Development of Hydrogen Rotary Engine Vehicle

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ABSTRACT:
A hydrogen ICE (internal combustion engine) vehicle has been delivered in Japanese market since March 2006 with a hydrogen rotary engine fueled by 35MPa compressed-hydrogen. The engine has both internal direct injectors and external premix injectors to realize both high output power and low NOx emissions. Combination of lean and stoichiometric burn operation has also made improvement in emissions and fuel efficiency. Consequently, the hydrogen vehicle achieves Japanese SULEV standard and ca.23% better fuel efficiency than that of gasoline fueled vehicle. The vehicle has Dual Fuel System that switches from hydrogen to gasoline when hydrogen is used up. The system makes hydrogen vehicles drivable even where hydrogen stations are scarce under transitional period toward the hydrogen society. Torque based control system and multi-CPU controller has been installed to realize Dual Fuel System. Hydrogen safety and reliability have also been developed to meet market severe requirements, as well as driving performance.

KEYWORDS : *Commercialized hydrogen vehicle, hydrogen internal combustion engine, rotary engine*

1. Introduction

Hydrogen fueled ICE vehicle has higher reliability and cost performance, and requires less investment for mass production than fuel cell vehicles. Therefore, hydrogen ICE CAN play an important role as an automotive power source in the future, though tank-to-wheel efficiency needs to be improved. Furthermore, when high power density and instant power response are required, hydrogen ICE will be a desirable choice.

Rotary engine (RE) provides merits such as prevention of pre-ignition of hydrogen combustion. Thus, Mazda has been developing hydrogen vehicles and hydrogen RE from the early 1990s. RX-8 Hydrogen RE (Fig.1) powered by the newest hydrogen RE (Fig.2) has been delivered to Japanese market (limited for companies and public offices) since March 2006. This paper describes details of the commercial hydrogen vehicle and applied technologies.


Fig.1 RX-8 Hydrogen RE


Fig.2 Hydrogen roraty engine

2. Specifications and layout

Table1 shows specifications of the vehicle. The vehicle is based on the standard RX-8 fueled by gasoline. Auto transmission is equipped to meet the easy-drive demand of customers. The vehicle is fueled both hydrogen and gasoline. Maximum output power achieves 80kW when hydrogen operation. Although the power is enough for this vehicle’s weight, further improvement is desirable compared with gasoline operation. Driving range is about 100km at Japan 10-15mode due to low energy density of gaseous hydrogen and the limited fuel tank capacity. Further fuel efficiency and increasing amount of loaded hydrogen are necessary to extend the driving range. However Dual Fuel System provides 649km range including gasoline operation. Drivers do not have to care about hydrogen fuel meter.

Table 1 Specifications of RX-8 Hydrogen RE

body and chassis	overall length	4,435 mm
	overall width	1,770 mm
	overall height	1,340 mm
	wheelbase	2,700 mm
	seating capacity	4 persons
	tires	225/55R16
engine	type	RENESIS Hydrogen Rotary Engine with Dual Fuel System
	fuels	compressed hydrogen gas and gasoline
	number of rotors	2
	maximum output	hydrogen operation: 80kW gasoline operation: 154kW
	maximum torque	hydrogen operation: 140 Nm gasoline operation: 222 Nm
transmission	4AT	
driving range (10-15 mode)	hydrogen operation: 100km gasoline operation: 549km	

Fig.3 shows layout of components. Two hydrogen tanks are installed in the trunk space. The tanks are for 35 MPa compressed gaseous hydrogen (typeIII). The cabin has enough space for 4 persons. Significant modification from the standard RX-8 is just addition of hydrogen supply system and engine controller. The cluster is also modified to insert hydrogen related information. The gasoline supply system remains intact.

