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ARTICLE *in* ENERGY & FUELS · APRIL 2008

Impact Factor: 2.79 · DOI: 10.1021/ef7006485

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Energy Fuels, **2008**, 22 (3), 1880-1887 • DOI: 10.1021/ef7006485 • Publication Date (Web): 05 April 2008

Energy & Fuels is published by the American Chemical Society. 1155 Sixteenth Street N.W., Washington, DC 20036

Influence of Different Volume Percent Hydrogen/Natural Gas Mixtures on Idle Performance of a CNG Engine

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Received October 31, 2007. Revised Manuscript Received February 25, 2008

In order to study the influence of the 0−50 vol % hydrogen addition on idle performance, an experimental research was conducted on a six-cylinder throttle body injection natural gas engine. Experiments have been made under various excess air ratios and ignition timings. The results show that hydrogen addition remarkably decreased CH_4 emission whereas it had no significant effect on the reduction of CO. NOx emission was relatively low at idle compared to other emissions. Hydrogen addition combined with ignition timing retardation was an effective way to reduce idle emission. The COV in IMEP and partial-burn ratio could be simultaneously reduced by hydrogen addition, which indicated the improvement of idle stability. In turn, the improvement of idle stability decreased the fuel consumption. Also, the curve for COV in IMEP was smoother versus ignition timing after hydrogen addition, which is desirable at idle because small idle speed error was adjusted by ignition timing in many electric idle control units. It can be concluded hydrogen addition is an effective and applicable approach to improve idle stability and decrease emission.

1. Introduction

In the past few years, public awareness has increased of environmental problems, and concern has risen over global air quality. Because of its relatively more reserves and lower emissions, natural gas is one of the alternative fuels to diesel being considered for low emissions heavy-duty applications. The operation of a CNG engine on lean fuel mixture has a number of positive features. It can, in principle, provide high thermal efficiency, low likelihood of knock, and reduced emissions, especially NOx, and permit using higher compression ratios while reducing heat transfer. However, slower flame propagation, less complete combustion, increased cyclic variations, and even the occasional flame failure arise associated with lean.[1]

Engine stability at idle is an important factor that influences the behavior of the internal combustion (IC) spark ignition (SI) engine, in terms of fuel efficiency, exhaust gas emissions, and the customer's comfort. The combustion variability at idle condition is fundamentally caused by cyclic variation of the mixture motion, amount of the air and fuel fed into the cylinder and their mixing, and residual exhaust gas dilution, especially in the vicinity of the spark plug, due to cam overlap or valve timing[2] In order to avoid rough idle, it is necessary to limit valve timing durations and especially valve overlap to reduce residual dilution to acceptable levels. Alternatively, swirl and tumble can be used to make the combustion faster in order to tolerate the higher residual dilution. Unfortunately, either method is limited due to reducing the power output.

Hence, there is a need to enhance the combustion process without bringing about some of these disadvantages. One approach is through the addition to the methane of a small amount of hydrogen, a fuel having a much cleaner and faster rate of burning than methane.

Therefore, the objective of this paper is to investigate the influence of the hydrogen addition on idle performance in a natural gas (NG) fueled spark ignition engine.

2. Previous Work

The increasing traffic congestion today has raised the percentage of the time in which the engine is at idle. The rough idle not only is unpleasant for the driver due to noise, vibration, and harshness (NVH) but also increases fuel consumption and exhaust emission. In order to improve idle quality, many researchers have dedicated to study the principle of the rough idle. Also, the effect of hydrogen addition on engine performance and emissions characteristics has been extensively investigated.

Hoard and Rehagen[3] introduced the parameters lowest normalized value (LNV) and standard deviation of indicated mean effective pressure (SDimep) to characterize idle quality. They found that acceptable levels of SDimep and LNV required fast burn engines. To be fairly confident in obtaining acceptable combustion, the idle 10%−90% burn duration should be shorter than about 35°. Additionally, they mentioned SDimep and LNV levels for acceptable idle quality were fairly similar for a wide range of vehicle and engine types according to their experiments.

Han and Chung[4] studied the influence of ignition energy, fuel injection timing, spark timing, and air−fuel ratio on gasoline engine stability at idle. They used engine speed variation, fuel consumption rate, maximum cylinder gas pressure (P_{max}), standard deviation of P_{max}, and HC concentrations to evaluate

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(1) Bade Shrestha, S. O.; Karim, G. A. Hydrogen as an additive to methane for spark ignition engine applications. *Int. J. Hydrogen Energy* **1999**, *24*, 577–586.

(2) Di Martino, U.; Formisano, G.; Lucignano, G. Combustion Stability at Idle: A Non-Indicated Methodology for Analysis. SAE paper 2003-01-0640.

(3) Hoard, J.; Rehagen, L. Relating Subjective Idle Quality to Engine Combustion. SAE paper 970035.

(4) Han, S. B.; Chung, Y. J. The Influence of Air-Fuel Ratio on Combustion Stability of a Gasoline Engine at Idle. SAE paper 1999-01-1488.

10.1021/ef7006485 CCC: $40.75
Published on Web 04/05/2008

the stability at idle. They found fuel injection timing before the inlet process at 90° before top deed center (BTDC) was best for the stability at idle. In addition, as the spark timing was advanced, the engine speed variations increased. For the air−fuel ratio of 12:1, the engine speed variations did not change much as the spark timing was advanced.

Sierens and Rosseel[5] tested a GM V8 engine with natural gas, pure hydrogen, and different blends of these two fuels. It is found that to obtain maximum engine efficiency for the whole load range while taking low exhaust emissions into account, the mixtures composition should be varied with respect to engine load. They proposed at low loads pure hydrogen should be used (lamda > 2), limiting NOx and eliminating non-methane organic gas (NMOG) and CO emission. At intermediate loads, hydrogen-enriched natural gas (HCNG) was used in such a way that NOx remained low. The oxidation catalyst reduced CO and NMOG emissions to acceptable levels. At full load pure natural gas was used, providing high maximum brake meant effective pressure (BMEP).

