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Performance Enhancement and NO_x Reduction in a Hydrogen-Fueled Engine with External Injection by Using VVT

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VVT 사용에 의한 흡기관 분사식 수소기관의 성능 향상 및 NO_x 감소

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ABSTRACT

수소 기관에서 역화없이 고성능과 저NO_x를 실현시기키 위하여 밸브 타이밍 변화에 따른 흡기관 분사식 수소 기관의 성능을 파악하고 가솔린의 경우와 비교하였다.

그 결과 흡기밸브 타이밍은 역화억제와 성능향상에 큰 영향을 미치는 것을 확인하였다. 흡기밸브 타이밍의 진각은 역화를 억제하며 효율과 출력을 동시에 향상된다. 비록 흡기밸브 타이밍 변화에 의해 NOx는 증가하지만, 희박영역인 Φ =0.5에서 현저히 감소된다. 또한 열효율은 Φ=0.5, 토크는 Φ =1.0에서 가장 높게 나타난다. 흡기밸브 타이밍을 ATDC20°에서 TDC로 변화시켰을 때, Φ =1.0에서 토크는 약 28%증가되고, Φ =0.5에서 효율은 약 7%향상된다.

KEY WORDS : Hydrogen-fueled engine with external injection(흡기관 분사식 수소기관), Variable valve timing(밸브타이밍 변화), Backfire limit equivalence ratio(역화한계 당량비), NO_x emission(NO_x 배출가스), Backfire(역화), EGR(배기가스재순환)

1. Introduction

Hydrogen-fueled engines with external mixture formation offer potentially high efficiency because of a more homogeneous inlet mixture, simplicity of structure, and avoidance of high-pressure fuel injection system. However, such engines have the demerits of significant lower power output and higher NO_x emissions compared with gasoline engines and backfire[1,2]. To put such engines with the high performances and without backfire into practical use, the occurrence of backfire, the low power and NO_x emissions are the most important problems to

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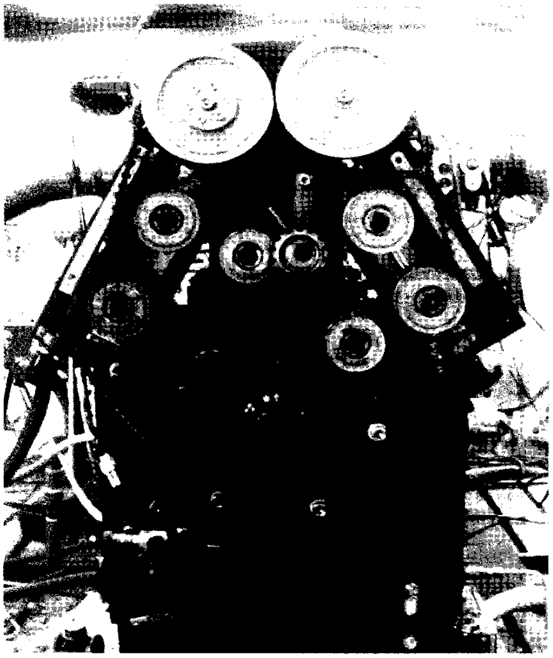

Fig. 1 MCVVT H_2 engine

solve. The reduction of NO_x emissions in such engines using the effects of EGR (exhaust gas recirculation)[3] and water injection in the inlet system[4] were studied. However, the increasing combustion instability for high EGR rate and many adverse effects may be the limits in practical use. The change of valve overlap period seems to be a proper way to reduce NO_x emissions (by decreasing the combustion temperature) and to control backfire in hydrogen engines[1,5].

The potential issues of hydrogen-fueled engine with external injection for high power high efficiency, and low NO_x emissions, however, were not demonstrated for change of valve timings.

In this paper, backfire characteristics, engine performance, and NO_x emissions are investigated by changing the valve timings. A MCVVT (Mechanical Continuous Variable Valve Timing) system which permits a wide range of valve timing to be continuously varied during firing is used in experiments[5]. The utilities of variable valve timing and fuel-air equivalence ratio are evaluated for engine brake torque and thermal efficiency. The changing rate of NO_x emissions for hydrogen operation is qualitatively compared to gasoline by changing EVC timing and spark timing in the same engine.