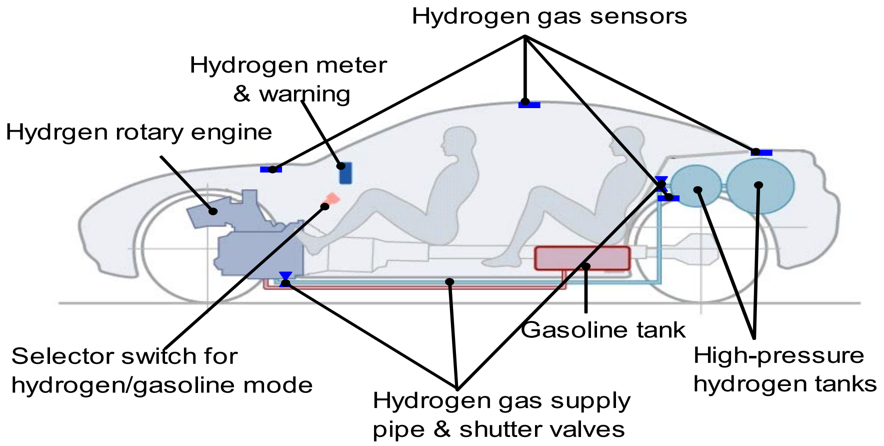

Fig.3 Schematic diagram of RX-8 Hydrogen RE

3. Advantages in Hydrogen combustion with RE

RE is a standard Otto cycle engine. Instead of ordinary pistons and a cylinder block, the engine has three-sided rotors and trochoid-shape housings (Fig.4). The rotors spin around the output shaft. Charged air and fuel move in the housing along the rotor. Each process of Otto cycle takes place in different chambers.

One of important issues of hydrogen ICE is to prevent pre-ignition and backfire. RE has no exhaust valves that sometimes bring backfire in reciprocating engines. Furthermore, the intake chamber is separated from the combustion chamber, keeping air/fuel mixture away from localized hot spots. These structural features enable the use of hydrogen without pre-ignition and backfire.

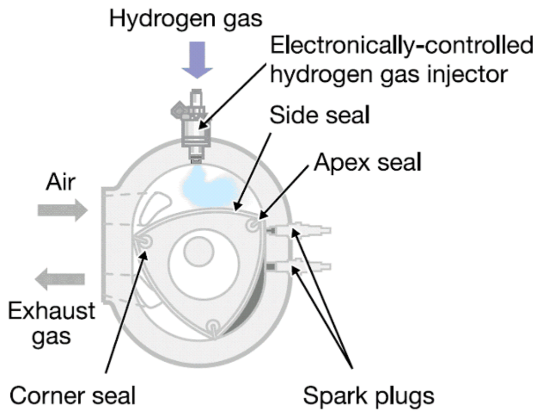

Fig.4 Cross-sectional diagrams of the hydrogen RE

4. Injection and air/fuel ratio strategy

To achieve high power density, injectors are installed on the top of the housing for direct injection (internal air-hydrogen mixture). Other injectors are placed on air intake ports for external air-hydrogen mixture during high engine speed (Fig.5). The external injection brings better air-hydrogen mixture. The combination of the direct and port injection has brought simultaneous achievement of high power, NOx reduction and better thermal efficiency.

For further improvement in fuel efficiency, lean burn operation is basically used. NOx emissions are reduced by keeping air excess ratio over 1.6. Stoichiometric operation with EGR (exhaust gas recirculation) is used for lower engine speed and higher engine load (Fig.6). The stoichiometric operation offers higher output torque and reduces NOx emissions with a 3-way catalyst.

