

Enhancement of Low-temperature Combustion in Flexible Fuel Vehicle (FFV) Engine

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ABSTRACT

A variety of vegetable oil-based alternative fuels have been suggested in recent years with a view to preventing global warming due to the CO₂ emitted by internal combustion engines. One of those fuels is bio-ethanol. Flexible fuel vehicles (FFV) that are able to run on varieties ranging from 100% aqueous ethanol (E100) to a 22% mixture of ethanol with gasoline (E22) are in use in Brazil. Ethanol is a single-component fuel that does not contain any low-boiling-point components, and there are issues with combustion at low temperatures. The optimum compression ratio was selected to enhance the combustion of ethanol at low temperatures. The flow was also raised and low-temperature combustion was enhanced by operating with one intake valve. In order to raise the commercial product appeal when using E100 at low temperatures, a new engine control was built exclusively for the FFV. Through the use of these technologies, a dedicated FFV engine was developed that achieves a balance of commercial product appeal and power output when using E100.

1. Introduction

Bio-ethanol has been the object of attention in recent years as an alternative fuel with potential for limiting global warming. Bio-ethanol is manufactured from plants that have grown by photosynthesis using the sun's energy. Consequently, extracting that energy by combustion will not increase the total amount of CO₂ in the atmosphere, which is why this is treated as a carbon neutral fuel.

On the other hand, there are issues with the use of ethanol in automobile engines. These are its high latent heat of evaporation and its low vaporizability at low temperatures because it does not include any low-boiling-point components.

In Brazil, bio-ethanol is produced from sugar cane, and fuel that is 100% ethanol is sold side-by-side with fuels containing mixtures of 20-25% ethanol with gasoline. In other words, an FFV engine⁽¹⁾ intended for Brazil will be required to provide adequate performance at any concentration of ethanol ranging from 20-100%.

2. Properties of Ethanol as an FFV Fuel

Table 1 shows the characteristics of ethanol and gasoline.

1. High octane number
2. No low-boiling-point components

3. High latent heat of evaporation
4. Rather high heating value per mass of air
5. Low heating value per volume

These fuel properties would suggest that the issue with ethanol as used for automobile engines would be combustion at low temperatures.

3. Characteristics of Ethanol Combustion at Low Temperatures

3.1. Confirmation of Combustion at Low Temperatures

Table 2 shows the specifications of the test engine. Figure 1 shows a comparison of E100 and gasoline at different excess air ratios in terms of total hydrocarbon (THC) and CO₂ at low temperature. The comparison was made at a low load (-60 kPa) corresponding to a fast idle and at a high load (-13 kPa) corresponding to a standing start. With E100, THC is higher at high load. The reason is probably that, since E100 has no low-boiling-point components, the latent heat of evaporation is higher, so that a large amount of fuel is not completely vaporized under high load. This explanation is supported by the phenomenon of CO₂ emissions characteristics tending to be displaced toward the rich side.

3.2. Demanding Driving Conditions for FFV

The FFV does not start easily at low temperatures with E100. Therefore, it is equipped with an E22 fuel tank and

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Table 1 Fuel characteristics

		Gasoline	Ethanol
Octane number RON/MON		93/81	110/92
Boiling point (°C)		25-200	78
Latent heat of evaporation (kJ/Air kg)		30.2	101
Low calorific value	(MJ/Air kg)	2.95	2.99
	(MJ/kg)	43.4	26.9
	(MJ/L)	32	21.2
Theoretical air fuel ratio	(Weight)	14.7	8.9
	(Volume after carburetion)	43.1	14.3
Ratio of the number of moles of combustion before and after		1.07	1.14
Specific gravity (kg/L)		0.737	0.789

Table 2 Engine specifications

Fuel		Gasoline
Cylinder configuration		In-line 4-cylinder
Bore × stroke (mm)		81 × 87.3
Displacement (cm ³)		1799
Compression ratio		10.5
Valve		2 intake valves
Valve diameter (mm)	In.	32
	Ex.	26

injection system dedicated to low-temperature starts. Figure 2 shows how the different fuels are used for different purposes immediately after startup. The solid line represents the low-temperature fuel injection amount, and the broken line represents the high-temperature fuel injection amount. When the temperature is low, E22 is used for starting, and then the system switches over to E100. It is desirable to keep the time spent operating with E22 to a minimum, and in that case, the conditions that make FFV operation challenging are:

1. Startability at the lower temperature limit when using E100 (part A of Fig. 2)
2. Shift to high-load driving when ambient temperature is low (part B of Fig. 2)

