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Feasibility of Backfire Control and Engine Performance with Different Valve Overlap Period of Hydrogen-Fueled Engine with External Mixture

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흡기관 분사식 수소기관의 밸브오버랩 기간 변화에 따른 기관성능과 역화억제 가능성

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ABSTRACT

고효율의 실현이 가능한 흡기관 분사식 수소기관의 역화 억제 가능성을 파악하고자 밸브 오버랩 기간의 변화에 따른 제반 기관성능과 역화가 발생되는 역화한계 당량비를 실험적으로 해석하였다. 실험에는 기계식 연속 가변밸브 타이밍 시스템이 부착된 연구용 수소기관을 사용하였다. 밸브 오버랩기간은 배기밸브 개폐시기를 고정하고 흡기밸브 캠의 위상각을 조절하여 변화시켰다.

해석결과 밸브 오버랩 기간의 감소에 따른 제반기관성능은 통상의 기관과 유사하지만 역화한계 당량비가 확장되어 초기 단계이지만 수소기관의 역화발생에 밸브오버랩 기간이 관여하는 것이 보였다. 기관회전수 1600 rpm, WOT의 실험 조건에서 밸브 오버랩 기간을 20°CA에서 0°CA로 감소시킨 경우 역화한계당량비는 약 45% 정도 확장되고 정미 토크는 16% 감소했다.

KEY WORDS : hydrogen fueled engine with external mixture(흡기관 분사식 수소기관), mechanical continuous variable valve timing(기계식 연속 가변 밸브 타이밍), backfire limit equivalence ratio(역화한계당량비), valve overlap period(밸브 오버랩 기간), performance characteristics(성능특성)

1. Introduction

The combustion characteristics of hydrogen such as wide flammability limit, fast burning velocity, and low ignition energy[1,2] enable a stable engine operation which results in high thermal efficiency and low NOx emission level, but backfire still occurs at higher load conditions. Hence in order to

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Table 1 Specifications of test engine

Item	Specifications
Combustion chamber	Pent-roof
Valve mechanism	DOHC
Bore×Stroke, mm	86×86
Compression ratio	10.5
Cam phase control	MCVVT system
Original valve timing :	
- Intake valve opening	10° CA BTC
- Intake valve closing	67° CA ABC
- Exhaust valve opening	34° CA BBC
- Exhaust valve closing	10° CA ATC

put hydrogen-fueled engine with external mixture into the practice use, the countermeasure of backfire control is an important problem. Backfire phenomenon is well known as H_2-air mixture in intake pipe is burned by backflow of fast flame which is pre-ignited due to unknown ignition source in the combustion chamber during valve overlap period.

By considering the above backfire phenomenon, the decrease of the ignition source's temperature and burning velocity by using cooling approaches and/or lean burn techniques is considered to prevent backfire in a H_2 engine with external mixture by many researchers[3-9]. However, the distinct methods for preventing backfire are not established. It seems difficult to control the unknown ignition source and the rapid burning velocity. In case that valve overlap period is reduced, however, backfire will be avoided by the fact that the pre-ignited flame cannot flow backward into intake system.

In order to prove the feasibility of backfire control by the reduction of valve overlap period, first, a single-cylinder research engine with a mechanical continuous variable valve timing system (MCVVT) which a wide range of valve overlap period can be continuously varied during the engine operation, has been developed by authors[10-12].

In this investigation, overall engine performance and improvement of backfire limit equivalence ratio are analyzed and evaluated to realize high power H_2 engine with external mixture.

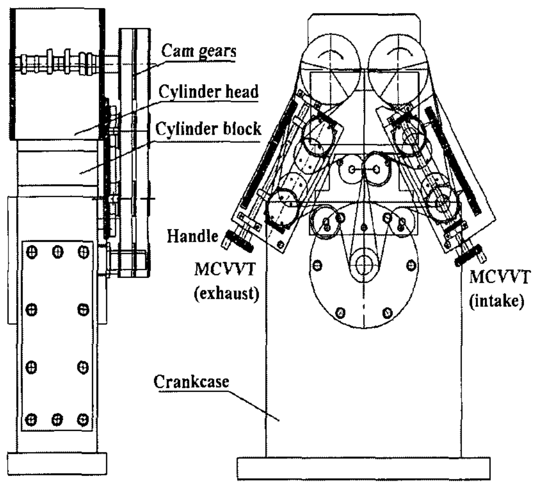

Fig. 1 Configuration of hydrogen-fueled engine with external mixture and MCVVT system

