

Vaporization Characteristic of High-ethanol Gasoline (E85) and Cold Startability

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ABSTRACT

The research discussed in this paper focused on the vaporization characteristics of high-ethanol gasoline (E85) and cold startability. The cold startability of an E85 (ASTM Class 3) and a gasoline with identical Reid Vapor Pressures (RVP: 71 kPa at 37.8 °C) was tested at -30 °C. When the E85 was injected in the same quantity as that which enabled engine start using gasoline, the engine failed to start. The results of a simulation of the fuel concentration in the air-fuel mixture showed that the mixture concentration formed by the E85 was lower than the mixture concentration formed by the gasoline, and that the E85 mixture did not reach the concentration required for engine start. Meanwhile, the formation of a mixture with a fuel concentration of approximately 2 vol% during cranking was necessary for engine start at low temperatures. Both simulation and test results showed that increasing the fuel injection quantity was an effective method of increasing the mixture concentration. Increasing the RVP of the fuel is another effective method of increasing the mixture concentration. The results of a simulation of the conditions required for low-temperature engine start using E85 at the same injection quantity as gasoline indicated that it would be necessary to increase the RVP of the E85 by approximately 30-35 kPa against that of gasoline.

1. Introduction

Today, concern with energy issues and the reduction of CO₂ emissions are seeing increasing attention directed towards ethanol as an alternative fuel. Ethanol is chiefly produced from plants such as corn, sugar cane, and sugar beets, and can be considered to be carbon neutral, given that the amount of CO₂ released by combustion is equivalent to the amount of CO₂ absorbed by the plants. Ethanol is presently being used as a fuel around the world in a variety of forms. The most common method is to use a mixture of 5-10% ethanol (E5-E10) with gasoline. In Brazil, the use of 100% ethanol (E100) is widespread, and in the EU and U.S., the use of high-alcohol gasoline such as E85, a mixture of 15% gasoline with ethanol, is spreading. When high-ethanol fuels are employed, the reduced vaporization of the ethanol at low temperatures makes cold startability an issue⁽¹⁾⁻⁽⁷⁾. In Brazil, where E100 is in use, a sub-fuel tank containing gasohol, which has good vaporization characteristics, is used at low temperatures in order to increase startability. In Europe

and the U.S., the Reid Vapor Pressure (RVP) of E85 in use is changed seasonally to help ensure cold startability.

It has been reported that there is a close relationship between the RVP of gasoline and cold engine startability⁽⁸⁾. The appropriate mixture concentration is necessary for ignition of the mixture, and the higher the RVP, the easier it becomes to vaporize the fuel and control the air-fuel ratio to the range enabling combustion at low temperatures. E85 displays a different characteristic toward gasoline, and even if its RVP was equivalent to the level enabling engine start using gasoline, the engine would not start. As this indicates, the study of vaporization characteristics is of considerable interest from the perspective of cold startability. However, to date, the majority of studies have focused on modifying engine hardware as a method of increasing cold startability⁽¹⁾⁻⁽⁷⁾, and very few have considered vaporization characteristics⁽⁹⁾. The research discussed in this paper set out to study the vaporization characteristics of E85, and to consider the necessary conditions for cold startability based on the results.

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Table 1 Specifications for ethanol fuel

Property	US E85			EU E85	
	ASTM D5898			CWA 15293	
Volatility class	1	2	3	A	B
Alcohol [vol%]	79 min	74 min	70 min		
Ethanol [vol%]	–			75 min	70 min
Methanol [vol%]	0.5 max			1 max	
High alcohol (C3-C8) [vol%]	2 max			2 max	
Hydrocarbons [vol%]	17-21	17-26	17-30		
Water [vol%]	1 max			1 max	
RVP [kPa]	38-59	48-65	66-83	35-60	50-100

Table 2 Test fuel characteristics

Property	No. 1	No. 2	No. 3	No. 4	No. 5
Standard	ASTM D5898		CWA 15293	ASTM D4814	
Volatility class	1	3	B	C	D
Ethanol [vol%]	81	71	75	–	
Water [vol%]	1	1	1	1	1
RVP [kPa]	40	71	55	71	83

