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Study of cyclic variations of direct-injection combustion fueled with natural gas–hydrogen blends using a constant volume vessel

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ABSTRACT

Cyclic variations of direct-injection combustion fueled with natural gas–hydrogen fuel blends were experimentally studied using a constant volume vessel. Direct-injection combustion was realized by injecting the high-pressure fuel into the vessel. Flame propagating photographs and pressure history in the vessel were recorded at various hydrogen volumetric fractions in the fuel blends (from 0% to 40%) under the same lean-burn conditions where the overall equivalence ratios are 0.6 and 0.8, respectively. The effect of fuel–air mixture inhomogeneous distribution and hydrogen addition on the cyclic variations was analyzed via flame development photographs and pressure-derived combustion parameters. The results indicated that the cyclic variations were initiated at the early stage of flame development. The flame kernel is closely concentric to the spark electrode and flame pattern has less irregular with hydrogen addition. Direct-injection natural gas combustion can achieve the stable lean combustion along with low cyclic variations due to the mixture stratification in the vessel. The cyclic variations decreased with the increase of hydrogen addition and this trend is more obvious at ultra-lean-burn condition. Hydrogen addition weakened the effect from turbulent flow on flame propagating process, thus reduce the cyclic variations related to the gas flow. There exists interdependency between the early combustion stage and the subsequent combustion process for direct-injection combustion.

1. Introduction

With increasing concern about energy shortage and environmental protection, research on improving thermal efficiency and reduction of exhaust emissions has become the major research aspect in the combustion community and engine development society. Lean mixture combustion of hydrocarbon–hydrogen hybrid fuel has attracted the increased attention for combustion scientists and engineers in recent years [1,2]. Lean combustion has distinct potential to provide high thermal efficiency, low exhaust emissions especially CO, soot particles and NO_x. Good anti-knock capability of lean combustion permits using the high compression ratio in the spark-ignition engine leading to the further improvement on thermal efficiency. However, the high lean flammability limit of most of the hydrocarbon fuels makes it extremely difficult to achieve a stable lean combustion. The key difficulty of the lean hydrocarbons combustion is the slow flame propagation speed at lean combustion condition. One of the effective methods to solve the problem is to mix a fuel that possesses

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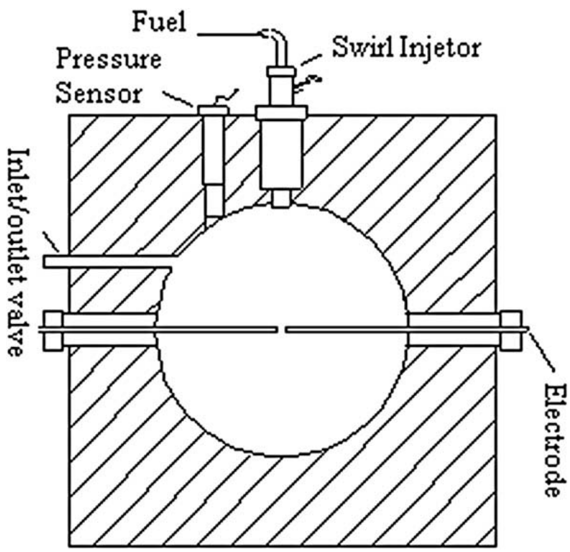

Fig. 1 – Schematic diagram of the constant volume combustion vessel.

high burning velocity. Hydrogen with high burning velocity and low ignition energy is regarded as the best additive to the gaseous hydrocarbons. The combination of hydrogen with hydrocarbon fuel is expected to improve the lean-burn capability and decrease the emissions [3–5].

Natural gas is regarded as one of the most promising clean alternative fuel and has been used widely in spark-ignition engines [6]. Methane which is the main *component* of natural gas has unique tetrahedral molecular structure with larger C–H bond energies, thus demonstrates some unique combustion characteristics such as high ignition temperature and low flame propagation speed [7], leading to the slow burning velocity and poor lean-burn ability. Hydrogen addition to natural gas is helpful to improve the combustion characteristics as described in previous. Natural gas–hydrogen fuel blends have been extensively studied [8–14].