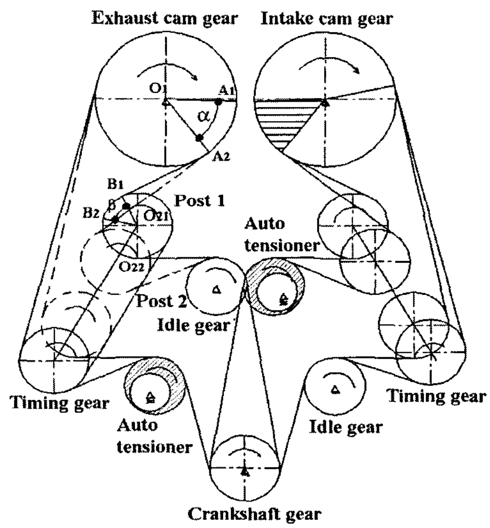

Fig. 2 Schematic diagram of MCVVT system

2. Experiments and methods

2.1. Hydrogen-Fueled Engine and MCVVT System

The test engine used is a single-cylinder four-stroke SI hydrogen-fueled engine, which is converted from a 2.0 L DOHC commercial engine. Fig. 1 shows the configuration of the H_2 engine with external mixture and the mechanical variable valve timing system. Flat-head piston is used to form the pent-proof combustion chamber, and compression ratio is fixed at 10.5 : 1. Engine specifications are shown in Table 1.

A detailed structure of MCVVT system that is able to control intake/exhaust valve timings independently is shown in Fig. 2. The fundamental principle of MCVVT system[10-12] is that the angle of intake/exhaust cam gear (α) is varied (advanced or retarded) by change of the angle of timing gear (β) as timing gear moves from post 1 to post 2 in figure.

2.2. Experimental setup

Schematic diagram of experimental setup presented in Fig. 3 consists of hydrogen-fueled engine, AC dynamometer, hydrogen gas supply system, cooling system, lubricant system, and data acquisition system. Hydrogen gas charged by 12-15 MPa in the commercial high-pressure bomb is decompressed to 1.5 MPa by a pressure regulator and is controlled to 0.3 MPa by a secondary precise regulator installed in front of the H_2 mass flow meter. Hydrogen gas was then injected to intake port by using a CNG injector. Injection timing and injection duration can be adjusted by the injector control system. Airflow rate and hydrogen flow rate are measured by an orifice and a H_2 mass flow controller(MFC/MFM Manager, FM-30V4). In-cylinder pressure is monitored using a piezoelectric transducer(Kistler 6061-B) inserted in the cylinder head. For detecting inlet and exhaust pipe pressures, two piezo-resistive types(Kistler 4045A-1 MPa and 0.5 MPa) are utilized. Coolant water is supplied to a modified cylinder head and a block, separately. The coolant temperature is controlled by coolant flow valve at outlet and fixed at 70℃. The measured data is stored in data recorder.