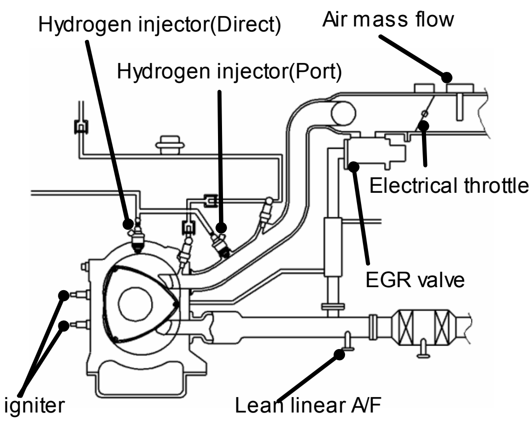

Fig.5 Schematic layout of the hydrogen RE

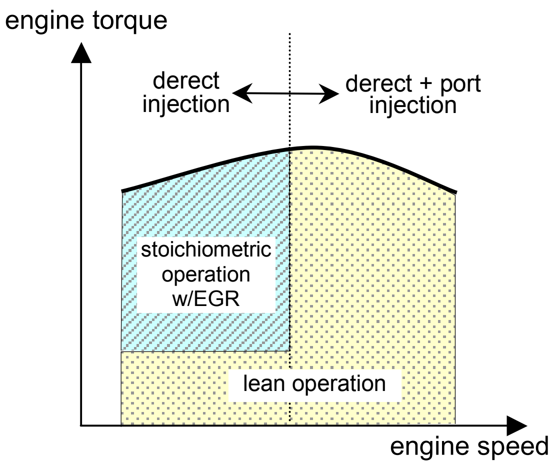

Fig.6 Injection and air/fuel ratio strategy

Fig.7 and Fig.8 are showing the effects of the air/fuel ratio strategy. Thermal efficiency of hydrogen operation has been improved by ca.23% with the lean operation than that of gasoline operation (whole stoichiometric operation). Although the lean operation emits little NOx, total amount of engine-out NOx exceeds Japanese SULEV standard. The supplementary stoichiometic operation combined with a catalyst provides additional NOx reduction. Accordingly, the vehicle satisfies the SULEV standard.

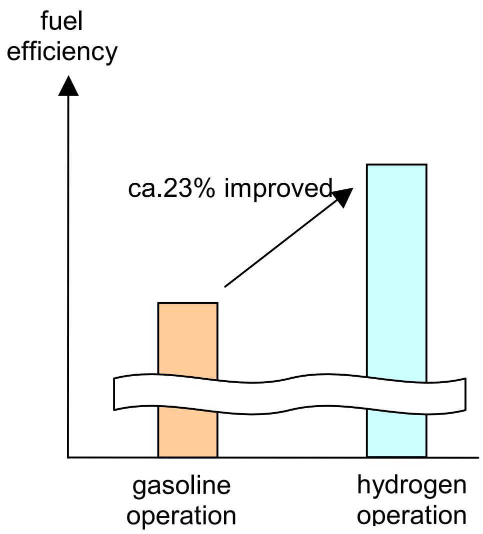

Fig.7 Comparison of efficiency between hydrogen and gasoline operation

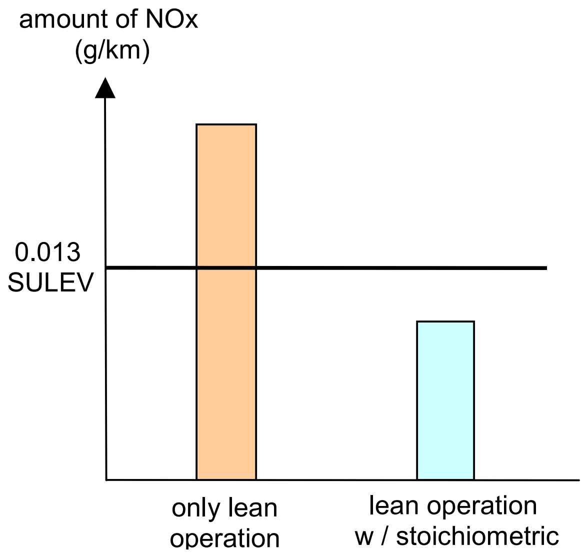

Fig.8 Effect of lean operation with stoichiometic operaition

Switching lean and stoichiometic operation creates a NOx spike because of imperative transition of air excess ratio through NOx rich area. Quick switching of excess ratio can reduce the NOx spike. However, when switching to stoichiometic from lean burn, the quick switching also produces excessive combustion noise and shock of engine torque due to delay of EGR flow. For this reason air excess ratio is gradually switched matching with the delay of EGR flow. EGR and throttle valve has been optimized to keep enough EGR flow during the switching (Fig.9), resulting in successful elimination of the NOx spike.