3.3. Starting Test with E100

Startability with E100 at low ambient temperature was confirmed. Figure 3 shows the relationship between

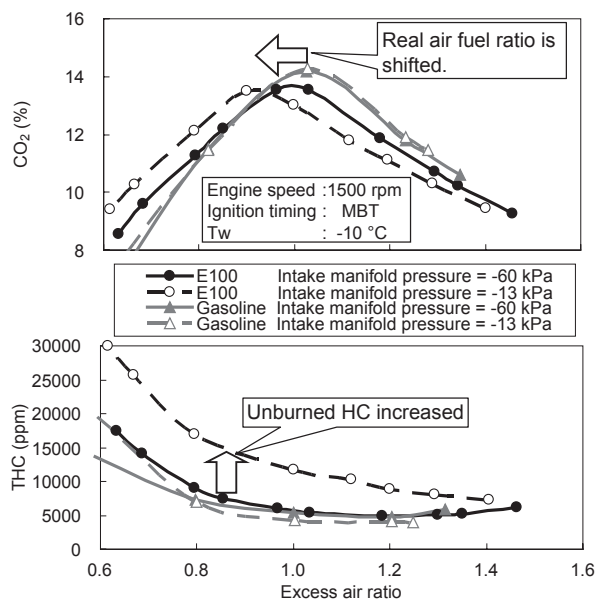


Fig. 1 Characteristics of excess air ratio at low temperature

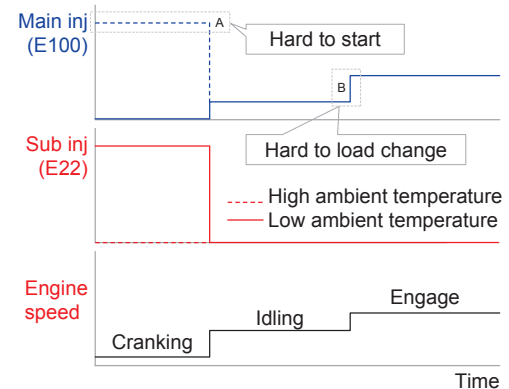


Fig. 2 Fuel used at starting and after start

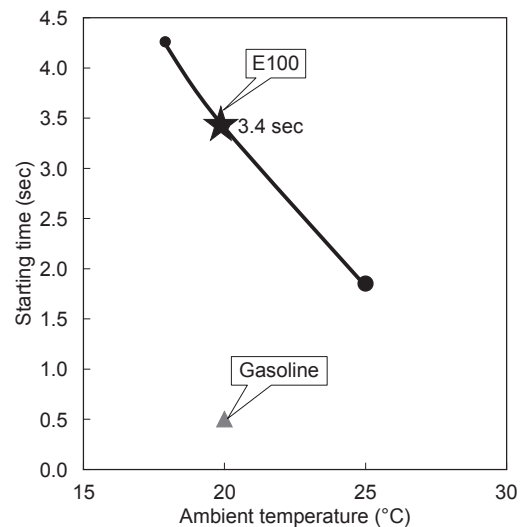


Fig. 3 Relationship between ambient temperature and starting time

ambient temperature and starting time, with lower ambient temperatures bringing longer starting times. The reason is probably the reduced vaporizability of ethanol during a cold start. Considering that E100 is used for starting at temperatures down to 20°C, it is necessary to shorten the starting time of 3.4 sec.

3.4. Load-increasing Test at Low Temperature

The FFV starts up with E22 when the temperature is low, then runs with E100. Figure 4 shows a conceptual diagram of the transient torque characteristics when the engine idles for two seconds immediately after startup and then is suddenly placed under a high load equivalent to a standing start in a manual transmission car. When the temperature of the water (T_w) is high, torque is generated in proportion to the throttle opening. When the water temperature is low, however, the engine misfires. Figure 5 shows the water temperature and torque characteristics when

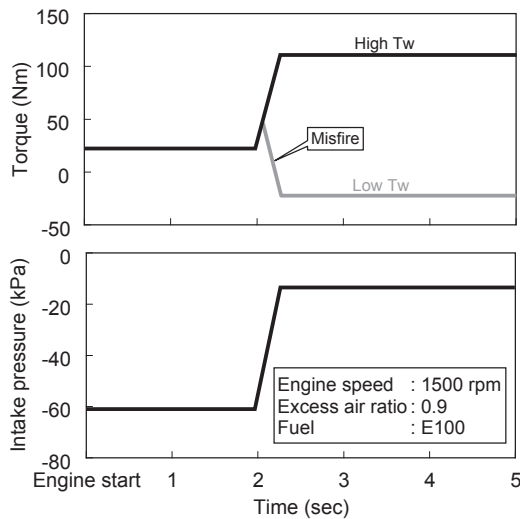


Fig. 4 Transient torque characteristics under high loads immediately after starting