2. Test Conditions

Table 1 shows the current specifications for E85 fuels in the U.S. and EU. The ethanol concentration and RVP of E85 differ seasonally. The minimum ethanol concentration is 70%; the maximum concentration differs depending on the country, but is approximately 85%. RVP becomes higher as seasonal temperatures become colder, to aid cold startability. As a test of high-ethanol gasoline, the research discussed in this paper used E85-Class 1 (Fuel No. 1) and Class 3 (Fuel No. 2), as specified by the U.S. ASTM's D5788-06⁽¹⁰⁾, and E85-Class B (Fuel No. 3), as specified by the EU's CWA 15293⁽¹¹⁾. For comparison, the project used an ASTM D4814-06⁽¹²⁾ Class C gasoline (Fuel No. 4), modified to give it an RVP value equivalent to U.S. Fuel No. 4, and an ASTM D4814-06 Class D gasoline specified for fall and winter use (Fuel No. 5). Table 2 shows the representative characteristics of these fuels. An 1800 cm³ natural-aspiration 4-cylinder engine was employed to evaluate cold startability. Table 3 shows the specifications of the engine. The temperature for evaluation of cold startability was set at -30 °C.

3. Characteristics of High-ethanol Gasoline

3.1. Calculation of Mixture Concentration and Vapor Pressure

The calculation of the mixture concentration and the vapor pressure of multi-component fuels, such as gasoline and E85, is complex because of the presence of interaction of the chemical species, including the azeotropic phenomenon. Calculations in the project discussed in this paper were conducted using the chemical engineering process simulator CHEMDAD, produced by Chemstations, Inc. The components of each fuel for use in the

Table 3 Test engine specifications

Cylinder configuration	In-line 4-cylinder
Bore × Stroke [mm]	81.0 × 87.3
Displacement [cm ³]	1799
Compression ratio	11.5
Valve train	SOHC
Number of valves	4 valves / cylinder
Fuel injection system	MPI

calculations were qualitatively identified using Gas Chromatography-Mass Spectrometry (GC-MS), and were quantitatively determined using a flame ionization detector (FID).

3.2. Relationship between Saturated Vapor Pressure and Cold Startability

Figure 1 shows the temperature characteristics of the saturated vapor pressures of the test fuels. Actually measured values are plotted as points, while the calculated values produced by the simulation are shown as lines. RVP were measured using a SETAVAP TESTER manufactured by Stanhope-Seta, Ltd. Vapor pressure at low temperature was measured by supplying fuel to the stainless steel vessel shown in Fig. 2, and measuring its internal pressure. E85 (Fuel No. 2) and the gasoline modified to make its RVP identical to that of E85 (Fuel No. 4) display largely identical saturated vapor pressures, even at low temperatures. Figure 3 shows the saturated vapor pressure of hydrocarbons (HCs) by carbon number. The results indicate that it is mainly lighter HCs such as butane (C4) and pentane (C5) that form vapor at low temperatures. If it is the light HC components of the fuels that vaporize at -30 °C, then it can be predicted that fuels would display identical cold startability as long as their saturated vapor pressures were the same. Figure 4 shows

the results of tests of engine start at -30°C using Fuel Nos. 2 and 4. In order to help ensure that only the effects of the fuels themselves were reflected in the results, the fuel injection quantity, ignition timing, and other conditions employed in the tests were set at levels that would enable engine start using Fuel No. 4. Contrary to expectations, there was a difference in startability between the fuels, with the engine failing to start when E85 was used. This result suggests that even when their saturated