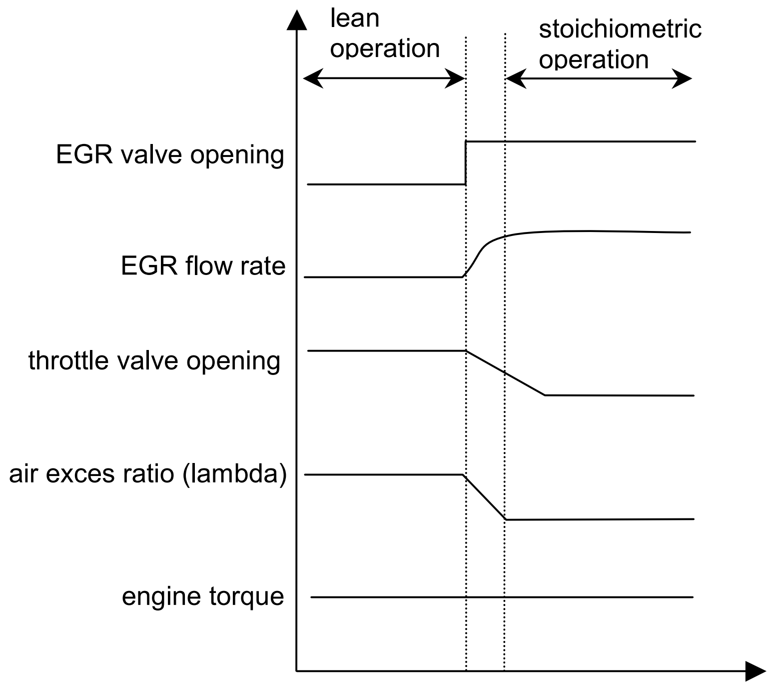

Fig.9 Time chart of engine control when siwtcing from lean to stoichiometric operation

5. Dual Fuel System

At present the number of hydrogen stations is limited and it might take a long time before hydrogen becomes the major in the energy market. Drivers of hydrogen vehicles always have "out of fuel" concern, which limits the vehicles only driven nearby the stations. The vehicle is fueled by both hydrogen and gasoline. The additional gasoline operation relieves the concern and makes hydrogen vehicle drivable in non-hydrogen station area. The system can promote hydrogen vehicles and hence contribute to spread the hydrogen infrastructure.

Dual Fuel System automatically switches fuels when hydrogen is used up, even during acceleration, without any discomfort such as torque shock. The system also works immediately when a hydrogen-related part is failed to ensure safety of customers. Furthermore, drivers are allowed to select the fuel at their will with the selector switch (Fig.10).

Fig.10 Selector switch for hydrogen/gasoline

Torque based control has been developed for smooth and quick fuel switching. Accelerator pedal position is directly transferred to driver's engine torque demand. Fuel injectors and the throttle valve are controlled to provide the demanded torque. Fuels are immediately switched without transitional mixture of both fuels. Throttle valve, EGR valve and amount of fuels are accurately controlled to provide the same torque.

To keep the control for gasoline operation the same as standard RX-8, a multi-CPU controller has been built (Fig.11). The controller has an additional CPU for hydrogen operation keeping the RX-8 gasoline control unchanged. The addition of CPU also contributes to effective fuel switching control. Moreover, the CPUs are monitoring each other to enhance failsafe of the control.

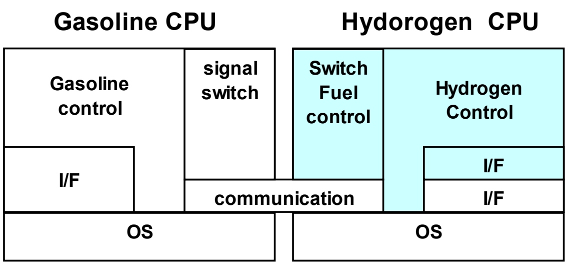

Fig.11 Schematic diagram of the multi-CPU controller

6. Safety and reliability

Followings are main safety measures for hydrogen.

- -Hydrogen leakage sensors
- -Hydrogen shutter valves
- -Structural design to prevent leaked hydrogen from accumulating
- -Failure diagnosis for hydrogen related components
- -Emergency shutdown of hydrogen supply within 500ms
- -Switching fuels when a hydrogen-related component is failed

The safety is confirmed by severe vehicle tests such as endurance tests (Fig.12) for the demanding market. The tests were conducted on pubic roads and testing courses. The vehicle also meets the safety requirements on hydrogen vehicles set under Japanese Ministry of Land Infrastructure and Transport.

Fig.12 Pictures of the endurance test

7. Conclusion

The hydrogen ICE vehicle has been developed with the usability and low cost, hoping that it contributes to realization of hydrogen society. The vehicle meets the severe standard of emissions and the fuel efficiency is better than that of gasoline, though further driving range is desirable. Dual fuel system can cover the hydrogen storage issue. The development proves the practicality of hydrogen ICE vehicles.

Several hydrogen vehicles have been delivered in the market. However automakers are often asked a question “Which way is the best for future hydrogen source?” No one knows the right answer at present. Other tough issues such as transport and storage of hydrogen are still unsolved. We would like to continuously and positively work with other hydrogen researchers to tackle these issues.

References:

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