

Study of High-Compression-Ratio Engine Combined with an Ethanol-Gasoline Fuel Separation System

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ABSTRACT

Bio-ethanol is used in many areas of the world as ethanol blended gasoline at low concentrations such as "E10 gasoline". In this study, a method was examined to effectively use this small amount of ethanol within ethanol blended gasoline to improve thermal efficiency and high-load performance in a high-compression-ratio engine. Ethanol blended gasoline was separated into high-concentration ethanol fuel and gasoline using a fuel separation system employing a membrane. High-ethanol-concentration fuel was selectively used at high-load conditions to suppress knocking. In this system, a method to decrease ethanol consumption is necessary to cover the wide range of engine operation. Lower ethanol consumption could be achieved by Miller-cycle operation because decrease of the effective compression ratio suppresses knocking. However, high-load operation was limited due to the decrease in intake air volume with Miller-cycle operation. To solve this problem, conventional Otto-cycle operation is used in high-load conditions, utilizing large quantities of ethanol injection to avoid knocking. The two different cycles were smoothly switched with innovative application of a variable valve timing system. In summary, optimum control of the variable valve timing (i.e. effective compression ratio) and ethanol injection fraction allows efficient use of the limited amount of ethanol available. As a result, higher-load and higher thermal efficiency operation was achieved due to the increased compression ratio. Additionally, it is possible to complete the US-06 driving cycle using the above-mentioned system, assuming a realistic engine displacement has been selected according to the vehicle weight.

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INTRODUCTION

Bio-ethanol is one of the major alternative liquid fuels used to replace conventional fossil fuels for motor vehicles because of its productivity, lower CO₂ emissions and compatibility with conventional fuels. Especially, the biggest advantage of bio-ethanol is its non-influential property on global warming according to the carbon-neutral effect. Ethanol has high anti-knock characteristics because of chemical property and high latent heat of evaporation, thus many SI engine studies for ethanol fuel improving thermal efficiency with high compression ratio have reported. Suppression of knocking in SI combustion can be achieved by using ethanol, depending on vehicle operating conditions such as engine speed and load.[1, 2, 3] Knocking suppression in all operating conditions enables ignition timing at MBT (Minimum Spark Advance for Best Torque) to increase thermal efficiency, and makes engine downsizing possible [4, 5, 6].

Flexible Fuel Vehicles (FFV) that support the use of fuels containing high concentrations of bio-ethanol have also been developed and are in widespread use, especially in Brazil. Ethanol-containing fuel can be used in a similar way as conventional gasoline by control of the air-fuel ratio suitable for

the component of the fuel [7, 8, 9]. The main issues of FFV are start-ability and combustion in cold conditions. Use in a state mixed with gasoline has not employed the advantage of the ethanol characteristics efficiently. For additional improvement of fuel consumption, it is important to investigate the combustion procedure for employing this advantage efficiently.

The technology of Miller-cycle engines was investigated to improve thermal efficiency by reducing pumping loss with a high expansion ratio. This is a technology in which high thermal efficiency and knocking control can be simultaneously obtained by decreasing the effective compression ratio with a high-geometrical-compression ratio. Significant development of the Miller-cycle engine with variable intake valve timing and valve lift has resulted in an engine for production vehicles [10, 11, 12, 13].

In this study, a method was examined to effectively use a small amount of ethanol within ethanol-blended gasoline "E10" to improve thermal efficiency and high-load performance in a high-compression-ratio engine with minimum modification and additional devices.

EXPERIMENTAL APPARATUS

Experiments in fuel separation and engine performance were investigated separately in order to establish the principles of each element.

Fuel Separation System

A prototype fuel separation system that used a membrane for pervaporation was applied for the fuel separation experiment. The system mainly consists of a membrane, heat exchanger and vacuum pump as shown in Figure 1. The components with excess capability were applied as experimental device to determine the requirement of performance for the on-board separation in the same way as previous study [14]. A progression of fuel separation depends on the temperature at the inlet of the membrane, and the pressure on the separated-fuel side. Thus, control of fuel temperature and pressure is an important factor in fuel separation performance. Fuel was heated by the engine coolant to the adequate temperature for fuel separation. The evaluation was conducted from a separation rate and the ethanol concentration of the separated fuel.