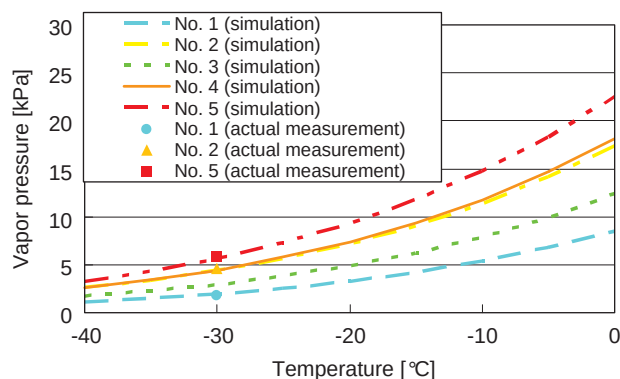


Fig. 1 Vapor pressure of test fuels

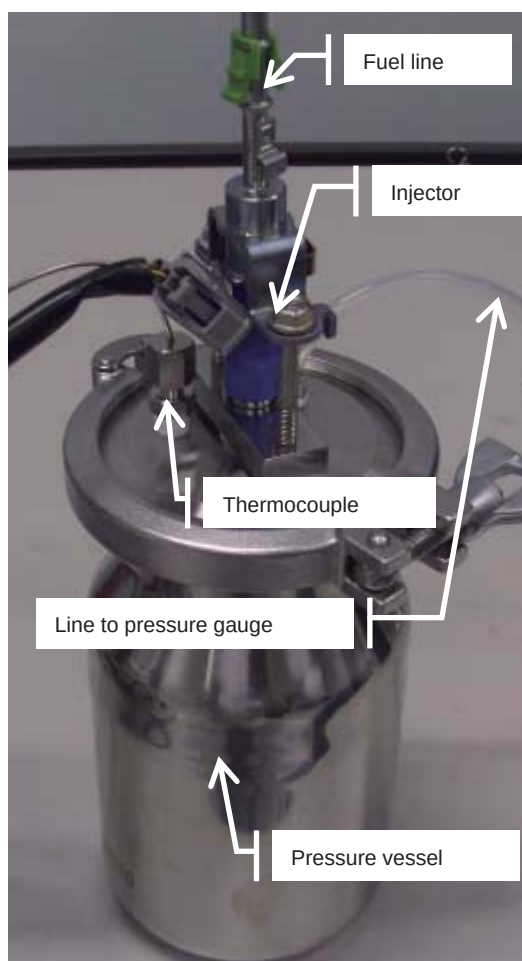


Fig. 2 Vapor pressure measurement device

vapor pressures are identical, the vaporization of E85 differs from that of gasoline.

3.3. Mixture Concentration in Unsaturated Vapor Range

Figure 5 shows the results of simulations of the relationship between fuel injection quantity (amount of fuel injected per 1000 cm^3 of air) and the mixture concentration for Fuel Nos. 2 and 4 at -30°C . When the fuel injection quantity is sufficient, that is, when a saturated vapor exists, both fuels form largely identical mixture concentrations. However, differences occur in the concentrations in ranges in which the fuel injection quantity is insufficient, that is, when the vapor is unsaturated. This is thought to be because the components making up the E85 fuel differ from the components of gasoline. Figure 6 shows the constituent ratio of Fuel Nos. 2 and 4. The ratio of HCs with a carbon number of 5 is higher in Fuel No. 4 (gasoline) than in Fuel No. 2 (E85). It is believed that when the fuel injection quantity is in the unsaturated vapor range, Fuel No. 4, which

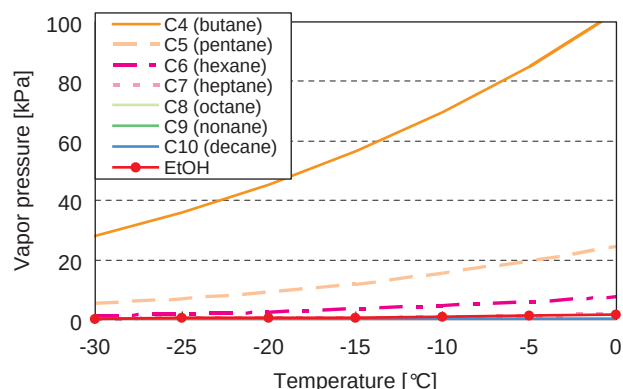
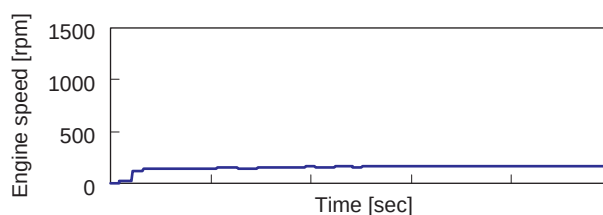
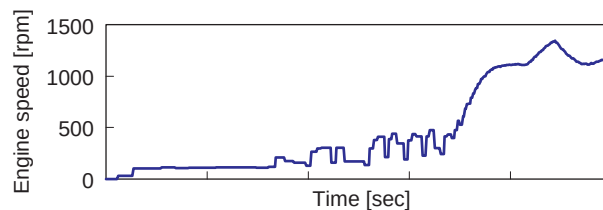