2. Experiments and Methods

2.1 Experimental apparatus

2.1.1 The tested engine

Fig. 1 is a photo of the single cylinder research hydrogen-fueled engine with external injection installed the MCVVT system. The tested engine is a 4-stroke DOHC engine with displacement of 500cc. Both bore and stroke of the piston are 86 mm. Compression ratio is 10.5:1. The base engine has the valve timings as follows: IVO (intake valve opening) / IVC (intake valve closing) are 10BTDC (before top dead center) / 67ABDC (after bottom dead center) while EVO (exhaust valve opening) / EVC (exhaust valve closing) are 34BBDC (before bottom dead center) / 10ATDC (after top dead center), respectively.

A distributor type to prevent abnormal discharge and a separate water-cooled type were respectively used for the ignition system and the cooling system. The engine cylinder head, the crank mechanism, and the combustion chamber are specially modified from commercial engine parts.

The fuel supply system is properly modified to operate on hydrogen and gasoline fuels for the same base engine. Hydrogen gas (12 - 15

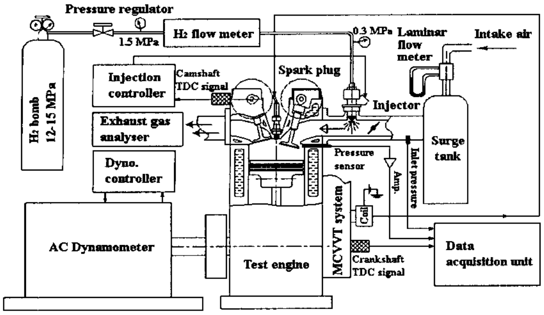

Fig. 2 Experimental apparatus

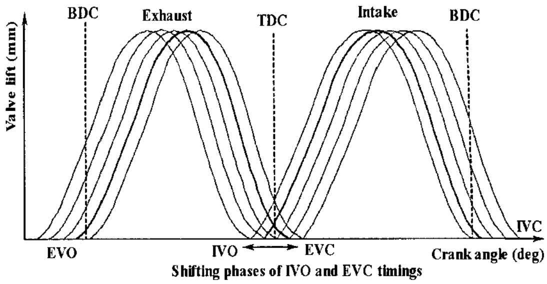

Fig. 3 Schematic diagram of valve timing

MPa) in the commercial high-pressure bomb is decompressed to 0.3 MPa by a two precise regulators. Hydrogen gas is then injected into the intake port by using a low pressure gas injector. Injection timing and injection duration can be adjusted by an electronic injection control system. In case of gasoline operation, a conventional carburetor is used, the fuel-air equivalence ratio is obtained by a fuel controlling needle installed inside carburetor.

2.1.2 Experimental setup

An experimental setup is composed of the MCVVT hydrogen-fueled engine, the AC dynamometer, the engine accessaries part, and the data acquisition system. The schematic diagram of the experimental setup is shown in Fig. 2. Air flow rate and hydrogen flow rate are measured by an orifice and a hydrogen mass flow controller (MFC/MFM Manager, FM-30V4), respectively. In-cylinder pressure is obtained by using a piezo-electric transducer (Kistler 6061-B) inserted in the cylinder head. Coolant temperature is fixed about 70°C for cylinder head and cylinder block, separately. NO_X emissions are measured by an automotive emission gas analyzer (Horiba Mexa-554JK) with range of 0-5000ppm.

2.2 Experimental methods

The main experimental variables are the change of IVO and EVC. Measuring points are set at the vicinity of intake TDC from 20BTDC to 20ATDC for both IVO timing and EVC timing by a step of 10 degrees crank angle (CA). Those are totally 25 points and represented in Fig. 3.

At each point, NO_X emissions and engine torque are measured with varying fuel-air equivalence ratio from a lean mixture ratio of 0.3 (ϕ = 0.3) to a BFL (backfire limit) equivalence ratio by step = 0.1. Here, BFL equivalence ratio is defined as the maximum fuel-air equivalence ratio before backfire occurs. Experiments are conducted at a fixed engine speed of 1600rpm for wide-open throttle (WOT), and minimum spark advance for the best torque (MBT). To evaluate the behavior of NO_X emissions and engine performance as the function of fuel-air equivalence ratio, spark timing, and EVC timing, the positions of IVO timings at TDC, 10ATDC, and 20ATDC with a base EVC timing at 10ATDC are employed.