2.3. Experimental methods

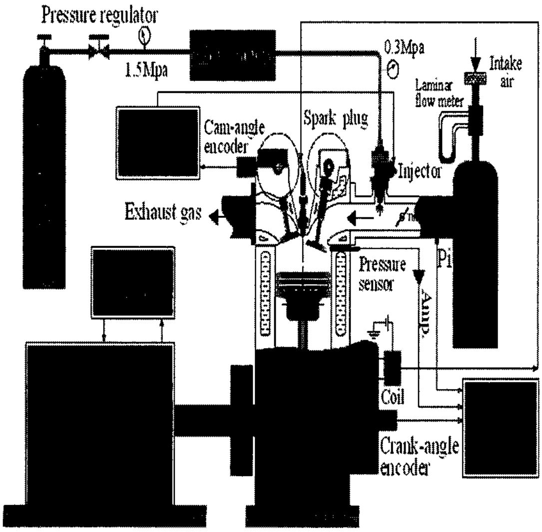

Fig. 3 Schematic diagram of experimental setup

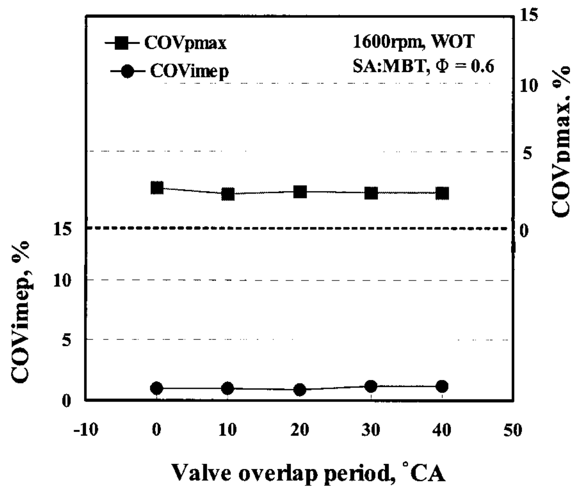

Fig. 4 Variation of COVimep and COVpmax as a function of various valve overlap period at ϕ=0.6, 1600 rpm, WOT

The experimental variables is valve overlap period(0°, 10°, 20°, 30°, 40°, and 50°CA, and respectively labeled as VOP0, VOP10, VOP20, VOP30, VOP40, VOP50). Valve overlap period is analogically varied by changing cam phase angle of intake valve while exhaust valve timing is fixed. For each VOP, fuel/air equivalence ratio is varied from a lean limit of 0.25(ϕ=0.25) at which stable operation was ensured to a rich limit in which backfire was detected. All experiments are carried out at a fixed engine speed of 1600 rpm, a wide-open throttle, and MBT(Maximum Brake Torque) conditions.

3. Results and Discussion

3.1. Performance Characteristics with Valve Overlap Period

The coefficient of variations in indicated mean effective pressure(COVimep) and in maximum cylinder pressure(COVpmax) as a function of VOP at constant fuel/air equivalence ratio are indicated in Fig. 4. It comes clearly out of this figure that at 1600 rpm, WOT, and ϕ=0.6, beyond VOP between 0 and 40°CA, COVimep and COVpmax of all VOP are less than 5% which means all engine operating conditions under the high drive-ability.

One possible explanation for above results is that there is the good mixing of the injected hydrogen and the intake air in the intake system. Enhancement of mixing rate results in stable combustion of hydrogen due to the fast burning velocity and good ignitability of hydrogen engine. Also the shorter flame development angle is, the lower COV becomes as COV is mainly affected by flame development angle and then the more stable operation may accomplish. These effects were also reported by some researchers[7,8].

Fig. 5 shows volumetric efficiency versus valve overlap period for each fuel/air equivalence ratio at 1600 rpm, WOT, and MBT.

As indicated in figure, the volumetric efficiency improves with increase of VOP except decreasing at VOP50. Besides, as volumetric efficiency is decreased with the increasing of fuel/air

