FEASIBILITY OF BACKFIRE CONTROL AND PERFORMANCE USING CHANGES OF VALVE OVERLAP PERIOD FOR A HYDROGEN-FUELED ENGINE WITH EXTERNAL MIXTURE

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ABSTRACT: *The development of a hydrogen-fueled engine using an external mixture (e.g., using port injection) with high efficiency and high power is dependent on the control of backfire. This work has developed a method to control backfire by reducing the valve overlap period. For this goal, a single-cylinder hydrogen-fueled research engine with a mechanical continuous variable valve timing (MCVVT) system was developed. This facility provides a wide range of valve overlap periods that can be continuously and independently varied during firing operation. In experiments, the behavior of backfire occurrence and engine performance are determined as functions of the valve overlap period for fuel-air equivalence ratios between 0.25 and 1.2. The results showed that the research engine with the MCVVT system has similar performance to a conventional engine, and is especially effective in controlling the valve overlap period. The obtained results demonstrate that decreasing the valve overlap period may be one of the methods for controlling backfire in a H_2 engine. Also, a method for compensating performance loss due to shortened valve overlap period is recommended.*

Keywords: *Hydrogen-fueled Engine with External Mixture, MCVVT System, Backfire, Valve Overlap Period, Backfire Limit Equivalence Ratio.*

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 NO_x emission level, but backfire still occurs at higher load conditions. Hence in order to 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 and independently varied during firing 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.

2. EXPERIMENTS AND METHODS

2.1 H_2 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. Flat-head piston is used to form the pent-proof combustion chamber, and compression ratio is fixed at 10.5:1. Bore and stroke are both 86 mm. Cam phasing control is under MCVVT system. The crank mechanism and combustion chamber are modified from conventional engine parts and their specifications are determined to allow for variable compression ratios for later work.

The fundamental principle of MCVVT system was studied by the authors [10-12]. The schematic of MCVVT system that is able to control intake/exhaust valve timings independently is shown in Fig. 2. Valve timing is adjusted by the change of the angle of camshaft (α) as the VVT timing gear moves from position 1 to position 2 in the figure. The belt length between tangential points of belt and timing gear is not changed because when timing gear 1 moves from position 1 to position 2, the timing gear 2 which is installed on the opposite side moves from position 1' to position 2'.

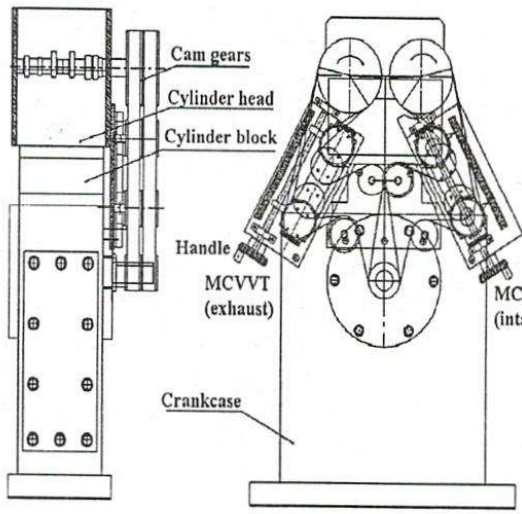

Fig. 1 Structure of the hydrogen-fueled engine

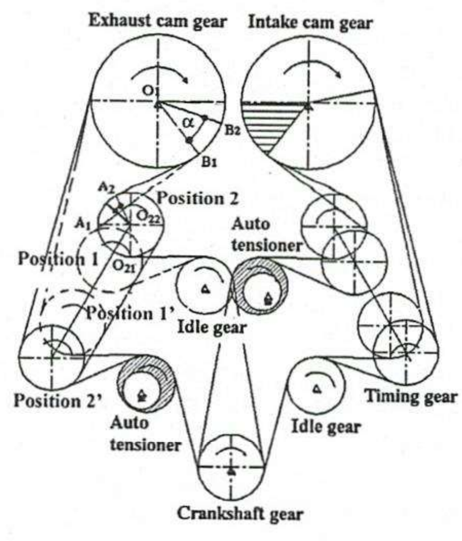

Fig. 2 Schematic diagram of MCVVT system

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.