3. Results and Discussions

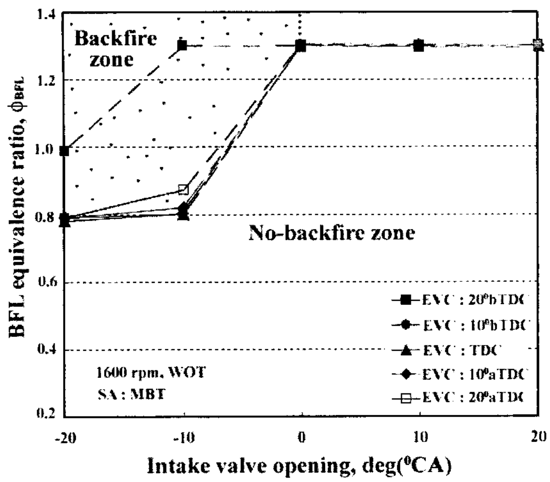

Fig. 4 Backfire limit equivalence ratio as a function of IVO timing

3.1 Backfire prevention by changing the valve timings

Fig. 4 shows the variation of backfire limit (BFL) equivalence ratio as a function of IVO for each EVC. In the figure, backfire occurs in the region above each curve (backfire zone). Hence, it could be controlled by limiting operation to equivalence ratio below the BFL values for each IVO. BFL equivalence ratio increases when the IVO retards from 20BTDC to 20ATDC.

Especially, retarding IVO from TDC to 20ATDC position allows increasing remarkably BFL equivalence ratio up to 1.0 or more. This is mainly caused by the reduction of intake period[5]. The results implied that changing in the IVO timing could be employed to avoid the occurrence of backfire effectively and the IVO timing is the main prevention factor for method of preventing backfire. Consequently, methods to increase the engine performances without backfire by controlling the IVO timings will be examined and analyzed.

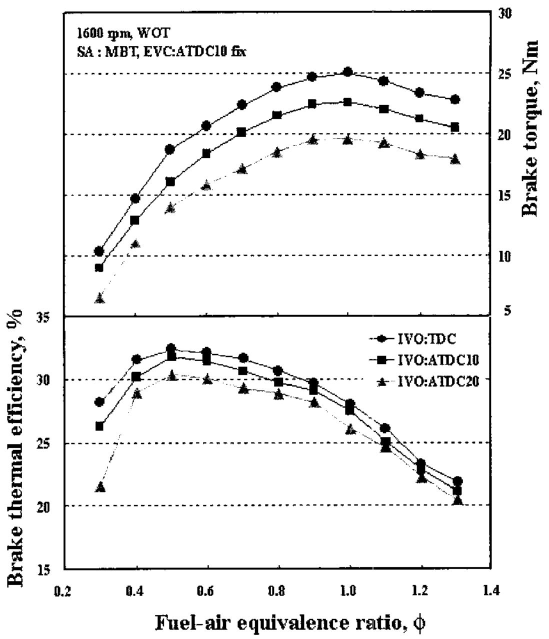

Fig. 5 Variation of brake torque and brake thermal efficiency as the functions of equivalence ratio

3.2 Enhancement of performance

To quantify these mentioned tendency, Fig. 5 presents the brake torques and the brake thermal efficiencies (BTE) as the functions of fuel-air equivalence ratio when EVC timing is fixed at 10ATDC and IVO timing advances from 20ATDC to TDC.

The maximum brake torques are observed at ϕ = 1.0 while the peak values of brake thermal efficiencies (BTE) are found at around ϕ = 0.5. The reason for the maximum torques is affected by increase of supply energy. The maximum BTE are contributed by the reduced cooling loss resulted from low combustion temperature with lean operation.

Observation of the results in Fig. 5, the advancement of IVO timing has affected greatly to enhance engine torque and efficiency at these optimum equivalence ratios. The expansion of IVO timing from after TDC to TDC (where backfire did not occur) has resulted in the large increase of inertial force and momentum of fresh charge and hence volumetric efficiency. As a result of these, the engine power and efficiency are improved. For example, when IVO advances from 20ATDC to TDC, the brake torques enhances by 28% at ϕ = 1.0. Meanwhile, about 7% of BTE is increased at ϕ = 0.5 due to the increasing rate of brake torque is low (5%). Compared with at ϕ = 0.5, the brake torques for IVO timing at TDC and EVC timing at 10ATDC for ϕ = 1.0 is approximately 70% higher, but about 13% lower in BTEs. The above results confirmed that the engine performances could be increased (without backfire) by controlling IVO timings.