Karim[6] reported that the lean equivalence ratio operational limit in an SI engine when fueled with hydrogen was much lower than that for other common fuels. This permitted stable lean mixtures operation and control in hydrogen fuelled engines.

Di Martino et al.[2] introduced an alternative approach to evaluate the idle quality, concerning statistic analysis of instantaneous engine speed, in comparison with pressure indicated analysis. Four different engine-based parameters, including CAA_180 (crankshaft angular acceleration upon 180° crank angle), standard deviation of CAA_180, lowest acceleration values, and cumulative lower acceleration value, were chose. They found speed-based parameters and pressure-based parameters showed quite a good correlation.

Manzie and Watson[7] investigated the combustion variability of an LPG injected engine, with particular focus on the behavior at idle speed operation. They observed the combustion variability increased with decreasing manifold pressure and engine speeds. Additionally, variability decreased as the engine coolant temperature increased.

Kim et al.[8] analyzed the pressure data of a natural gas engine at idle to investigate the combustion stability. The result of their experiments showed advancing the spark timing past a critical point caused LNV to decrease and sometimes become negative, including misfire and dropout. They also got that the optimum idle quality was achieved when compression ratio was above 11. Moreover, the engine had a tendency to misfire or partial burn when the relative air/fuel ratio was increased much higher than 1.4.

Huang et al.[9] examined combustion characteristics and heat release of a spark-ignited engine fueled with natural gas−hydrogen blends on a three-cylinder automotive CNG spark-ignited engine. Their experiments results showed that the initial combustion duration and total combustion duration decreased with the increase of hydrogen fraction; likewise, the addition of hydrogen into natural gas decreased ignition delay.

Porpatham et al.[10] conducted experiments on a single-cylinder constant speed SI engine at different hydrogen levels adding to biogas. They found that hydrogen significantly enhanced the combustion ratio and extended the lean limit of combustion of biogas. There is an improvement in the brake thermal efficiency and brake power. Also, drastic reduction of HC levels was seen. Additionally, there was significant drop in the coefficient of variation (COV) in indicated mean effective of pressure (IMEP) with lean mixtures with hydrogen addition.

Huang et al.[11] investigated engine performance and emissions for an engine fueled with natural gas−hydrogen mixtures. They concluded that engine lean-burn limited was extended by the addition of hydrogen. They also found that engine power output and thermal efficiency increased when hydrogen fraction was larger than 20%. Addition of hydrogen decreased the exhaust hydrocarbon concentration, meanwhile increasing the NOx concentration.

Ma et al.[12] conducted experimental research on a spark ignition engine operating on NG with 0, 10, 30, and 50 vol % hydrogen enrichment. They found that engine lean burn limit could be extended by hydrogen addition mainly due to hydrogen's broader burn limit and fast burn speed. They also got that after optimizing spark timing to minimum advance for best torque (MBT) engine efficiency rose with increase of hydrogen fraction, and NOx emission for fuel blends with different hydrogen fraction showed little difference at this MBT spark timing. Additionally, they concluded hydrogen addition was beneficial to the alleviation of the tradeoff relation between HC and NOx emission.

Later study, however, focused on the improvement of idle stability for existing fuels or the effect of adding hydrogen at normal operating conditions. The results showed fast burn can improve the idle stability.[2–4] Therefore, the high burning velocity of hydrogen may contribute relatively to improve the idle stability with a shorter combustion period. Additionally, low spark energy requirement would lower the cyclic combustion fluctuation.[13] Considering that quite few researches focus on the effect of adding hydrogen on idle performance, the purpose of this study is to investigate the influence of the hydrogen addition on idle performance in a natural gas (NG) fueled spark ignition engine.

3. Experimental Setup and Strategy

The engine used was an overhead cam L-6 turbocharged intercooler one, for full size passenger vehicles. The engine specification characteristics are shown in Table 1. The engine was connected to an eddy-current dynamometer for engine speed and load measurement and control. An engine control system was used to control the spark timing, air fuel ratio, and desired idle speed.

The emission monitoring instrument manufactured by MRU GmbH was used to measure exhaust emissions. An electrochemistry detector was used to measure NOx and CO, with an accuracy of

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Table 1. Engine Specifications

item	value
engine make	Dongfeng Motor Co. Ltd
engine type	in-line 6 cylinders, spark ignition
displacement volume (L)	6.234
compression ratio	10.5
bore (mm)	105
stroke (mm)	120
connecting rod length (mm)	192
intake valve timing	IVO: 18°21′ BTDC; IVC: 37°39′ ABDC
exhaust valve timing	EVO: 56°21′ BADC; EVC: 11°39′ ATDC

±20 ppm. A NDIR detector was used to measure HC with an accuracy of ±0.02%. Wide-range lambda analyzer is manufactured by Horiba Co. The analyzer detector is mounted 40 cm from the exhaust manifold.

The in-cylinder pressure was measured by kistler 6117B piezoelectric high-pressure transducer which is integrated with a spark plug. The crankshaft position was measured using a Kistler crank angle encoder with a resolution of 1° of crank angle. After being amplified by the Kistler 5011B charge amplifier, the pressure and the corresponding crank angle are recorded by the Yokogawa signal collector.

The different vol % hydrogen/natural gas mixture which the experiments required was acquired through online H2/NG mixtures fueling supply system. In the CNG supplement pipeline, a CNG flow meter using the Coriolis effect measured the CNG mass flow. Afterward, the voltage signal corresponded the mass flow was sent to the NI module, in which the voltage corresponded target hydrogen fraction was calculated. A high-accuracy mass flow controller (ALICAT) was fixed in the hydrogen pipeline to make sure the hydrogen mass flow equal to the calculated value.