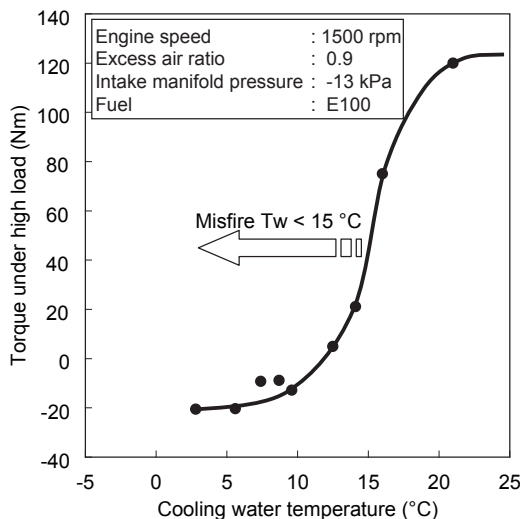


Fig. 5 Relationship between cooling water temperature and torque immediately after shifting to high load

Table 3 Comparison of engine performance when using gasoline and E100

Engine type		Gasoline	
Fuel		Gasoline	E100
Bore × stroke (mm)		81 × 87.3	
Displacement (cm ³)		1799	
Compression ratio		10.5	
Valve		2 intake valves	
Power		97.8	102
Torque (Nm)	Max	165	173
	At 2000 rpm	147	151
Starting time (sec; $T_a = 20^\circ\text{C}$)		0.5	3.4
Ambient temperature limit (°C)		-25 °C	15 °C

under high load. It is apparent that at water temperatures of 15°C or lower, attempting to change to high-load driving immediately after startup would cause misfires when E100 is being used. The cause, as discussed earlier, is probably that when driving under high load, there is a large amount of fuel that cannot be completely vaporized.

Table 3 shows the performance of an engine configured for gasoline when it is used without modification in an FFV. This confirms that at low temperatures there are issues with increased starting time due to decreased vaporizability and with commercial product appeal due to ambient temperature limits and related matters. Optimization of the air fuel ratio (A/F), which was lean because of vaporizability at low temperatures, was considered as a means of resolving these issues.

4. Examination of Low-temperature A/F Optimization

Methods for optimization of low-temperature A/F include increasing the proportion of vaporized fuel and decreasing the amount of air. Among the methods to promote vaporization of the fuel are:

1. Raise the temperature of the air-fuel mixture
2. Minimize amount of fuel adhering to the cylinder wall
3. Lower the boiling point by reducing the pressure during compression

A method for reducing the amount of air is to optimize the air-fuel mixture volume during startup.

More specifically, these methods include:

1. Raise the compression ratio and advance the ignition timing in order to use the resultant cooling loss to raise the temperature of compression stroke ends
2. Minimize adhesion by strengthening the in-cylinder flow
3. Optimize the volume of air-fuel mixture to reduce fuel and reduce pressure during compression

The following describes confirmation of the effectiveness of these methods.

4.1. Optimization of the Compression Ratio

Raising the compression ratio causes the temperature

of compression stroke ends to rise, which increases the vaporizability of the fuel. The following shows the perspectives involved in determining the optimal compression ratio for an FFV.

1. Output characteristics are adequate at any of the ethanol concentrations
2. Enhanced fuel economy and power when using E100

Figure 6 shows the power output at different compression ratios when using E100. Since E100 has a high octane number, it enables minimum advance for best torque (MBT) operation largely across the entire range with a compression ratio of 12.5. This verified that a compression ratio of 12.5 or higher is desirable when using E100. Figure 7 shows the power output when E22 was