3.3 Reduction of NO_x emissions

The change of IVO timing increased engine torques and hence the gas temperature in cylinder. This may lead to increase the NO_x emissions.

Fig. 6 indicates the variation of NO_x emissions with change of fuel-air equivalence ratio. For each IVO timing, NO_x emissions are almost negligible up to the equivalence ratio of about 0.5 due to low combustion temperature. When the equivalence ratio increases above this value (ϕ = 0.6 - 0.8), the NO_x emission was observed to be rising up owing to the increased pressure and temperature resulted from larger supply energy. A peak value (e.g., around 4000 ppm for IVO timing at TDC) of NO_x emissions is around at equivalence ratio of 0.8. While approaching stoichiometric equivalence ratio or richer, NO_x emissions drops down significantly because of the lack of oxygen.

The peak NO_x levels for hydrogen-fueled engine occur at a leaner mixture ratio (ϕ = 0.8) compared to a mixture ratio where has the maximum flame temperatures (ϕ = 0.9). This is mainly because of the dissociation of NO formed due to very high temperatures after the equivalence ratio of 0.8 resulting in the drastic reduction of NO near stoichiometric ratio. The similar tendencies of these results were reported by some researchers[3,4,6].

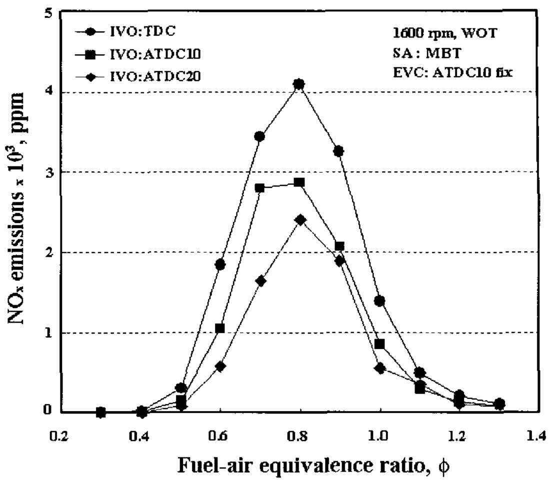

Fig. 6 NO_x emissions as a function of equivalence ratio

When IVO advances from 20ATDC to TDC while EVC is fixed at 10ATDC, the amounts of NO_x emissions increase remarkably for every equivalence ratio. For example, the NO_x levels for IVO at TDC is about 3 and 2.5 times higher than those of IVO at 20ATDC for ϕ = 0.5 and ϕ =1.0, respectively. At ϕ =0.8, the rate is 1.7 times higher for IVO at TDC. The reason of these results is attributed by the change of flow pattern and charge efficiency with the advancement of IVO.

As clearly indicated in figure, the NO_x levels at ϕ = 0.5 is insignificant when compared to those of ϕ = 0.8, where is the peak point of NO_x emissions. Under the operating conditions, the

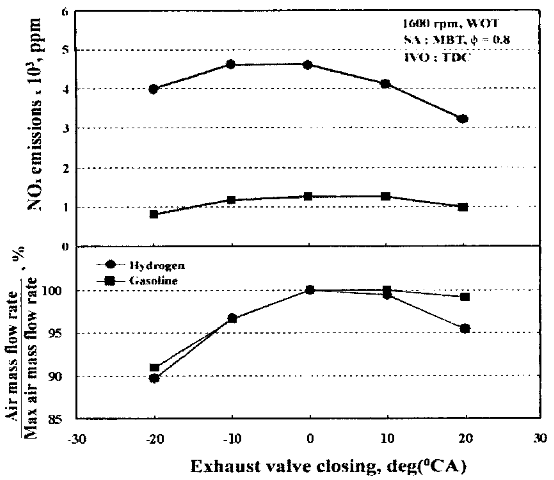

Fig. 7 Variation of NOx emissions and air mass flow rate as functions of EVC timing