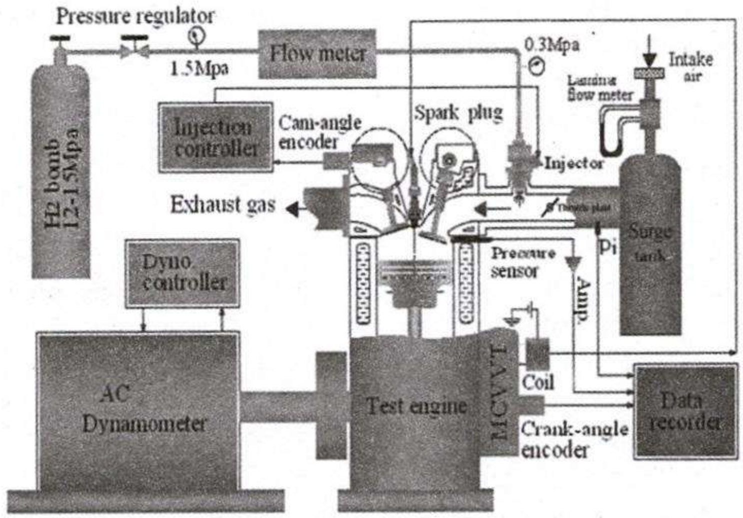

Fig. 3 Schematic diagram of experimental setup

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 was stored in data recorder.

2.3 Experimental methods

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 intake valve opening timing from 10°ATDC to 40°BTDC while exhaust valve closing timing is fixed at 10°ATDC. For each VOP, fuel-air equivalence ratio is varied from a lean limit of 0.25 ($\phi = 0.25$) 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 (WOT), and MBT (Minimum spark timing for Best Torque) conditions.

3. RESULTS AND DISCUSSION

3.1 Performance characteristics with changes of valve overlap period

The coefficient of cyclic 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 H_2 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].

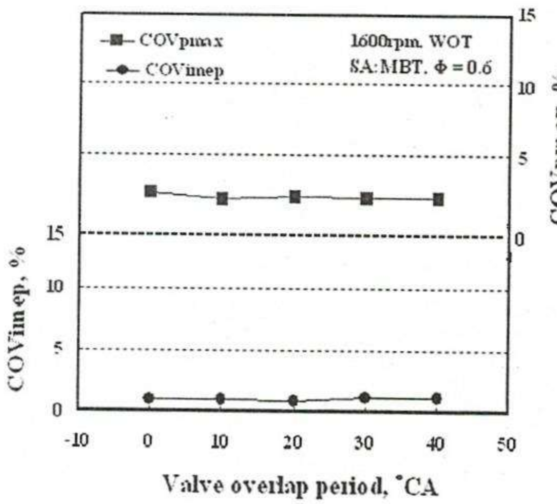

Fig. 4 COVimep and COVpmax versus VOP

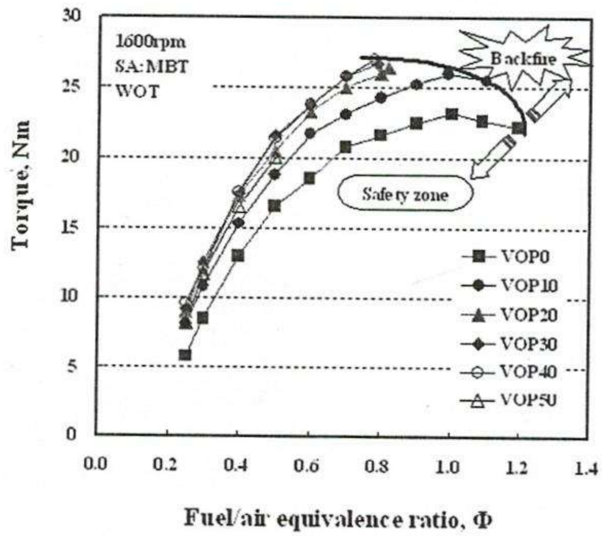

Fig. 5 Brake torque as a function of fuel-air equivalence ratio for each VOP

Figures 5 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. For VOP0 and VOP10, however, as fuel-air equivalence ratio is over 1.0 the brake torque show the decreasing tendency. It is sure that the H_2 engine with premixed charge 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, it is observed 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 Typical combustion characteristics

The obtained results of in-cylinder pressure are indicated in Fig. 6. Here, the experimental condition is engine speed of 1600 rpm, $\phi = 0.6$, WOT and MBT. The maximum peak of cylinder pressure increases with increase of VOP. It is explained that there exists the turbulence of intake flow and the different pattern of the charge flows as VOP is changed. The mass fraction burned rate that is obtained from the data of in-cylinder pressure is 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.