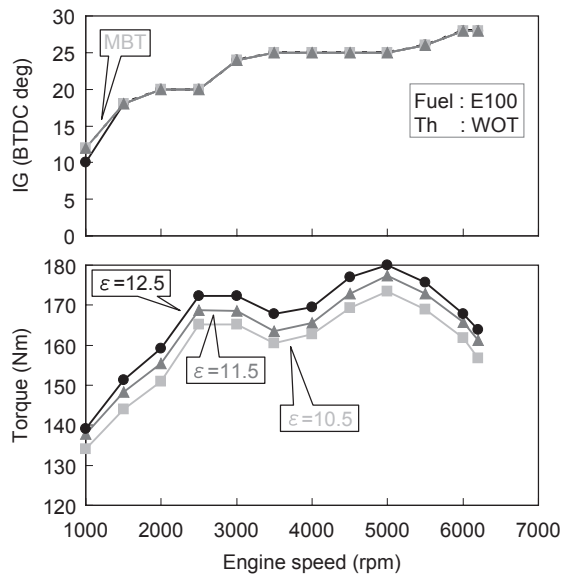


Fig. 6 Relationship between compression ratio and torque (E100)

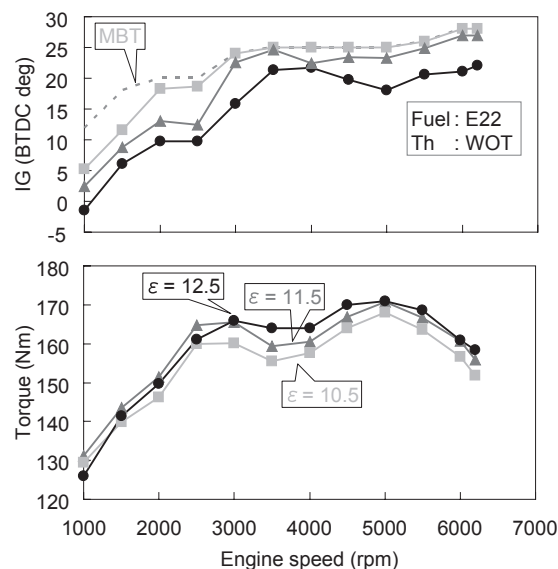


Fig. 7 Relationship between compression ratio and torque (E22)

used. It is clear that with E22, which is at the lower limit for ethanol concentration, raising the compression ratio too much would cause knocking. This necessitates retarding the ignition timing, which reduces the power output. Figure 8 shows the relationship of compression ratio, low-speed torque, and power output. A compression ratio of 11.5 was selected in order to provide torque equal to or higher than a gasoline engine even when driving with a fuel at the lower limit for ethanol concentration.

4.2. Strengthening the In-cylinder Flow

In order to verify the effectiveness of enhancing the flow, an examination was made of operation with one intake valve, which can increase flow speed and generate swirls. The simulation and test below were conducted on the assumption of an engine idling immediately after startup.

4.2.1. Enhancing flow speed and generating swirls

When the lift of one intake valve is set to the bottom limit and the engine is operated with one intake valve, the flow speed increases and swirls are generated. Figure 9 shows the results from simulation of operation on one intake valve and operation on two intake valves with a state of turbulence at the compression stroke ends. It is apparent that turbulence remains to the compression stroke ends when operating with one intake valve. These swirls reduce the adhesion of fuel to the cylinder wall and are expected to promote flame propagation after ignition.

4.2.2. Reducing amount of fuel adhesion to cylinder wall

A simulation was conducted to show the amount of fuel adhering in the various areas of the piston, cylinder head, and sleeve in order to verify that enhancing flow speed is

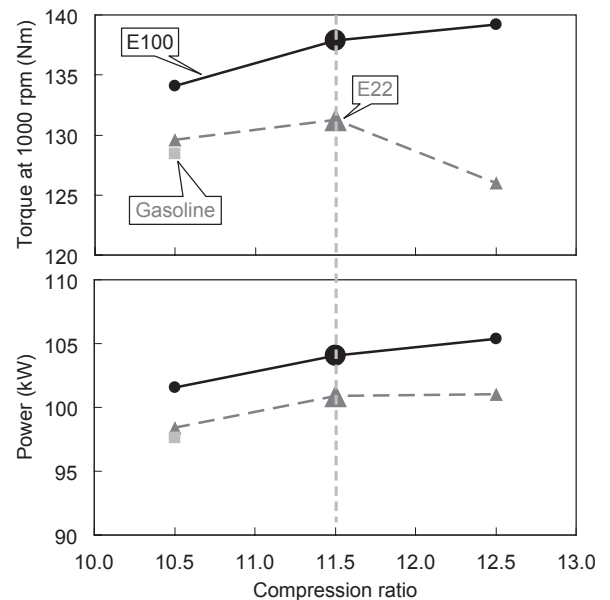


Fig. 8 Relationship between compression ratio and engine power (E22, E100)

an effective means of reducing fuel adhesion to the cylinder wall. Gasoline was used as the fuel. Figure 10 shows the simulation results. It can be seen that fuel adhesion to the sleeve primarily on the exhaust side decreases during operation with one intake valve. It can be reasoned that vaporizability will be enhanced as a result.