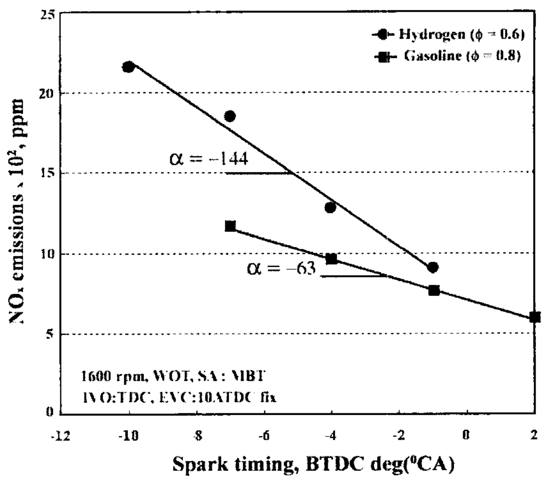

Fig. 8 Behavior of NO_x emissions as a function of spark timing

averaged NO_x reduction is about 94% when equivalence ratio decreases from 0.8 to 0.5. When increasing equivalence ratio from 0.8 to 1.0 or more, the level of NO_x reduction is remarkable. This depicts that decrease of NO_x emissions is possible at the rich mixture regions.

To avoid backfire and enable to operate under a high equivalence ratio of 0.8, IVO timing is fixed at TDC. Fig. 7 shows the variation of NO_x emissions and the rate of air mass flow with the change of EVC timing. Here, the rate of air mass flow is defined as ratio (in %) of an arbitrary air mass flow rate to maximum air mass flow rate.

As shown in the figure, the level of NO_x emissions for both fuels has a similarly reducing tendency when EVC timing advances or retards around TDC. This is because the gas temperature decreased by the increase of residual gases with reduction of air mass flow rate. Further, the decreasing rate of NO_x emissions of hydrogen operation is bigger than that of gasoline. This is owing to higher in increasing rate of residual gases of hydrogen operation compared with that of gasoline (for the same equivalence ratio).

All the values of NO_x emissions for hydrogen engine show clearly to be higher than those of gasoline under the change of EVC. When EVC is at TDC, the level of NO_x emissions of hydrogen engine is approximately 3.5 times higher when comparing to gasoline. This is mainly attributed by the much higher peak cylinder temperature for hydrogen when comparing with gasoline at $\phi = 0.8$. This results implies that the effect of EVC on NO_x reduction for hydrogen engine is more effective than gasoline.

Fig. 8 demonstrates the influence of spark timings on the decrease of NO_x emissions for hydrogen and gasoline operation. Due to knock limits with variation of spark timings, the hydrogen engine is operated at a equivalence ratio of around 0.6 while gasoline engine is about 0.8. Retarding SA results in reduction of NO_x emission for both fuels due to decrease of clearance volume in cylinder and hence peak gas temperature.

The reducing rate of hydrogen engine is higher compared with that of gasoline. As showed in figure, the correlated tangent factor (α) of NO_x to spark timing in hydrogen operation is around minus 144 and about 2 times higher than that in gasoline. The reason is contributed by the much larger reduction in peak cylinder temperature with retardation of spark timing for hydrogen engine than that for gasoline. This result exposes that the retardation of SA is also effective method to reduce NO_x in hydrogen-fueled engine with external injection.

The results obtained exposes that H_2 engine with high performances and without backfire and the low NO_x levels could be obtained through the change of valve timings and lean operation, but a careful selection of optimized operating conditions compromising between NO_x emissions and performances is really needed.

4. Conclusion

The goals of work are to study the effects of variable valve timing with the potential to prevent backfire, to enhance engine performances, and to reduce NO_x emissions in a hydrogen-fueled engine with external injection. The results obtained reveal that:

1) The IVO timing is the main prevention factor for method of controlling backfire even under high load conditions. The backfire did not occur as IVO timings are retarded after TDC.
2) The engine torques and efficiencies are optimized at the equivalence ratios of 1.0 and 0.5, respectively. The change of IVO timing at ϕ = 1.0 has more significant effect on NO_x reduction and performance enhancement than that at ϕ = 0.5.
3) Although NO_x emissions were increased with the advancement of intake valve opening timing, the NO_x emissions could be limited by lean operation at ϕ = 0.5.
4) The lean operation and retardation of spark timing offer a remarkable reduction in NO_x emissions for hydrogen and gasoline engines at IVO timing at TDC and EVC timing at 10ATDC. The reduction of NO_x emissions by spark timings is more effective for H_2 engine than gasoline engine.

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