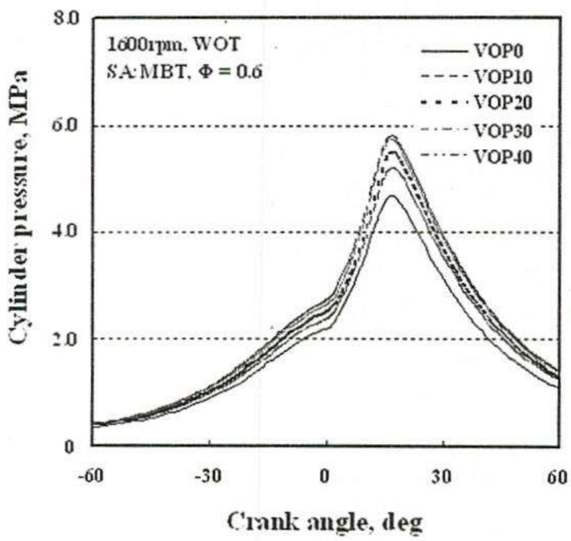

Fig. 6 Cylinder pressure versus crank angle

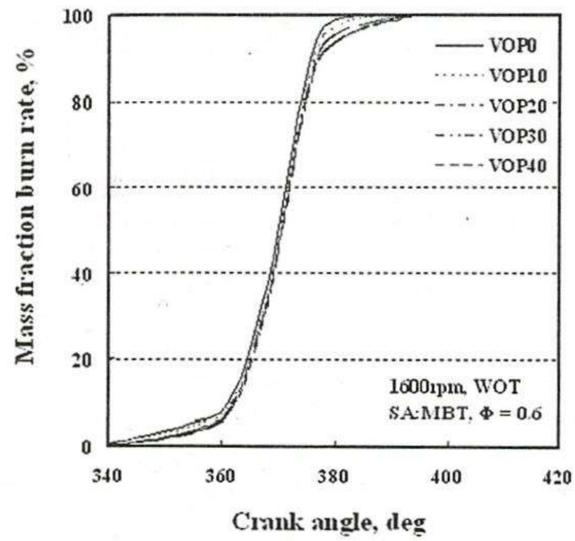

Fig. 7 Mass fraction burned rate versus crank angle

Only the different in the beginning and late stages of flame-development makes their shape and total heat release rate become different. As indicated in Fig. 6, 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 VOP. It seems that this phenomenon results from the higher temperature and pressure of compression process 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 is attained respectively.

3.3 Extension of backfire limit equivalence ratio

Figure 8 shows examples of the pressure curves of in-cylinder and intake pipe when backfire occurs. In the figure, the trace in channel 2 display the in-cylinder pressure curves for normal combustion, for backfire occurrence and for misfiring cycles due to backfires. The trace in channel 3 display the pressure curve for the inlet pipe corresponding to backfire occurrence. This pressure information and the detection of backfire noise are used to estimate whether backfire occurs or not.

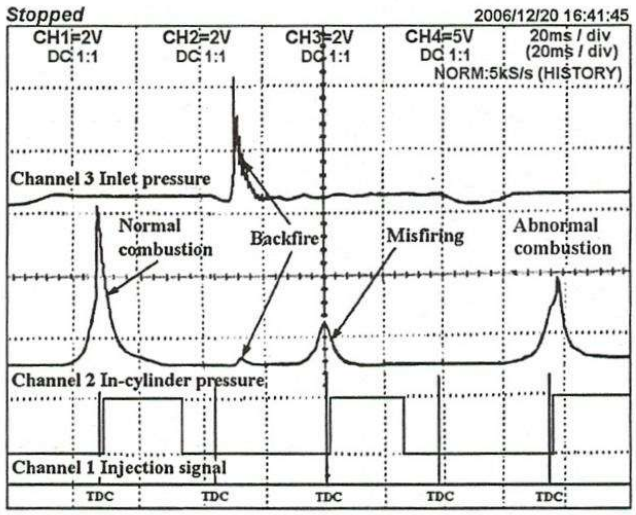

Fig. 8 Examples of backfire occurrence

Figure 9 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 0.79 to 1.19 or about 50% of enhancement when valve overlap period changes from VOP30 to VOP0. However, brake torque is reduced. The figure clearly shows that BMEP at VOP0 is 0.11 MPa lower than that at VOP30. 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, BFL equivalence ratio and BMEP of VOP50 is 37% and 25% lower than that of VOP30, 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 shortened valve overlap period the impossibility of backfire occurrence may be attained by the decrease 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.