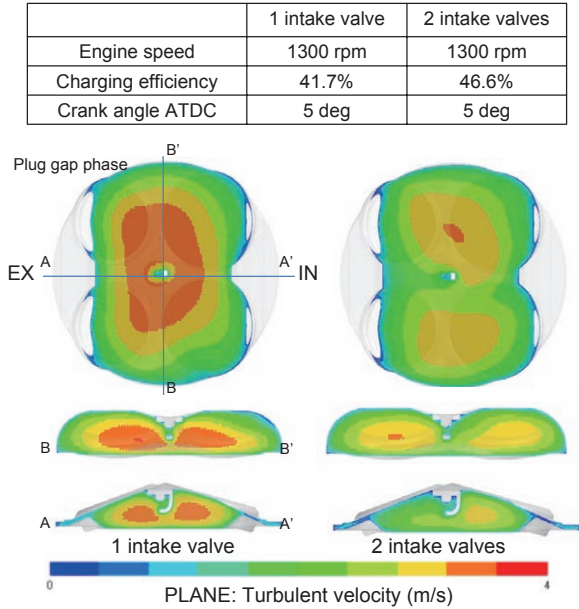


Fig. 9 Turbulent velocity simulation results (1 intake valve, 2 intake valves)

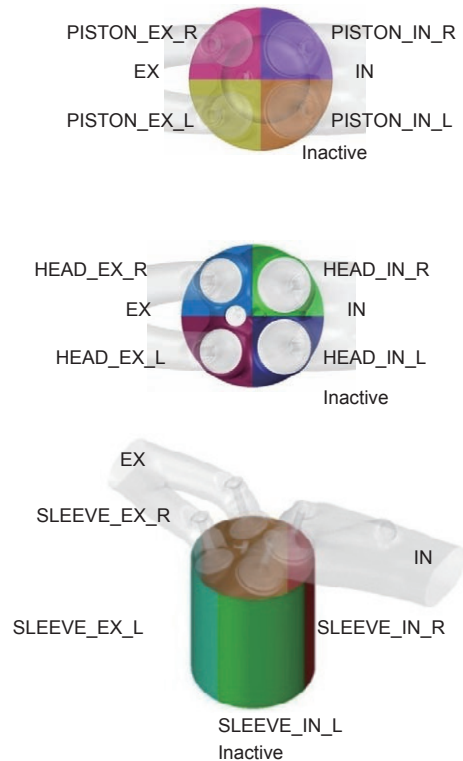


Fig. 10 Results of simulation of liquid film weight of fuel

4.2.3. Promoting flame propagation

When swirls remain until compression stroke ends, fuel vaporizability increases. This is thought to promote flame propagation. In order to verify this, a high-speed flame ionization detector was used to measure the THC concentrations in the different areas of the combustion chamber. The state of consumption of the fuel was measured. In order to match with the simulation, gasoline was used as the fuel. Figure 11 shows the measurement results. The angle at which the combustion THC concentration has decreased to approximately one-half is defined as the angle at which flame is propagated in that part.