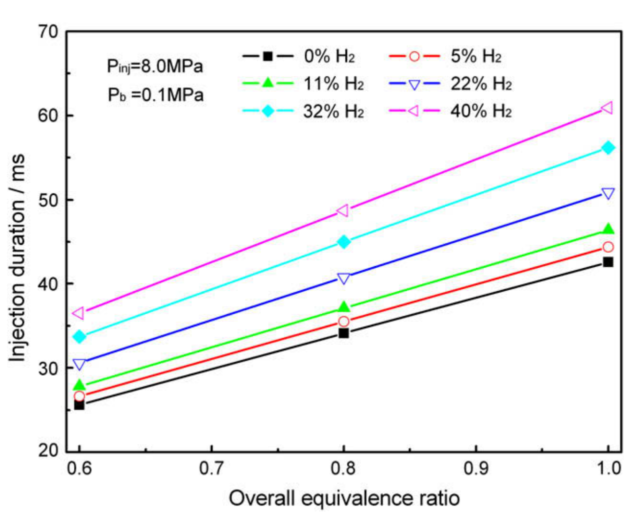

Fig. 2 – Injection duration setting of fuel blends at various overall equivalence ratios.

The studies showed that the improvement of engine thermal efficiency and reduction of emissions would be obtained by adding a small amount of hydrogen into the natural gas when operating on the lean-burn condition. Lean-burn capability of natural gas could be extended by hydrogen addition, leading to the further improvement of engine thermal efficiency and reduction of emissions [3,5,15].

However, one unfavorable phenomenon for natural gas engine is the lowering of power output compared with that of gasoline engine due to the lower energy density of natural gas [6]. The direct-injection combustion is one promising concept to increase thermal efficiency and reduce emissions [16,17]. The combination of gaseous fuel and direct-injection combustion can increase the volumetric efficiency compared to that of port-injection system and maintain high power output. Experimental studies have been conducted on a direct-injection engine fueled with natural gas–hydrogen fuel blends (hydrogen volumetric fraction from 0% to 37%) under lean-burn condition [18,19]. The results showed that the thermal efficiency increased and HC emission decreased with hydrogen addition while the NO_x emission increased remarkably when the hydrogen volumetric fraction exceeds 20%. Thus some approaches like ultra-lean combustion or EGR (exhaust gas recirculation) need to be used combining with hydrogen addition to provide a comprehensive target in natural gas direct-injection engine [2,20,21].

It is well known that cyclic variations exist in the spark-ignition engine and this phenomenon will become more severe at lean burn or highly diluted mixtures such as high EGR ratio [22,23]. Many studies were conducted on the engine cyclic variations [24–29] and the studies revealed that the variations in the early combustion stage mainly determined the cyclic variations of engines. However for direct-injection spark-ignition engine fueled with natural gas–hydrogen blends, additional factors may influence engine cyclic variations like mixture stratification and hydrogen addition. Mixture inhomogeneity will contribute to the cyclic variations in direct-injection combustion engine. Thus, to create a stable mixture distribution in the chamber is an effective approach in realizing low cyclic variations for direct-injection engines [28,30]. Meanwhile, the increase in flame propagation speed of mixture can promote the burning rate of mixture and decrease the cyclic variations of engines [23]. For the stoichiometric hydrocarbon–air mixtures, the turbulent flame speed is the order of 10 times of laminar flame speed, while for the hydrogen–air mixtures, the turbulent flame speed is of the order of (though larger than) the laminar flame speed at typical spark timing in an engine [31]. These suggested that hydrogen addition would increase the burning velocity and weaken the effect of turbulent flow fluctuations on the combustion process and give low cyclic variations. Experimental studies conducted on a port-mixed spark-ignition engine fueled with natural gas–hydrogen blends showed that hydrogen addition can reduce the cyclic variations of homogeneous spark-ignition natural gas engine, especially on the lean-burn condition [32,33]. While, the effect of hydrogen addition on a direct-injection natural gas engine with stratified mixture charge still needs further investigation. Thus the