Fig. 3 Vapor pressures of ethanol and hydrocarbons [C4-C10]



(a) Fuel No. 2



(b) Fuel No. 4

Fig. 4 Cold startability with Fuel No. 2 and No. 4 at -30°C

contains a greater quantity of C5 HCs able to vaporize at low temperatures, forms a higher concentration mixture. The fuel injection quantity employed in the engine start tests shown in Fig. 4 was approximately 1 g per 1000 cm³ of air, and the mixture was unsaturated. Under these conditions, the mixture concentration formed by Fuel No. 2 was only approximately 60% that of the Fuel No. 4 mixture. It is believed that this difference in the mixture concentration is related to the difference in cold startability between the fuels.

The results discussed above indicate that even at an identical RVP, E85 vaporizes less than gasoline, and its cold startability is inferior to that of gasoline. The achievement of equivalent cold startability to gasoline would be necessary for the practical use of E85. If the difference in startability was a result of the difference in the mixture concentration formed by the fuels, it was considered that it would be possible to increase the cold startability of E85 by increasing its level of vaporization to equal that of gasoline. Imparting heat energy to the fuel is an effective means of increasing mixture concentration. Increasing the compression ratio or increasing the cranking speed at engine start in order to approach adiabatic compression as closely as possible can be considered methods of imparting heat energy to the fuel. As Fig. 5 shows, increasing the fuel injection quantity is also an effective method of increasing the vaporization of the fuel.

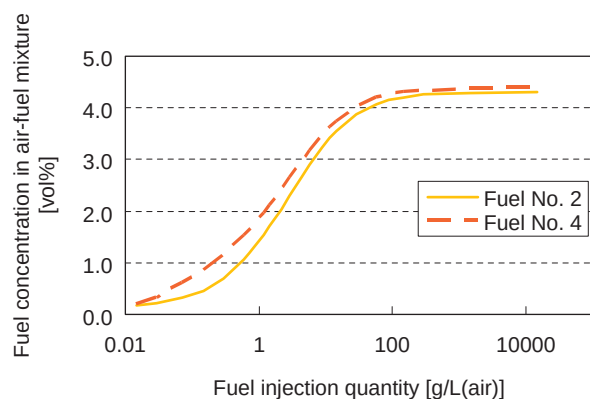


Fig. 5 Relationship between fuel injection quantity and fuel concentration in mixture at -30 °C