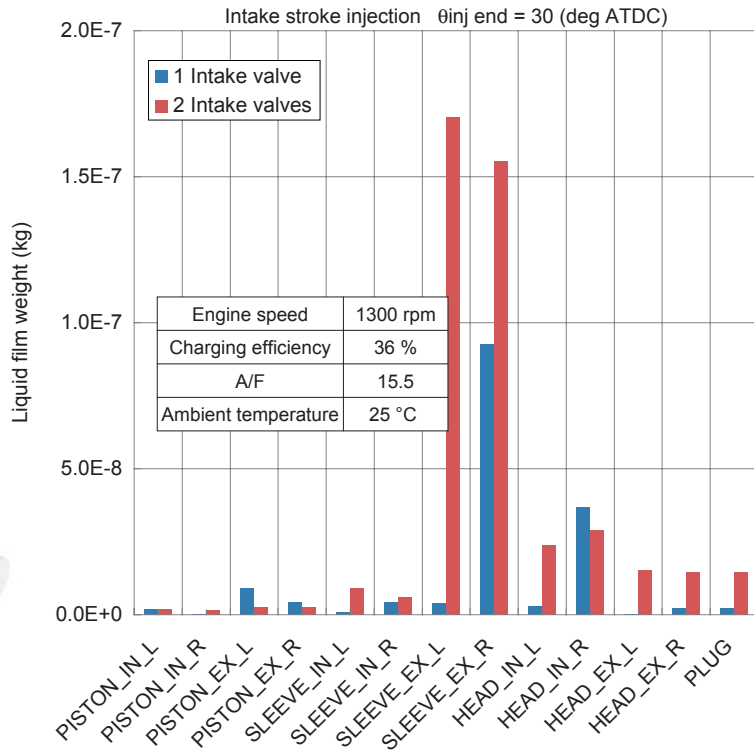
(1) Operation with two intake valves

The sequence of flame propagation has combustion go from ignition to the vicinity of the plug part (A in Fig. 11), following which, almost simultaneously, the flame propagates to the exhaust side (D and E in Fig. 11). After that, it propagates to the intake side (B and C in Fig. 11). Flame propagation is thought to proceed radially with the plug part as its center, and to advance somewhat faster in the exhaust system, where temperatures are higher.

(2) Operation with one intake valve

The sequence of advancing combustion goes from ignition to combustion of the air-fuel mixture in the vicinity of the plug part (A in Fig. 11). After that, the flame propagates in the same direction as the swirling flow (E-C-B-D in Fig. 11), and combustion advances rapidly.

It can be confirmed that the generation of a swirling flow



by operation with one intake valve results in enhancement of vaporizability as well as promotion of flame propagation. Figure 12 shows a conceptual diagram of flame propagation. The above simulations and measurements confirmed that operation with one intake valve enhances vaporizability and promotes flame propagation.

4.3. Ignition Timing Angle

The temperature of the combustion chamber can be made to rise by advancing the ignition timing, which increases the cooling loss. In order to extend the advance limit, vaporization has to have advanced sufficiently even during the compression stroke.

4.3.1. Extending the advance limit during operation with one intake valve

Operation with one intake valve, which proved effective in enhancing vaporizability, is also effective in extending

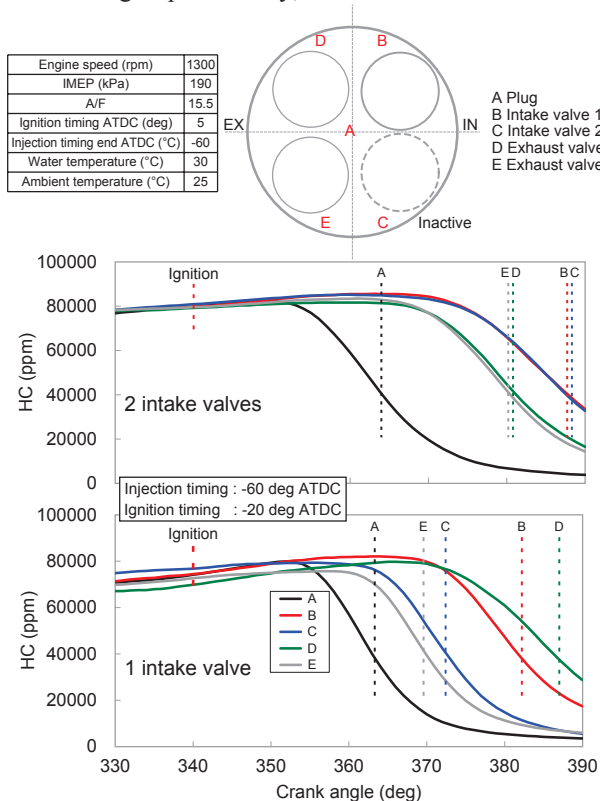


Fig. 11 Test result using high speed FID

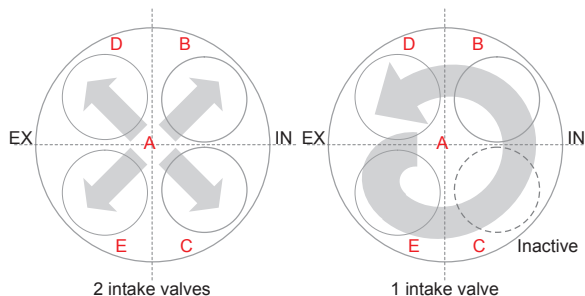


Fig. 12 Conceptual diagram of fire propagation

the advance limit. The combustion stability zone was represented by defining it in terms of excess air ratio and ignition timing. Stable combustion is defined as the zone in which the variation of the mean effective pressure is 7.5% or less. Figure 13 shows the advance limit and retard limit versus the excess air ratio. It is apparent that operation with one intake valve extends the combustion limit on the advanced side.