In order to have accuracy result, it was important to avoid negative influences from variation in engine conditions. Particular care must be taken as regards coolant and lubricating oil temperatures. In this article all the experiment data were monitored after the engine coolant temperature reached 75 °C and the lubricating oil temperature reached 80 °C. Furthermore, a significantly high number of cycles must be sampled in order to guarantee the best possible indicating measuring repeatability. The average cylinder pressure diagram of 400 consecutive cycles was used to evaluate the stability at idle in this article. The engine speed at idle was fixed at 800 rpm without the automatic idling control device. The throttle was closed completely, and no load was put on the engine. The mixture entering engine was controlled by idle bypass valve, which also controlled the idle speed. When the idle speed changed caused by the variation of the excess air ratio and ignition timing, the idle bypass valve was adjusted artificially to maintain the idle speed at 800 rpm.

4. Test Results and Discussion

4.1. Cyclic Variability of CNG Engine at Idle. Cyclic variability was shown by cylinder combustion pressure and speed. Figure 2 shows the variation of cylinder pressures versus crank angle over five consecutive cycles. As we can see, the variation was significant among the five consecutive cycles. The lowest peak cycle pressure was approximately half of the highest peak cycle pressure. From these graphs it can identity the occurrence of misfires or incomplete combustion. The variations were always associated with losses in terms of thermal efficiency and fluctuation in the amount of work done,[14] which also caused high emission. Likewise, it can be found that the CNG engine had poor idle stability, especially at over-advance ignition timing. This was mainly due to high ignition energy and slow burn ratio of CNG, which caused the initial flame growth and rapid combustion fluctuation. Furthermore, low flame propagation velocity also cannot tolerate high residual gas dilution.[3] Therefore, the objective of this paper was to improve the idle performance by adding hydrogen to CNG.

Periodic oscillations in engine speed of a SI engine at idle conditions were another phenomenon which was found to be affected by combustion perturbations. Some researchers used statistical analysis of the instantaneous engine speed at idle to evaluate the idle quality, in comparison with pressure indicated analysis,[2] especially in the control area. Figure 3 shows crankshaft speed variations vs crank angle over 80 s, one sample plot per second. As can be seen, the fluctuation of idle speed was serious, which meant the consumer should endure high noise and vibration. Otherwise, the instability of idle speed led to low disturbance rejection, such as air conditioner engagement, etc.

From Figures 2 and 3 it can be concluded that this compressed natural gas (CNG) engine had poor idle stability. Thus, the influence of different vol % hydrogen/natural gas mixtures on idle performance was investigated below. Table 2 shows the fuel properties of methane and hydrogen.

4.2. Influence of Air/Fuel Ratio. Because of time constraints, the ignition timing was not optimized for each condition in this set of measurements; instead, it was kept at 20° before TDC. More details can be seen in section 4.3. The engine was tested with different excess air ratios ranging from 0.75 to 1.25. The excess air was the reciprocal of the equivalence ratio. Too rich or too lean cannot maintain idle speed even if the idle bypass valve was totally open. Different excess air ratios were obtained by changing the fuel amount entering the engine, which can be realized in the engine control system.

The variation of CH_4 emission with equivalence ratio is shown in Figure 4. As we can see, CH_4 emission levels increased as the mixture became rich due to incomplete combustion. As the excess air ratio increased, the CH_4 emission decreased significantly. This was because adequate oxygen exists to ensure complete oxidation and good postcombustion oxidation of crevice gases that escape the main combustion event.[5] As the hydrogen addition increased, the CH_4 emission decreased. This phenomenon can be explained by introduction of hydrogen lower HC intake. In addition, a smaller quench zone as the flame was able to propagate closer to the wall, and a reduction of partial burning with H_2 addition resulted in a reduction of CH_4 emission. Meanwhile, it can be seen that CH_4 emission of pure CNG started to increase after lambda 1.15, whereas CH_4 emission of above 20% hydrogen addition still had the decrease trends after lambda 1.25. It indicated that hydrogen addition can enhance the lean burn ability of CNG.

In general, as shown in Figure 5, the CO emission level decreased significantly as the excess air ratio increased. After excess air ratio was above 1.05, the CO emission was nearly constant and maintains a relatively low level. Therefore, CO emission can be represented as a function of excess air ratio and might be considerably affect by it. In the rich region, CO level increased slightly probably due to oxygen amount decreased around rich conditions as hydrogen supplement was getting higher at a fixed excess air ratio.[15] Except for these areas, CO emission values for all hydrogen−methane mixtures had near value.

The coefficient of variation of IMEP vs excess air ratio is shown in Figure 6. IMEP was the integral of PdV over the compression and expansion strokes, i.e., the gross IMEP. This

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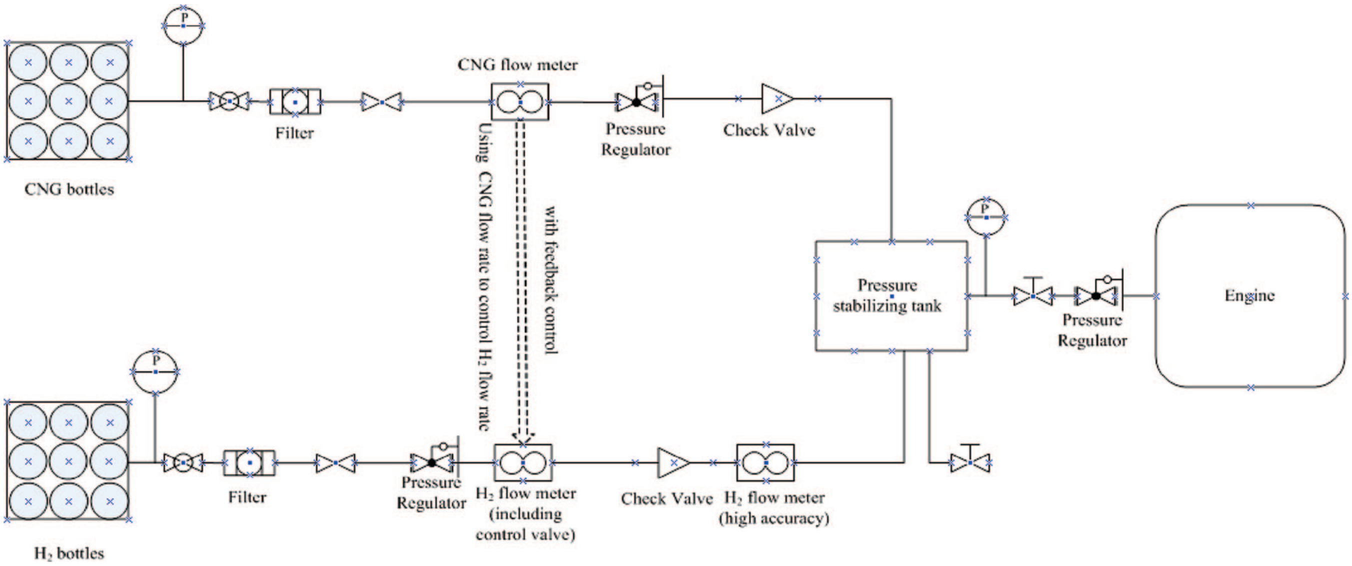