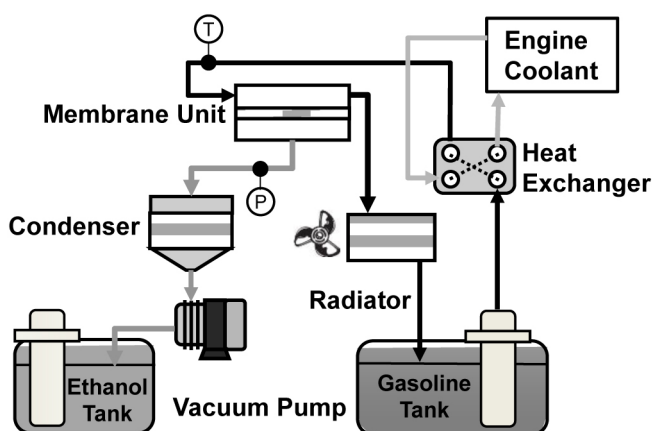


Figure 1. Fuel Separation System Set-up

Engine Setup and Fuels

In the experiment, a single-cylinder engine for comprehending fundamental characteristics and a 4-cylinder engine for acquiring more realistic data were used as appropriate. Table 1 shows the basic specifications of the engine developed for this study. Common gasoline engines were used with several small modifications to adopt the ethanol-gasoline dual fuel system. The engine was equipped with a multiple injection system, which had a port injector and a direct injector for each cylinder as shown in Figure 2. The fraction of injected fuel could be controlled according to the circumstances with stoichiometric mixture ratio. As shown in Table 2, regular gasoline and ethanol were used for the engine test on the assumption that they were separated from E10. The compression ratio was increased from the basic specification to take advantage of ethanol's high anti-knock quality. The 4-cylinder engine was equipped with a turbocharger; also the timing for opening and

closing the intake valves could be controlled by variable valve timing and lift control (VTEC) and continuous variable valve timing control (VTC).

Table 1. Engine Specifications

	Single-Cylinder	4-Cylinder
Displacement [cc]	372	1559
Stroke [mm]	89.4	77.5
Bore [mm]	73	80
Connecting Rod [mm]	142.5	161.55
Compression ratio	13.5:1	13.5 - 12.5:1
Number of Valves	4	4
Aspiration	Natural Aspiration	Turbocharged
Valve Control System	-	Variable Valve Lift, Variable Valve Timing
Combustion Chamber	Pent-roof	
Fuel Systems	1 x Port Injector 1 x Direct Injector	

Table 2. Fuel Properties

	Gasoline	Ethanol
Density g/cm ³	0.72	0.79
Boiling Point deg C	-	78
Calorific Value J/g	43.3	26.8
RON	>90	>115

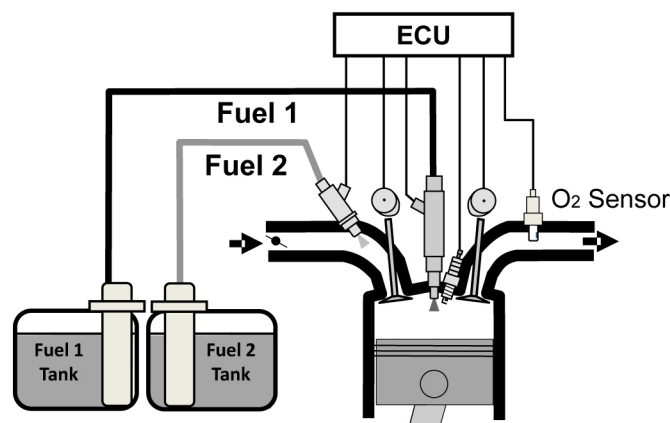


Figure 2. Experimental Engine System Set-up

EXPERIMENTAL RESULTS

Fuel Separation Test

Figure 3 shows the histories of ethanol concentration at the gasoline tank during the separation process at each fuel temperature. Table 3 shows the experimental conditions for fuel separation test. The separation rate greatly depends on the pressure on the ethanol-outlet side of the membrane due to the principle of pervaporation. It was set at -75kPa in this condition on the basis of balance of separation performance and power consumption of the vacuum pump. At the initial conditions, ethanol concentration is indicated as about 0% which indicates concentration of supplied fuel.

Table 3. Conditions of Fuel Separation Test

Fuel Flow [L/min]	2
Fuel Feed Pressure [kPaG]	300
Pressure of Ethanol-outlet side [kPaG]	-75