4.3.2. Verification by load change test

Based on the above results, the combination of operation with one intake valve and advanced ignition timing enables enhancement of the vaporizability of fuel when making the transition to high load at low temperatures (Fig. 14). Figure 15 shows the results from load change tests conducted during operation with a combination of one intake valve deactivation and advanced ignition timing. It is apparent

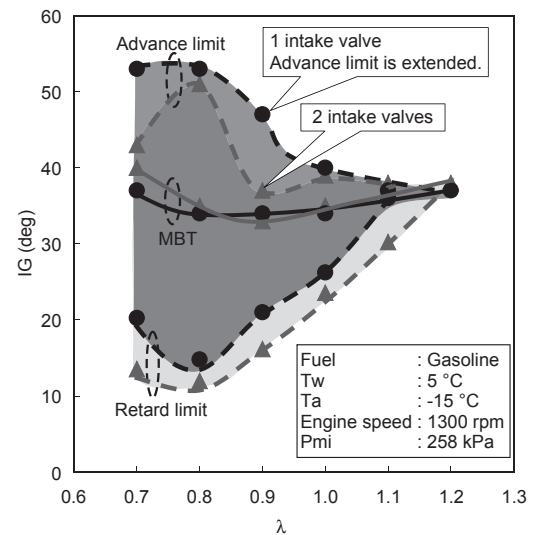


Fig. 13 Comparison of combustion stability zone with one intake valve and two intake valves

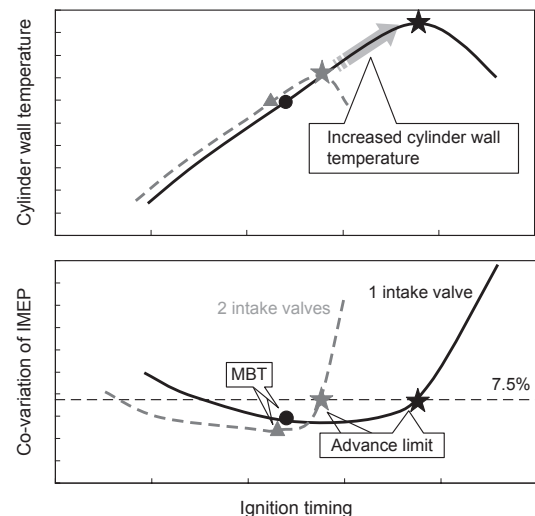


Fig. 14 Effect of ignition timing advance to increase cylinder wall temperature

Table 4 Test result at low ambient temperature

Engine type	Gasoline	FFV (optimized)
Compression ratio	10.5	11.5
Intake valve	2 intake valves	1 intake valve
Ignition timing (Fast idle at low T_w)	MBT	MBT + 5deg
Throttle opening angle (Engine start)	Normal	Close
Fuel	E100	E100
Starting time (sec; $T_a = 20^\circ\text{C}$)	3.4	2.0
Ambient temperature limit ($^\circ\text{C}$; at load change test)	15	-10

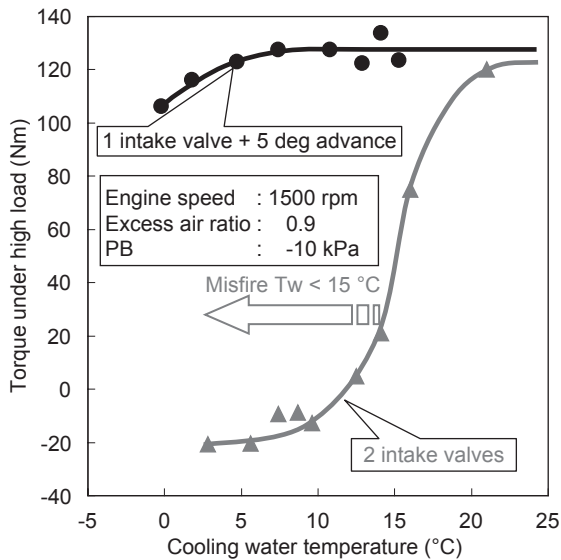


Fig. 15 Relationship between cooling water temperature and torque immediately after shifting to high load