Figure 1. Schematic of the fuel supply system.

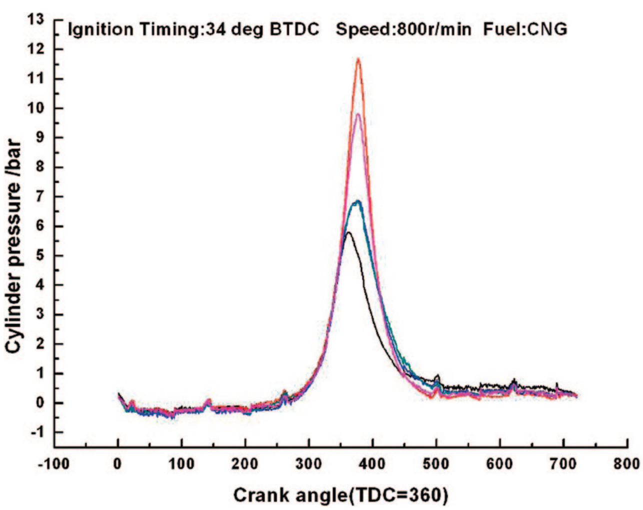

Figure 2. Combustion cylinder pressure vs crank angle (excess air ratio: 1.1).

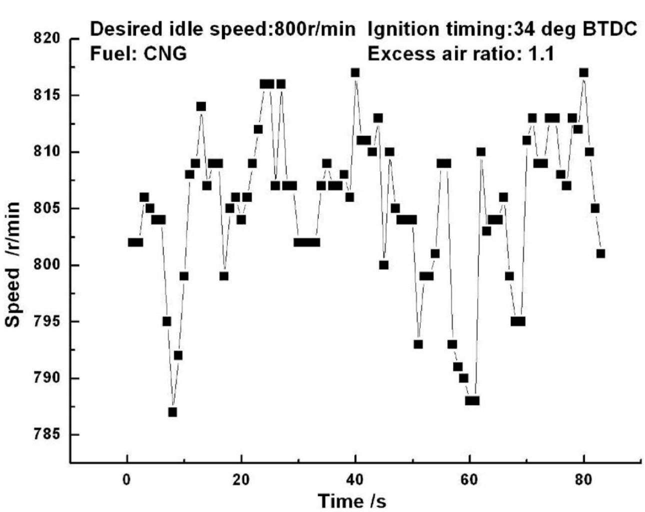

Figure 3. Crankshaft speed variations vs crank angle.

Table 2. Fuel Properties of Methane and Hydrogen

properties	hydrogen	methane
quenching distance [mm]	0.6	2.1
stoichiometric air/fuel ratio	34.2	17.3
lean limit equivalence ratio	0.1	0.5
flammability in air [vol %]	4−75	5.3−15
minimum ignition energy [MJ]	0.02	0.29
laminar burning velocity [m/s]	2.9	0.38
lower heating value [MJ/kg]	120	50

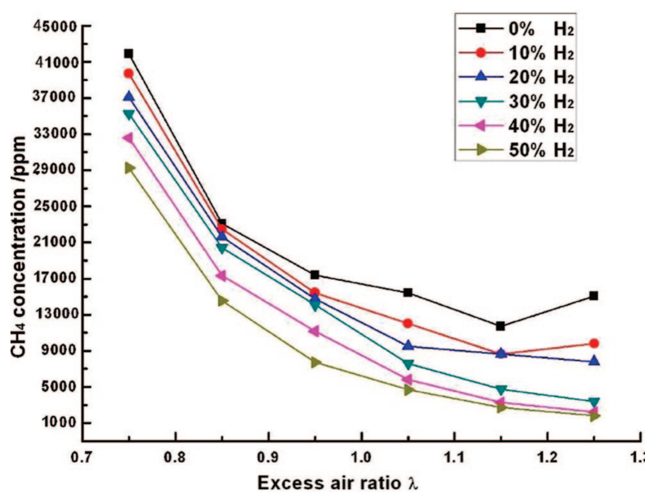

Figure 4. CH_4 concentration vs excess air ratio. Operating conditions: engine speed = 800 rpm, spark timing = 20° BTDC.

was defined as the standard deviation in IMEP divided by the mean IMEP. The trend illustrated by the curve was consistent with the trends of the CH_4 emission. The COV in IMEP reached a maximum at excess air ratio 0.75, reflecting incompletely combustion when the mixture was rich. As the excess air ratio increased, the COV in IMEP decreased substantially. However, after excess air ratio exceeds 1.05, the COV in IMEP of below 30% hydrogen addition increased distinctly. This is thought to be caused by the slower flame speed of lean air/fuel mixtures. Owing to more hydrogen addition higher flame velocity, the COV in IMEP increased slightly after lambda 1.2 while hydrogen fraction was larger than 30%. The addition of hydrogen to methane as shown in the Figure 6 decreased COV in IMEP substantially at a given excess air ratio, reflecting its great ability to ensure idle stability. This can be explained as below: First, hydrogen had lower ignition energy and wide flammability; consequently, hydrogen addition could reduce the risk of misfire and enhance the initial flame kernel formation, even in the high exhaust gas dilution condition. Second,