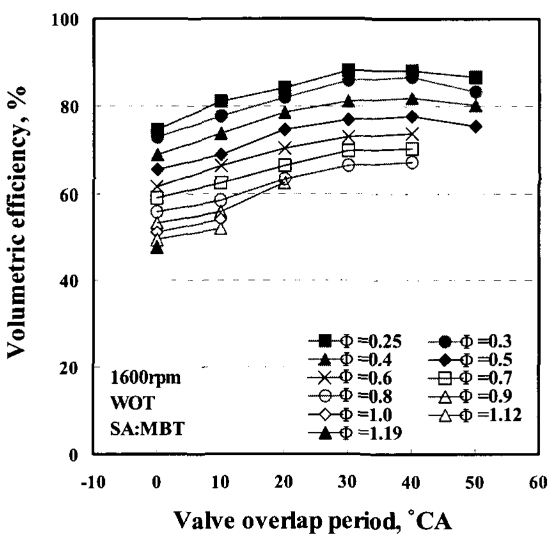

Fig. 5 Volumetric efficiency versus VOP for various fuel/air equivalence ratio

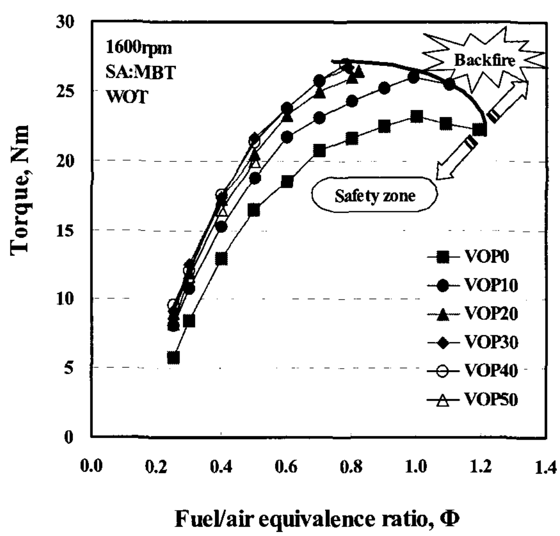

Fig. 6 Effect of fuel/air equivalence ratio on brake torque for each VOP

equivalence ratio for a given valve overlap period. The tendency of results agrees with those reported by previous researches[9-11].

Fig. 6 shows the variation of brake torque with fuel/air equivalence ratio at 1600 rpm, MTB, and WOT for various valve overlap period. This figure shows the increasing tendency of brake torque with increase of valve overlap period.

For a given valve overlap period, increasing the fuel/air equivalence ratio resulted in a proportional increase in brake torque due to increased supply energy. Also for VOP0 and VOP10, as fuel/air equivalence ratio is over 1.0 the brake torque show the decreasing tendency. It is further suspected that for the hydrogen engine using premixed charged or external mixture formation, as fuel/air equivalence ratio becomes rich, less air is usually inducted by the injection of hydrogen in intake pipe and hence less oxygen into the engine cylinder resulting in incomplete combustion and a loss of brake torque.

Additionally the other important observation that the distinct line of the safety operation zone and the zone of backfire occurrence for all valve overlap periods indicates the line of the backfire limit equivalence ratios. Generally it is found that the value of backfire limit equivalence ratio is increased with the decrease of valve overlap period. The tendency will be explained in section 3.3.

3.2. Combustion characteristics

The experimental results of in-cylinder pressure, and mass fraction burned rate versus crank angle are indicated in Fig. 7 and Fig. 8, respectively. Here, the experimental condition is engine speed=1600 rpm, ϕ=0.6, WOT and MBT. The mass fraction burned rate is obtained from the data of in-cylinder pressure shown in Fig. 7. The figure shows that the general shape of the mass fraction burned rate is similar. This shows that no major difference exist between the combustion phenomena of various VOP at constant fuel/air equivalence ratio and constant spark timing.

Only the different in the beginning and late stages of flame-development makes their shape