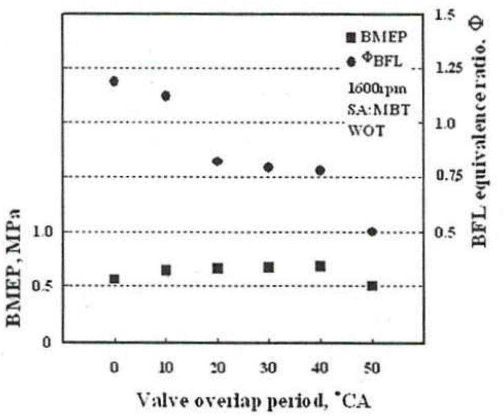

Fig. 9 Variation of BFL equivalence ratio and BMEPwith respect to VOP

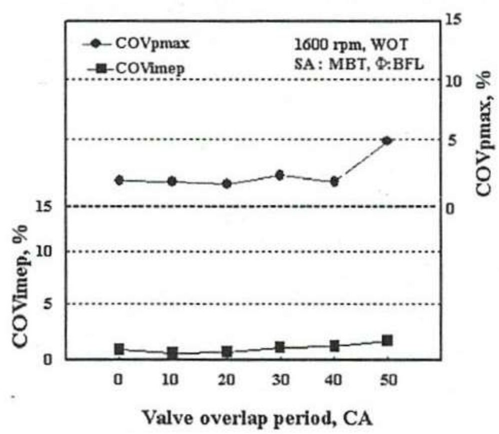

Fig. 10 COVimep and COVpmax versus VOP at ϕ - BFL equivalence ratio

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. 10. 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 energy input at shortened valve overlap period. In experiments, it is clearly found that the maximum brake torque is taken at around VOP30. Therefore it is necessary to study in more detail the effects of VOP on backfire occurrence by supplying a same value of supply energy as the cases of VOP30 by supercharging. That may compensate or improve the brake torque at shortened VOP and the BFL equivalence ratio is still increased at the same time. That would be for better performance characteristics and enhancement of the overall fuel economy of hydrogen powered vehicles.

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 1.5 times higher than that of VOP30 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. However, the brake torque is also reduced by the lower volumetric efficiency from the shortened valve overlap period.

TÍNH KHẢ THI TRONG ĐIỀU KHIỂN CHÁY NGƯỢC VÀ NÂNG CAO HIỆU SUẤT ĐỘNG CƠ HYDRO HÒA TRỘN NGOÀI DÙNG SỰ THAY ĐỔI THỜI ĐIỂM VAN

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TÓM TẮT: *Sự nghiên cứu phát triển của động cơ hydro dùng hỗn hợp hòa trộn ngoài (như phun trên họng nạp) với hiệu suất và công suất cao phụ thuộc chính vào sự kiểm soát hiện tượng cháy ngược trên đường nạp. Trong nghiên cứu này, các tác giả đã đề xuất biện pháp kiểm soát hiện tượng trên bằng cách thay đổi thời điểm đóng/mở van động cơ. Hệ thống điều khiển van liên tục tác động cơ đã được phát triển và lắp đặt trên động cơ hydro một xi-lanh cải tiến. Hệ thống này cung cấp dãy biến đổi van rộng và liên tục; có thể được điều khiển độc lập giữa hệ thống nạp và thải trong quá trình động cơ hoạt động. Sự xảy ra của hiện tượng cháy ngược và đặc tính của động cơ đã được xác định bằng thực nghiệm theo sự biến đổi của độ trùng van và độ đậm nhiên liệu từ 0.25 đến 1.2. Kết quả thí nghiệm cho thấy đặc tính công suất và đặc tính cháy của động cơ có sự thay đổi khi biến đổi thời điểm van tại một tốc độ động cơ. Khi tăng độ trùng lắp van tại một giá trị độ đậm nhiên liệu (hoặc lam-đa) biết trước, mô-men của động cơ gia tăng. Ngoài ra, các giá trị cực đại của mô-men ứng với các độ trùng van khác nhau bị giới hạn khi động cơ hoạt động ở chế độ tải cao. Tuy nhiên, nghiên cứu cho thấy hệ thống MCVVT phát triển trong bài báo này có thể được dùng để kiểm soát hiện tượng cháy ngược bằng cách thay đổi độ trùng van. Khi giảm độ trùng van, độ đậm tới hạn có thể gia tăng đáng kể. Điều này chứng minh rằng, việc giảm độ trùng van là một biện pháp kiểm soát hiện tượng cháy ngược hiệu quả.*

Từ khóa: *Động cơ hydro hòa trộn ngoài, hiện tượng cháy ngược, độ trùng van, tỉ số đậm tới hạn cho sự cháy ngược.*

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