydrogen enriched gasoline. He concluded that small amount hydrogen addition could extend the lean limit and improve the engine's thermal efficiency as well as combustion stability. Increase in flame speed was also observed, but the difference in exhaust emission concentration was not examined since people at that time were not quite concerned about vehicle pollution, which, by sharp contrast, is exactly the most effective catalyst for the development of new engine technologies nowadays.

Collier et al. [4] examined the untreated exhaust emissions of a hydrogen-enriched CNG production engine. They concluded that the addition of hydrogen would increase NO_x and decrease total hydrocarbon emissions, and was beneficial to alleviate the tradeoff relationship between them. Combustion stability was also improved as observed in their study.

Again, Collier et al. pointed out that the engine application which could achieve the greatest advantage from HCNG was heavy-duty engine [5]. They achieved a major reduction in NO_x emission in a Daewoo heavy-duty engine fuelled with HCNG containing 30% hydrogen at all power levels while kept CO and THC emissions in the same range of a conventional CNG engine. Through the experiments aimed at optimizing the intake system for HCNG application, they found that the homogeneousness of fuel–air mixture was very important to NO_x emission. So in our study described in the following sections, we chose an engine speed of 1200 r/min to minimize mixture heterogeneousness since high intake air velocity was detrimental to fuel–air mixing.

Ivanic et al. [6] investigated the effects of hydrogen enhancement on efficiency and NO_x emission of lean and EGR-diluted mixtures in a SI engine fuelled by indolene. Lean operation limit which was defined as 3% coefficient of variation of net IMEP in their study was significantly extended by hydrogen enrichment. They also found that hydrogen addition contributed more to speeding up the flame initiation phase of combustion than to speeding up the flame propagation phase. Improvement in thermal efficiency and potential to decrease NO_x emission by hydrogen enriched dilute operation was also observed.

Wang et al. [7] investigated the combustion behaviors of a direct-injection engine fuelled with various fractions of NG–hydrogen blends. The results showed that the brake effective thermal efficiency increased with the increase of hydrogen fraction at low and medium load. The rapid combustion duration decreased while the heat release rate and exhaust NO_x increased with increased hydrogen fraction. Their study suggested that the optimum hydrogen volumetric fraction in NG–hydrogen blends be around 20% to get the compromise in both engine performance and emissions.

It seems that many researches were conducted at MBT spark timing [3,4,6,7], however, in this study we examined the effect of hydrogen addition on thermal efficiency and emissions both at unchanged spark timing and MBT spark timing, by doing this we found that optimizing spark timing according to hydrogen's special combustion characteristics was critical to the engine's overall performance and emissions. That is, the importance of optimizing spark timing for hydrogen was highlighted. In addition, relatively wide range of hydrogen fractions (from 0% to 50% in volume) and excess air ratios (from stoichiometric to the misfire limited excess air ratio) was used in this study in order to make a comprehensive investigation of the effect of hydrogen addition.

3. Experimental setup and procedures

The test engine was an in-line six-cylinder, throttle body injection one designed for city bus application. It was modified from a diesel engine by replacing fuel injector with spark plug and reshaping the piston head to reduce compression ratio. The engine specifications are shown in Table 1.

The engine was coupled to an eddy-current dynamometer for engine speed and load measurement and control. Engine control management was carried out with an ITMS-6F control system (DELPHI Inc) which provided access to all calibration parameters. The ITMS-6F system allows the user to set a desired equivalence ratio and spark advance.

The exhaust concentration of HC, NO_x, CO, and H_2 were measured by MRU emission monitoring system manufactured by MRU GmbH in Germany. The emission pickup tube was