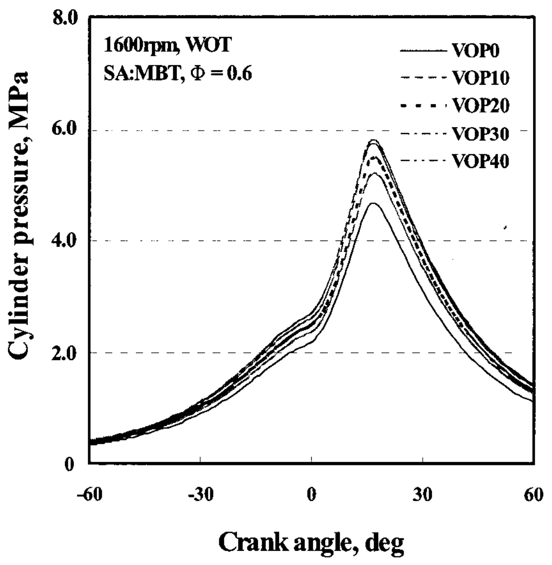

Fig. 7 Traces of cylinder pressure versus crank angle for various VOP

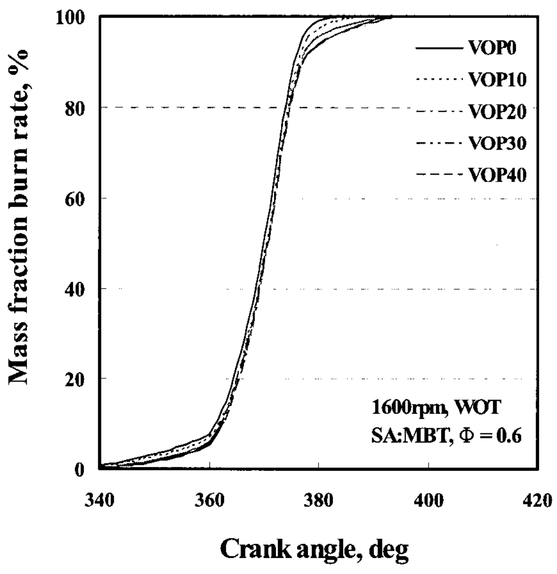

Fig. 8 Mass fraction burned rate versus crank angle for various VOP at ϕ=0.6

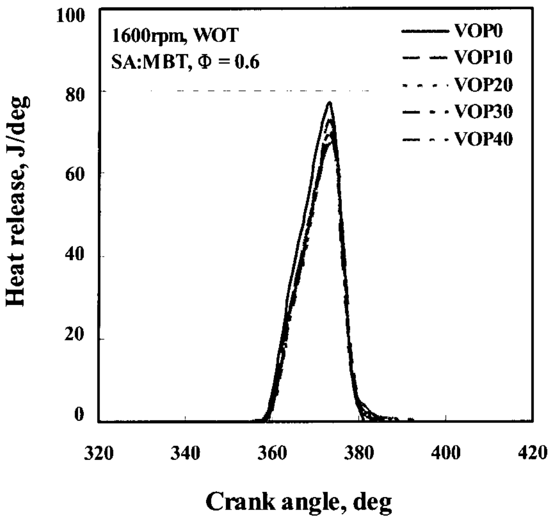

Fig. 9 Rate of heat release versus crank angle for various VOP at ϕ=0.6

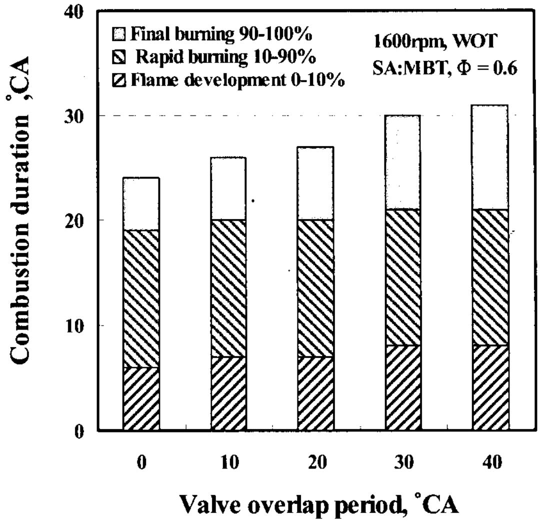

Fig. 10 Combustion duration with respect to various VOP at ϕ =0.6

and total heat release different. As indicated in Fig. 7, the maximum pressure of cycle is the highest with VOP40 case. Under the same condition, the difference of maximum pressure depends on the ignition delay and the homogeneity of mixture. The spark timing adjusted for all VOPs is around 7°CA BTC. It seems that this phenomenon results from the higher compression temperature and pressure and more homogeneous fuel/air mixture as VOP increases The relation between variation in combustion rate and variation in cylinder pressure is very complex. Also it changes in the shape and magnitude of the heat-release rate profile affects the pressure. As far as VOP increases, the intake air is increased and thus the rate of heat release becomes larger, then longer the combustion duration are attained respectively. These tendencies are verified in Fig. 9 and Fig. 10.

3.3. Extension of Backfire Limit Equivalence Ratio

Fig. 11 shows brake mean effective pressure and BFL equivalence ratio versus valve overlap period. With MCVVT system, it shows the increasing tendency of backfire limit equivalence ratio according to the decrease of valve overlap period. As shown in figure, backfire limit equivalence ratio improves from 0.82 to 1.19 or about 45% of enhancement when valve overlap period changes from VOP20 to VOP0. However, brake torque is reduced. The figure clearly shows that BMEP at VOP0 is 0.11 MPa lower than that of VOP20. It means that the valve overlap period strongly affects the backfire occurrence. This reason may be that enough fresh charge is not allowed to enter the cylinder under experimental condition. Particularly, at VOP50, the values of torque and fuel/air equivalence ratio are significantly decreased. Also, backfire limit equivalence ratio and BMEP of VOP50 is 39% and 24.5% lower than that of VOP20, respectively. It may be that volumetric efficiency decreases by the presence of hydrogen gas in the intake pipe and valve overlap period is absurdly large.