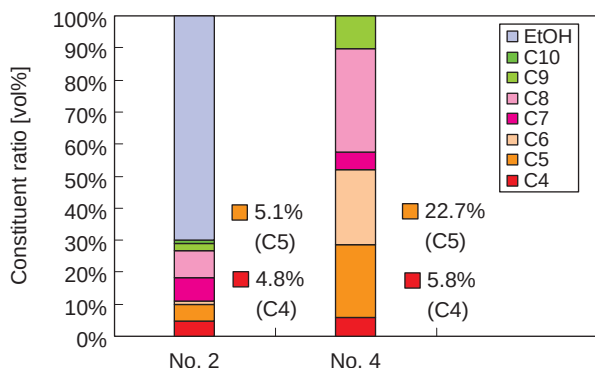


Fig. 6 Constituent ratio of fuel No. 2 and No. 4

Table 4 Combustible concentration of hydrocarbons

	Butane	Pentane
Combustible concentration [vol%]	1.6 – 8.5	1.5 – 7.8

4. Mixture Concentration Required for Engine Start

4.1. Combustible Mixture Concentration

A specific mixture concentration is needed to ignite the air-fuel mixture. For the engine to start, it is necessary for the mixture concentration to enter the range for ignition during the initial engine cranking. The mixture concentration is determined by how much air is mixed with the injected fuel. For this reason, even when there is a small amount of fuel vapor, the amount of air can be adjusted to increase the mixture concentration. However, the pressure of the intake manifold during the initial cranking in actual engine is almost equivalent to the atmospheric pressure, making adjustment of the volume of air a challenge. It was therefore conjectured that the potential for ignition during the initial cranking could be estimated from the mixture concentration formed under atmospheric pressure. Table 4 shows the combustible concentrations⁽¹³⁾ for butane (C4) and pentane (C5), the main fuel components of the mixture at low temperatures. While there will be slight changes in the fuel constituents of the mixture due to the constituents of the fuel and the temperature, because butane and pentane are the main components, estimation of the minimum combustible concentration at below freezing point based on Le Chatelier's principle⁽¹³⁾ gives a value of approximately 1.5 vol% for both gasoline and E85. This means that at low temperatures, unless the mixture concentration is at least 1.5 vol% during initial cranking for both gasoline and E85, the engine will fail to start.

4.2. Mixture Concentration Enabling Engine Start at Low Temperatures

The minimum fuel concentration for ignition of the air-fuel mixture was estimated in Section 4.1, but because in

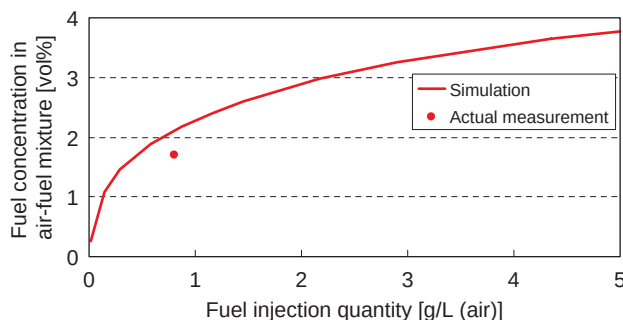


Fig. 7 Relationship between quantity of fuel injection and fuel concentration in combustion chamber for fuel No. 5 at -30 °C

an actual engine only sufficient energy is needed in order to push down the pistons and turn the crankshaft, there are cases in which the formation of a combustible mixture does not provide the condition for engine start, for example when ignition occurs but the engine still fails to start. The mixture concentration that would be necessary during cranking for engine start was therefore studied in the test engine. The fuel used for evaluation was the gasoline with the highest RVP (Fuel No. 5), because it would be possible to control the mixture concentration. A study of the minimum fuel injection quantity required for engine start at -30°C was conducted. The results showed that the minimum required fuel injection quantity was approximately 0.8 g for 1000 cm^3 of air. Figure 7 shows the relationship between the fuel injection quantity for Fuel No. 5 and the mixture concentration at -30°C , as determined by a simulation. The total pressure of the mixture was 1 atm (101.325 kPa). The results show that the mixture concentration reaches approximately 2 vol% at an injection quantity of 0.8 g of gasoline for 1000 cm^3 of air. Measurement of the concentration of a mixture sampled under identical conditions at compression top dead center produced a value of 1.7 vol%. Considering error in the analysis of the mixture, this is almost identical to the simulation result, and it was therefore conjectured that a mixture concentration of at least 2 vol% would be needed to enable the test engine to be started at low temperatures.

5. Effects of Compression Ratio and Cranking Speed

This section will consider the effectiveness of increasing the compression ratio and increasing the cranking speed as methods of increasing vaporization. The temperature changes occurring as a result of compression occur during such short periods that issues of responsiveness make their direct measurement via a thermocouple or other such device challenging. Fuel is made up of multiple components, and this project therefore focused on the changes occurring in the components of the vapor formed during heating. Figure 8 shows simulation results for the constituent ratio of fuel

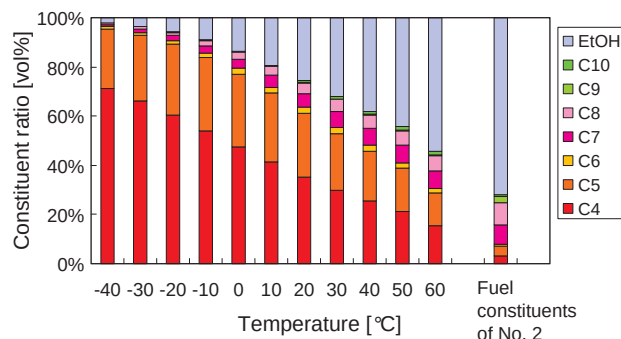


Fig. 8 Temperature dependence of mixture constituents for fuel No. 2

in a mixture of 2.4 g U.S. E85 Class 3 fuel (Fuel No. 2) and 1000 cm^3 of air at a total pressure of 101.325 kPa. The fraction of high-carbon-number HCs and ethanol increases as temperature increases. It was considered that this characteristic could be used to enable estimation of temperature by analyzing the composition of samples of the air-fuel mixture taken directly from the combustion chamber. Figure 9 shows a schematic diagram of the gas