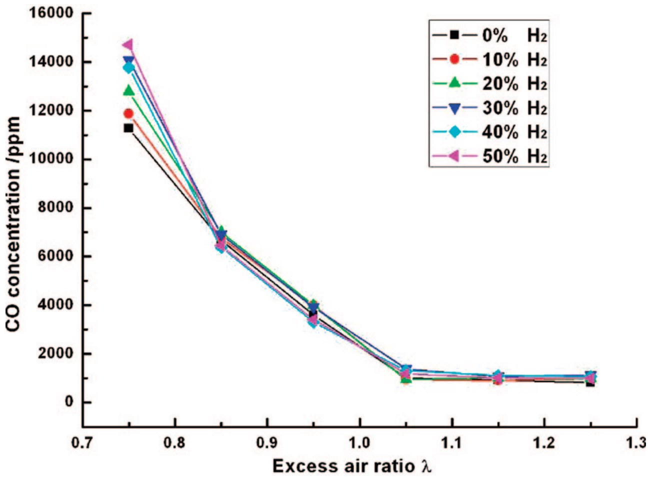

Figure 5. CO concentration vs excess air ratio. Operating conditions: engine speed = 800 rpm, spark timing = 20° BTDC.

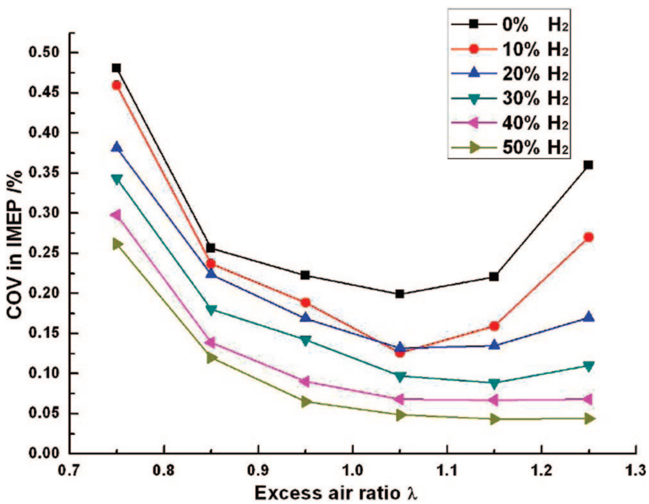

Figure 6. COV in IMEP vs excess air ratio. Operating conditions: engine speed = 800 rpm, spark timing = 20° BTDC.

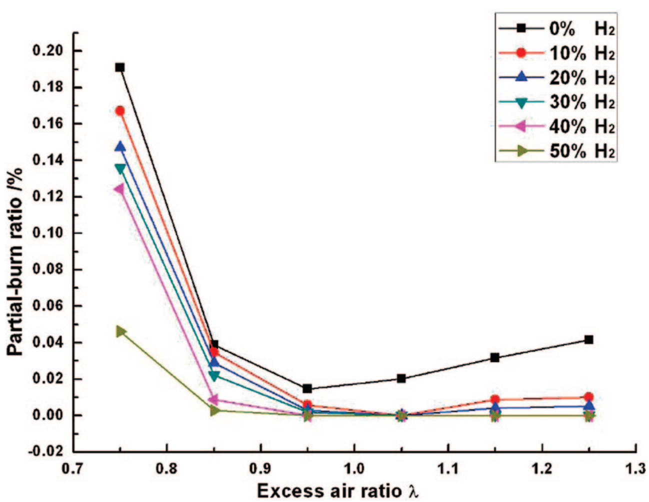

Figure 7. Partial-burn ratio vs excess air ratio. Operating conditions: engine speed = 800 rpm, spark timing = 20° BTDC.

hydrogen had high laminar burning velocity, which could also improve the idle stability.

Figure 7 shows partial-burn ratio vs excess air ratio. In general, most of the articles used misfire ratio to evaluate complete misfire, which may occur where the piston for one stroke produces no work. In this experiment there were a lot of

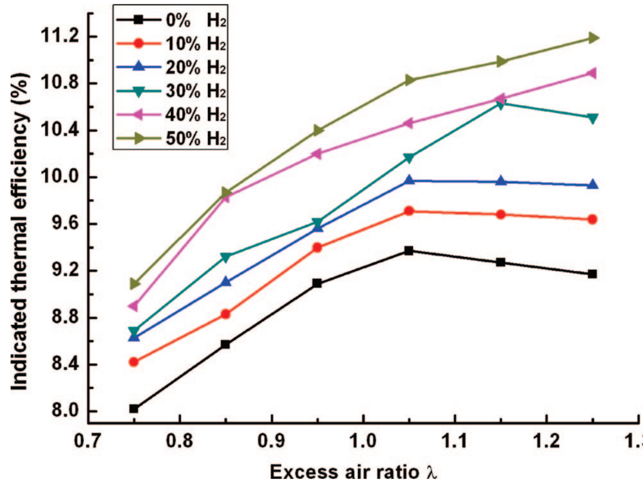

Figure 8. Indicated thermal efficiency vs excess air ratio. Operating conditions: engine speed = 800 rpm, spark timing = 20° BTDC.

partial cycles which caused the COV in IMEP high; however, the misfire ratio was not apparently different among different fuels in previous experiments. This can be explained that there were few complete misfire cycles. Therefore, the partial-burn ratio was used to evaluate the misfire trends. The partial-burn ratio was defined as the number of the cycles if the IMEP was less than 46% of the mean IMEP divided by the total cycle number.[16] As can be seen, the partial-burn ratio decreased after hydrogen addition. This was because addition of hydrogen enhances the flame velocity of the inducted fuel mixture and lowers the COV in IMEP. Furthermore, the excess air ratio corresponding the lowest partial-burn ratio was getting bigger, which reflected the addition of hydrogen can improve the lean-burn ability and reduce misfire cycles.