As above-mentioned, it clearly indicates that in the shorter valve overlap period the impossibility of backfire occurrence may be attained by the decrease

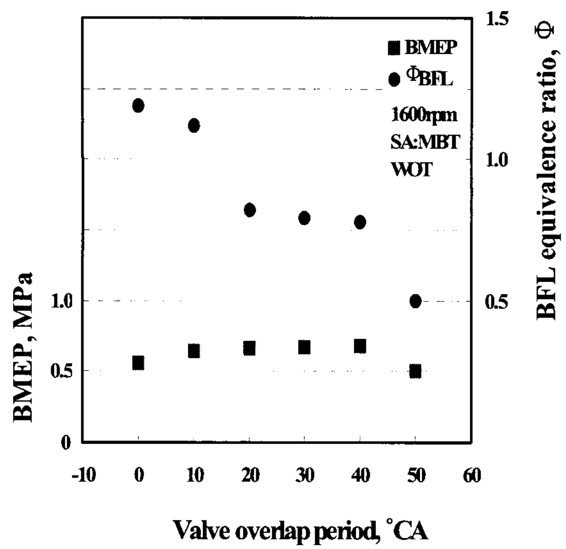

Fig. 11 Variation of BMEP versus VOP for various fuel/air equivalence ratio

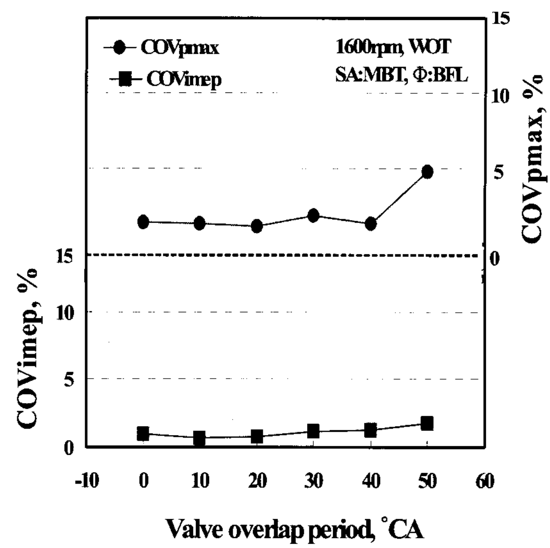

Fig. 12 COVimep and COVpmax with respect to valve overlap period at 1600 rpm, WOT, MBT, and ϕBFL

of the available supplied energy. It is thought that the reason of this effect is the decreasing tendency of combustion chamber's temperature with decrease of valve overlap period. Hence backfire phenomenon may be respectively avoided.

It is requested that the feasibility of extension of backfire limit equivalence ratio must be confirmed by the stability of engine operation. Hence the variation of COVimep and COVpmax under different valve overlap period at backfire limit equivalence ratio are estimated and presented in Fig.12. This figure indicates that all engine operating conditions at backfire limit equivalence ratio giving the COVimep and COVpmax as low as 5%. As discussed earlier in Fig. 4 the same explanation is valid for this case.

A precautionary measure was taken to eliminate the possibility of backfire control by the variation of valve overlap period. In the present works, it is doubted that the improvement of backfire limit equivalence ratio is attained by the decrease of supplied energy. Hence it is necessary to study in more detail the effects of VOP on backfire occurrence when supplied energy maintains constantly under various valve overlap period in order to develop better performance of hydrogen-fueled engine with external mixture.

4. Conclusion

It has been evident that an appropriately designed MCVVT system ensures successful operation of a hydrogen-fueled engine with external mixture over a wide range of loads and valve overlap periods without causing any undesirable combustion phenomenon. In summary,

1) Accordance to the variation of valve overlap period, the behavior of the basic qualitative performances of the test engine is similar to conventional engines but quantitative results have a little difference.
2) Backfire limit equivalence ratio increases significantly with decrease of valve overlap period. Backfire limit equivalence ratio with VOP0 is estimated to be 1.45 times higher than

that of VOP20 and brake torque is about 0.11 MPa less than respectively. However, brake torque or power output is limited by lower supplied energy due to reduction in volumetric efficiency.

3) Under above experimental conditions, the engine combustion process is stable as coefficient of variations in IMEP and in maximum pressure are less than 5%.

4) The increase of backfire limit equivalence ratio with the decreasing tendency of valve overlap period is analyzed by the diminution of supplied energy and the temperature of combustion chamber. Thus further investigation is required in case of the same supplied energy for better performance characteristics and enhancement of the overall fuel economy of hydrogen powered vehicles.

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