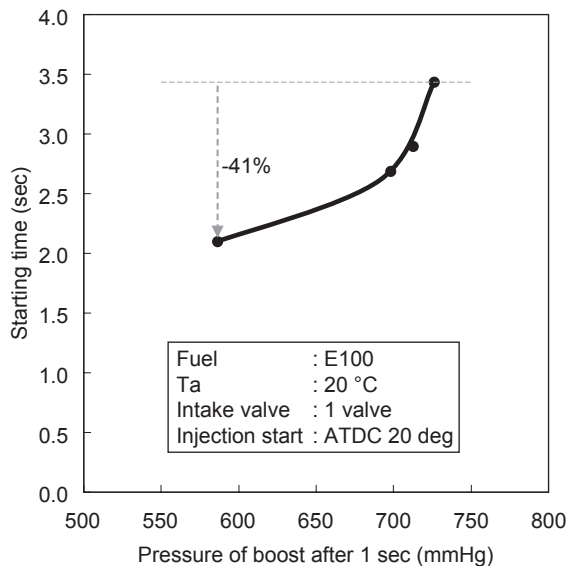


Fig. 16 Relationship between air intake pressure and starting time

that this combination enables high-load operation with E100 alone immediately after startup when the ambient temperature is low.

4.4. Optimizing the Volume of Air-fuel Mixture

As discussed above, the volume of air-fuel mixture is low and vaporizability is favorable under low load. It is conceivable that this characteristic could be used as a method for enhancing vaporizability by reducing the air-fuel mixture during startup to a volume lower than in a gasoline engine. Reducing the volume of air-fuel mixture reduces the quantity of heat required for vaporization. Furthermore, the pressure is reduced without changing the temperature at the compression stroke ends, so there is the additional effect of lowering the boiling point. Figure 16 shows the relationship between air intake pressure and starting time. It is apparent that as the air intake pressure is reduced, the starting time becomes shorter. The engine speed is raised without delay after startup by means of air volume control using drive-by-wire.

5. Effects of Optimizing Engine Specifications

5.1. Verification of Performance at Low Temperatures

Table 4 shows the results of enhanced combustion at low temperatures obtained by operation with one intake valve. Compared to the unmodified gasoline engine used for FFV, the engine with specifications optimized for FFV use has enhanced startability at low temperatures, is capable of load change operation from low water temperatures, and has enhanced commercial product appeal.

5.2. Achieving a Balance of Enhanced Combustion and Power Output

The balance of enhanced combustion at low temperatures with power output achieved through operation with one intake valve is enabled by the valve timing electronic control (VTEC) system. Table 5 shows a comparison of performance of an unmodified gasoline engine used for FFV with an engine optimized for FFV and including VTEC. It is apparent that the performance is enhanced beyond the gasoline engine for fuels from E22 to E100.

Table 5 Test result of engine performance

Engine type		Gasoline		FFV (optimized)	
Fuel		Gasoline	E100	E22	E100
Compression ratio		10.5		11.5	
Valve train system		Normal		VTEC	
	Low engine speed	2 intake valves		1 intake valve	
	High engine speed			2 intake valves	
Power (kW)		97.8	102	101	105
Torque (Nm)	Max	165	173	171	177
	2000 rpm	147	151	150	162

6. Conclusion

When a gasoline engine is applied to FFV use without modification, there will be issues with combustion at low temperatures and related matters. As the result of a search for methods to resolve such issues, the following conclusions were reached:

- (1) The issue of combustion with E100 at low temperatures probably arises because the latent heat of evaporation is approximately three times greater than gasoline. Consequently, the fuel cannot be completely vaporized at low temperatures, so that it adheres to the sleeve and other such areas.
- (2) Selection of an optimal compression ratio can enhance the vaporizability of E100, as well as power output and fuel economy, without degrading the performance when using E22.
- (3) Operation with one intake valve increases flow speed and generates swirls. This can reduce the amount of E100 adhesion at low temperatures, which enhances vaporizability and promotes flame propagation.
- (4) Operation with one intake valve extends the ignition timing advance limit.
- (5) Extension of the ignition timing advance limit can advance the timing beyond MBT, raise the cylinder temperature, and prevent misfires even in load change tests that envision standing starts.
- (6) Limitation of air intake volume during startup causes a reduction in the amount of fuel required, lowers the pressure at compression stroke ends, and lowers the boiling point so that both vaporizability and startability are enhanced.
- (7) By the adoption of VTEC, operation with one intake valve and operation with two intake valves can be utilized differently, thus achieving a balance of maximum power output and commercial product appeal at low ambient temperatures.

Reference

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