The indicated thermal efficiency vs excess air ratio is shown in Figure 8. As can be seen, the indicated thermal efficiency increased after hydrogen addition. The more hydrogen addition, the higher were the indicated thermal efficiency. This can be explained that addition of hydrogen into natural gas increased the flame speed, shortening the combustion duration, and the combustion took place near constant volume condition; consequently, the indicated thermal efficiency increased. In addition, the improvement of the indicated thermal efficiency was more significant at leaner condition. The results demonstrated that hydrogen addition can enhance combustion, especially in the lean mixture, therefore enhancing the toleration to the exhaust gas dilution at idle condition.

In order to investigate the effect of adding hydrogen to idle stability and emission, a plot of COV in IMEP vs CH_4 concentration is shown in Figure 9. As can be seen, CH_4 emission kept pace with the COV in IMEP for all fuels while the lambda below 1.05. After the lambda exceeded 1.15, CH_4 emission and COV in IMEP both increased when hydrogen fraction was smaller than 20%. However, CH_4 emission and COV in IMEP both decreased even if lambda was equal to 1.25 when hydrogen fraction was larger than 30%. The available data led to an understanding that hydrogen addition to natural gas will extend the lean limited of combustion, which enhanced the toleration to residual gas dilution at idle. The more hydrogen adding, the leaner mixture can be introduced. Thus, fuel consumption and emission would decrease.

In order to investigate the effect of adding hydrogen for stability and economy, fuel consumption ratio vs COV in IMEP

(16) Heywood, J. B. *Internal Combustion Engines Fundamentals*; McGraw-Hill: New York, 1988; p 424.

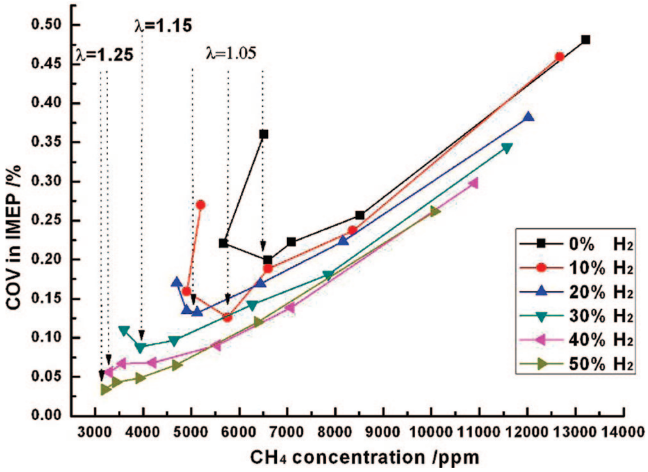

Figure 9. COV in IMEP vs CH_4 concentration. Operating conditions: engine speed = 800 rpm, spark timing = 20° BTDC.

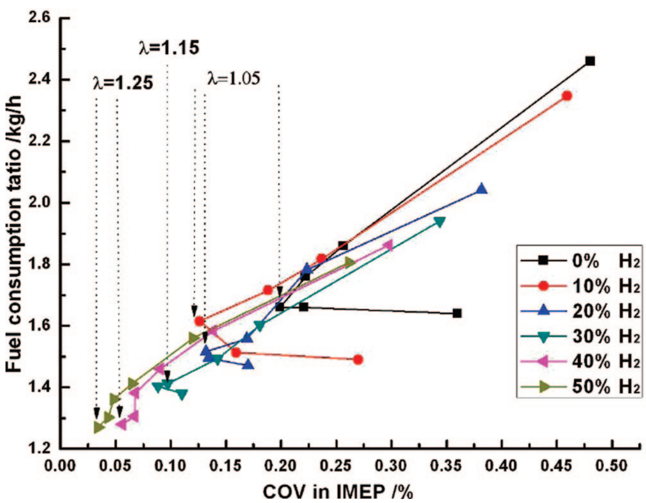

Figure 10. Fuel consumption ratio vs COV in IMEP. Operating conditions: engine speed = 800 rpm, spark timing = 20° BTDC.

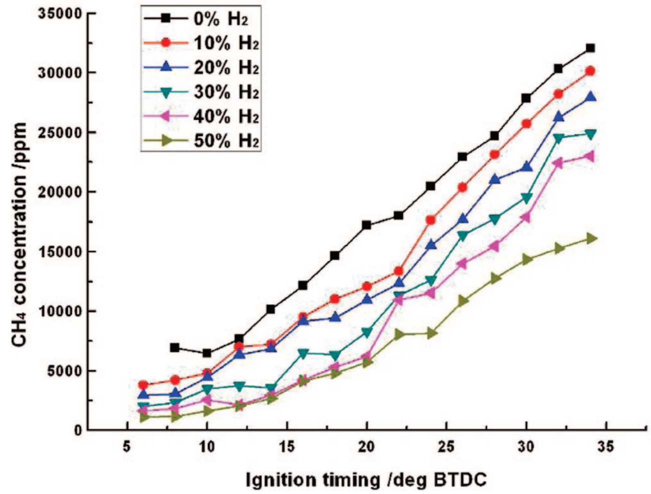

Figure 11. CH_4 concentration vs ignition timing. Operating conditions: engine speed = 800 rpm, excess air ratio = 1.1.

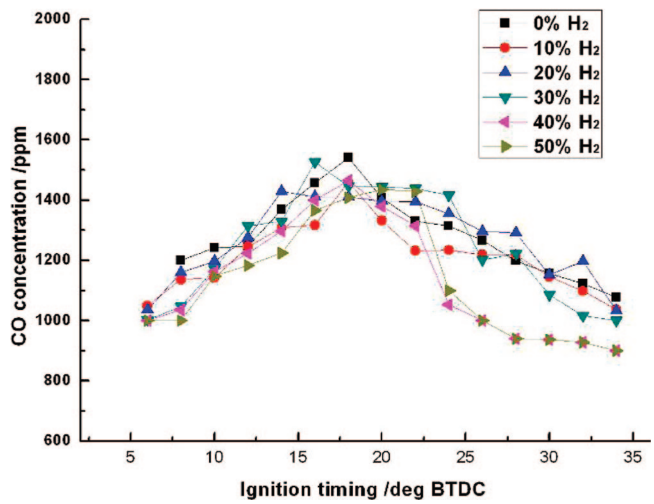

Figure 12. CO concentration vs ignition timing. Operating conditions: engine speed = 800 rpm, excess air ratio = 1.1.

is shown in Figure 10. The fuel consumption ratio was the corresponding CNG mass flow according to the conservation of energy. In general, the mass flow of hydrogen was converted to the same amount of energy CNG mass flow. As can be seen, the fuel consumption ratio and COV in IMEP contemporary decreased while adding more hydrogen in. Additionally, the fuel consumption ratio had a strong relationship with COV in IMEP. The improvement of idle stability always decreased the fuel consumption.