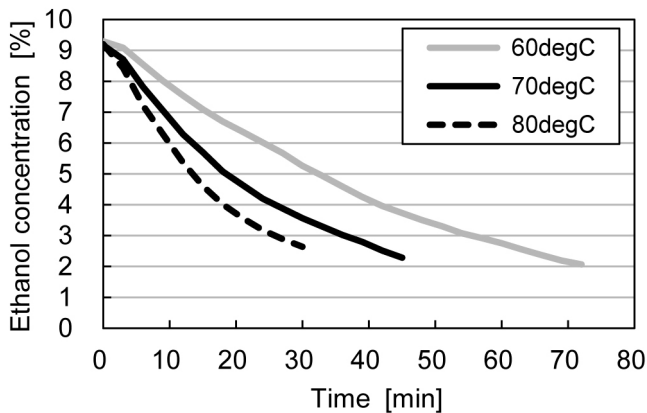


Figure 3. Effect of Inlet Fuel Temperature on Ethanol Separation Rate

Table 4. Properties of Supplied Fuel and Separated Fuels

	E10 (Supplied Fuel)	Separated Fuel (Low Ethanol Concentration)	Separated Fuel (High Ethanol Concentration)	ASTM (Volatility Class A)
Ethanol Concentration [vol%]	9.1	2.5	68.4	-
Density [g/cm ³]	0.743	0.740	0.791	-
Reid Vapor Pressure [kPa]	48.9	45.3	28.1	< 62
RON	94	89	107	-
MON	85	83	88	> 82
AKI	89	86	98	> 87
Net Heating Value [kJ/kg]	40600	42660	30980	-
Oxidation Stability [min]	> 1440	> 1440	> 1440	> 240

High-ethanol-concentration fuel piled up in the ethanol tank with separation progress, while at the same time, ethanol concentration in the gasoline tank decreased. The results were evaluated according to the conditions when ethanol concentration decreased by about 2% at the gasoline tank, because separation progress became diminished in those conditions. In addition, most of the ethanol contained in the supplied fuel was separated in these circumstances. As a result, the separation rate improved by raising fuel temperature. However, raising fuel temperature too much had the danger of causing boiling of the fuel. In this study, the optimal fuel temperature for separation was determined as 70°C, which could be sufficiently obtained with engine coolant. This test was conducted with about one-third of the actual fuel tank quantity, thus required time was practically three times longer than this test case. Nevertheless, there was sufficient performance for the engine with adequate fuel tank capacity.

Table 4 shows the former and the latter fuel properties of separation. Ethanol concentration of the separated fuel was greater than 60%.

Engine Test

Effect of Ethanol Addition

Figure 4 shows the effects of ethanol addition on fundamental gasoline combustion with natural aspiration. At high-load conditions, although indicated thermal efficiency deteriorated because the ignition timing should be retarded to avoid of knocking, higher thermal efficiency was achieved with ethanol addition. In the case of ethanol addition, it was possible to set MBT ignition timing at a wide-open-throttle condition with an approximately 30% ethanol fraction. Furthermore, maximum load increased by 20% over operation with gasoline. The system in this study was built on the concept of using E10 as a supplied fuel. Thus, excessive ethanol consumption in the middle-load range might cause shortage of ethanol in practical use. Therefore keeping the consumption fraction of ethanol under 10% was the most significant factor for realization of an E10-based concept.

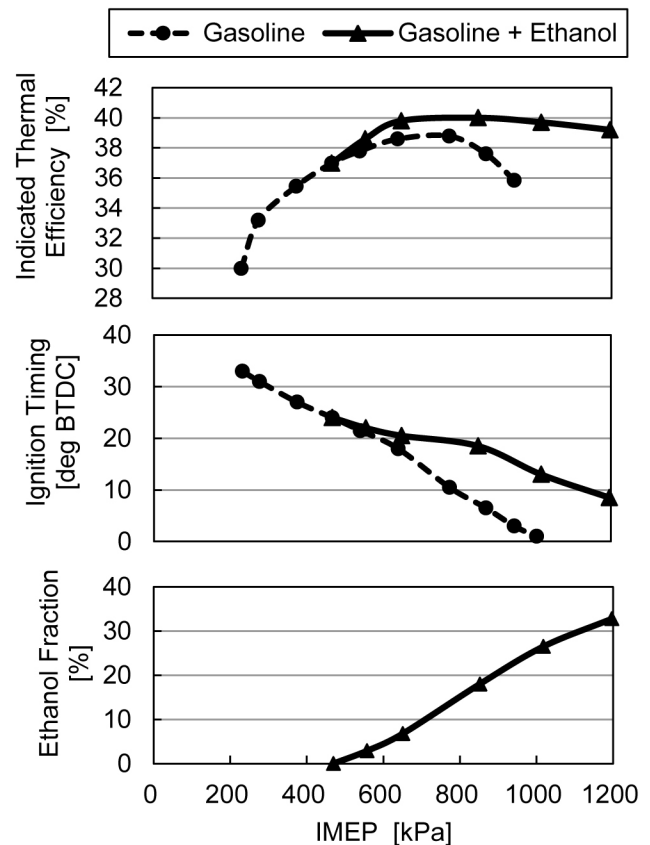


Figure 4. Effects of Suppression of knocking by Ethanol (1-cyl. Engine C.R.13.5:1; 1500rpm)

Comparison of Fuel Injection Configurations

Figure 5 shows the results from the comparison in the case of using ethanol as a direct injection (DI) fuel and as an indirect injection (PI) fuel. The required ethanol fraction of the ethanol