The available data led to concluding that the most suitable lambda were 1.05, 1.15, and 1.25, while the hydrogen fraction was lower than 30%, 30%, and above 30%, respectively.

4.3. Influence of Spark Timing. In general, most of small idle speed error was adjusted by ignition timing in many electric idle control units. Thus, the relationship between the performance of idle and the ignition timing was extremely important. Therefore, this section analyzes the effect of the ignition timing to the idle performance. In order to be convenient to compare, the lambda was fixed 1.1, at which all the fuels would work stability.

As a main emission, CH_4 played a great role in the idle emission. They were thought to form in the quench zone at the cool cylinder walls and the crevice volumes where the flame was extinguished. Figure 11 shows the relationship of CH_4 concentration and ignition timing. As can be seen, CH_4 emission decreased as the ignition timing retarded. This was consistent with other operating condition. It was clear that as the ignition timing was retarded, cylinder pressure would decrease, thus reducing the gas density in the crevice volume and in turn decreasing CH_4 emission. Additionally, as the proportion of hydrogen increased, the CH_4 emission decreased remarkably. This was mainly due to adding hydrogen faster combustion as a result improved the toleration to the idle residual dilution. Also, hydrogen addition resulted in smaller quenching distance and higher combustion temperature.[17]

It was clear that production of carbon monoxide primarily occurs in rich combustion when there was lack of oxygen to fully form carbon dioxide.[17] From Figure 12 it can be found an interesting phenomenon. The maximum CO emission occurred closely at ignition timing 20°, and retarding or advancing would reduce CO emission. However this was different from the trend of the CH_4 emission. It was clear that over-retarding can enhance postcombustion and higher exhaust temperature, which led to decreased CO emission. While the reason why overadvance can reduce CO emission may be increasing in-cylinder temperature. It also can be seen hydrogen addition does not have a significant effect on the reduction of CO emission.

(17) Bauer, C. G.; Forest, T. W. Effect of hydrogen addition on the performance of methane-fueled vehicles. Part I: effect on S.I. engine performance. *Int. J. Hydrogen Energy* **2001**, *26*, 55–70.

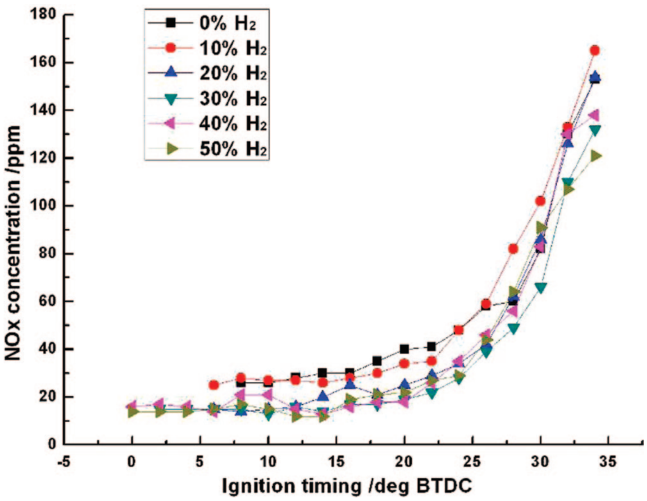

Figure 13. NOx concentration vs ignition timing. Operating conditions: engine speed = 800 rpm, excess air ratio = 1.1.

The combustion of nitrogen-free fuels in SI engines produces NOx mainly within the burned zone where some O_2 and N_2 coexist under high temperature for a relatively significant time.[18] Figure 13 shows NOx concentration vs ignition timing. As can be seen, NOx emission was relatively low at idle compared to other emissions. This can be explained that the combustion temperature was low due to the low load. Meanwhile, too much exhaust gas existing in the cylinder worsens the combustion, which also lowers the combustion temperature. Therefore, the objective of adding hydrogen at idle in this article was to enhance combustion in order to decrease CH_4 and CO emissions and improve idle stability. Also, it was found that hydrogen addition has no drastic effect on the NOx emission. It was very useful because the negative effect of hydrogen addition, such as increase of NOx, was without consideration at idle condition.

From Figures 11 and 12, it can be concluded that adding hydrogen combined with retarding ignition timing was an effective way to reduce idle emission.

Idle combustion stability was a fundamental factor which limited operating leaner mixtures to decreases emission and improves economy. COV in IMEP was a most popular parameter to evaluate the idle stability. Figure 14 shows the relationship of COV in IMEP and ignition timing. As can be seen, COV in IMEP of the pure CNG was high, indicating poor combustion in cylinder. After hydrogen addition, the COV in IMEP decreased remarkably. In addition, the lowest COV in IMEP occurred at MBT points, and over-advance or over-retard would cause poor stability. Advancing the ignition timing from MBT decreased the exhaust temperature, and lower temperature of residuals at the time of spark was likely to be adversely affecting ignition. The COV in IMEP was smoother versus ignition timing after hydrogen addition, which is useful at idle because small idle speed error was adjusted by ignition timing in many electric idle control units.

Because of low turbulences and high dilution at idle, the combustion duration was longer than that of normal operating conditions. The longer combustion duration implied more heat transfer loss and poorer stability. Figure 15 shows 10%−90% burn duration vs hydrogen fraction. Here, burn duration was calculated as the crank angle interval between 10% mass fraction and 90% mass fraction burned. The method used is the

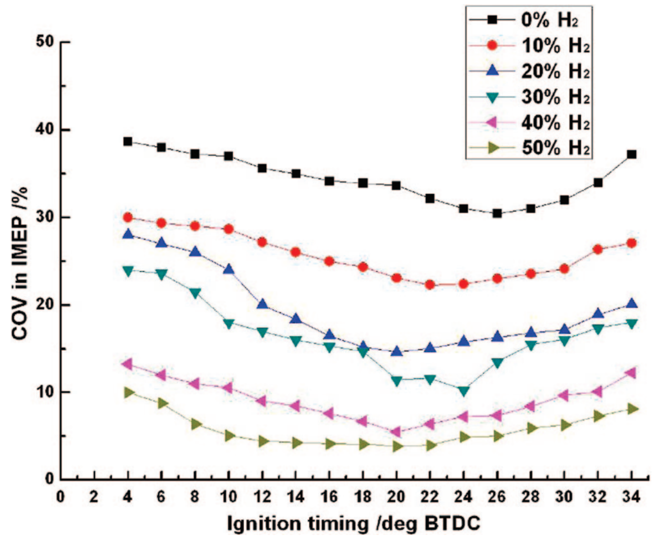

Figure 14. COV in IMEP vs ignition timing. Operating conditions: engine speed = 800 rpm, excess air ratio = 1.1.

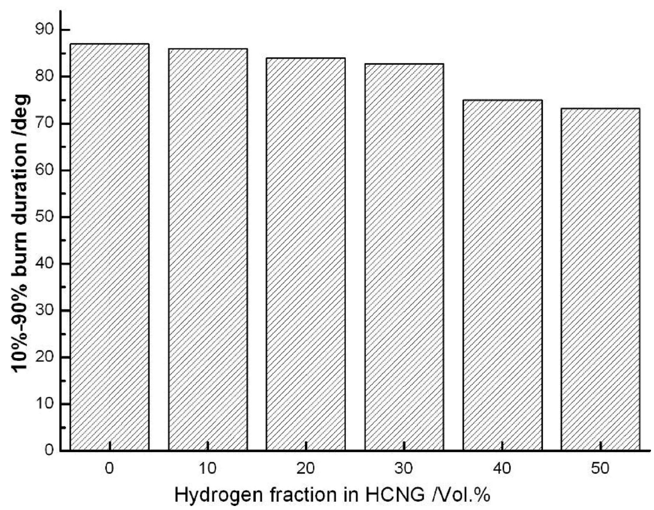

Figure 15. 10%−90% burn duration vs hydrogen fraction. Operating conditions: engine speed = 800 rpm, excess air ratio = 1.1, ignition timing = 20° BTDC.

Rassweiler−Withrow method, which we can see in ref 19. As can be seen, for a specific ignition timing, the 10%−90% burn duration decreased with the increased of hydrogen fraction. This can be explained that the addition of hydrogen can increase the burning velocity, due to the high laminar burning velocity of hydrogen, nearly 7 times higher than that of methane. The more hydrogen addition, the faster are the burning velocity. Therefore, idle combustion was enhanced and toleration to exhaust dilution was improved.

5. Conclusions

An experimental study aimed at examining the effects of hydrogen addition on idle performance in a SI engine was conducted on a six-cylinder throttle body injection natural gas engine. CNG and HCNG containing 0−50 vol % hydrogen were used for comparison purposes. The main results are summarized as follows.

1. As the excess air ratio increases, the CH_4 emission decreased significantly. CH_4 emission of pure CNG started to increase after lambda 1.15, whereas CH_4 emission of above 20% hydrogen addition still had the decrease trends after lambda 1.25.

(18) Li, H.; Karim, G. A. An Experimental Investigation of S.I. Engine Operation on Gaseous Fuels Lean Mixtures. SAE paper 2005-01-3765.

(19) Heywood, J. B. *Internal Combustion Engines Fundamentals*; McGraw-Hill: New York, 1988; p 385.

CO emission values for all hydrogen−methane mixtures had near value. Hydrogen addition can enhance the lean burn ability of CNG.

2. The addition of hydrogen to CH_4 decreased COV in IMEP substantially at a given excess air ratio, especially in the lean mixture. The partial-burn ratio decreased after hydrogen addition. Furthermore, the excess air ratio corresponded the lowest partial-burn ratio was getting bigger, reflecting the addition of hydrogen can improve the lean-burn ability and reduce misfire cycles.

3. Hydrogen addition to natural gas will extend the lean limited of combustion, which enhanced the toleration to residual gas dilution at idle. The fuel consumption ratio had a strong relationship with COV in IMEP. The improvement of idle stability always decreased the fuel consumption.

4. The available data led to a concluding that the most suitable lambda were 1.05, 1.15, and 1.25, while the hydrogen fraction was lower than 30%, 30%, and above 30%, respectively.

5. CH_4 emission decreased as the ignition timing retarded. The maximum CO emission occurred closely at ignition timing 20°, and retarding or advancing would reduce CO emission. NOx emission was relatively low at idle compared to other emission. Adding hydrogen combined with retarding ignition timing was an effective way to reduce idle emission.

6. The COV in IMEP was smoother versus ignition timing after hydrogen addition, which is useful at idle because small idle speed error was adjusted by ignition timing in many electric idle control units.

7. For a specific ignition timing, the 10%−90% burn duration decreased with the increased of hydrogen fraction.

On the whole, the addition of hydrogen up to 50% seems to be desirable to enhance stability and reduce emission with CNG at idle in this article. Because of low levels of NOx emission and knock at idle, the more hydrogen added, the better stability and emission theoretically. In future study, experiments can be made with higher hydrogen fraction.

Acknowledgment. This study was supported by the National 863 Project for new energy vehicle (2006AA11A1B7). The author wants to acknowledge all the teachers and students in the research group for their help with the experiment and their great advice for the preparation of the manuscript.

EF7006485