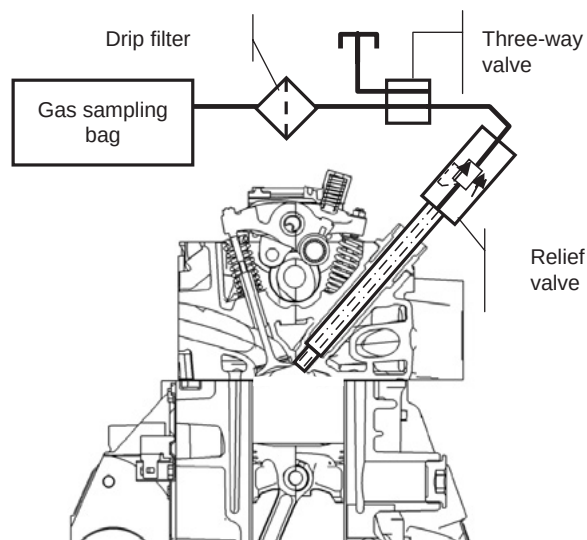


Fig. 9 Gas sampling device

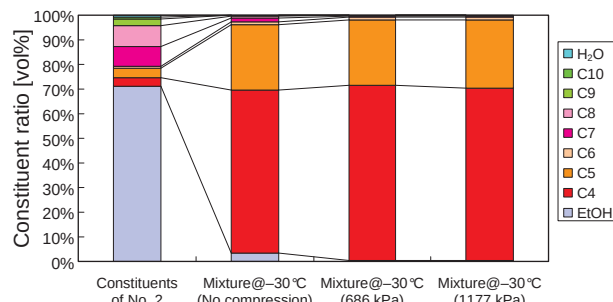


Fig. 10 Comparison of mixture constituents at 668 kPa and 1177 kPa at -30°C

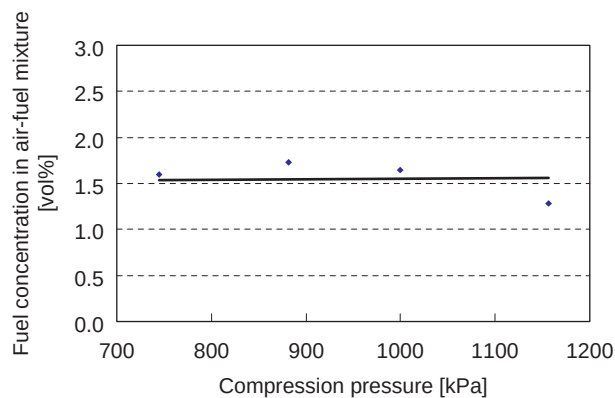


Fig. 11 Relationship between compression pressure and fuel concentration in combustion chamber at -30°C

sampling method. A pipe inserted in the spark plug hole was connected to the pressure relief valve, enabling gas in the combustion to be sampled at any pressure. The sampled gas was collected in an air bag, and its component ratios were analyzed using GC-MS and FID.

5.1. Effect of Compression Ratio

Because gas is sampled from the combustion chamber via the pressure relief valve, it can be sampled at any pressure. Changing the pressure at which the gas is sampled could be considered to be equivalent to changing the compression ratio. The effect of the compression ratio was therefore determined by changing the pressure of the gas sample. The fuel injection quantity was 2.4 g per 450 cm³ cylinder. Figure 10 shows the constituent ratio of mixtures sampled with relief pressures set at 686 kPa and 1177 kPa. The fractions for both gases are almost identical, and are similar to the fractions obtained from the simulation at -30 °C. Figure 11 shows the concentrations of mixtures sampled at various relief pressures. There is almost no change in mixture concentration in relation to relief pressure (that is, compression pressure). These results suggest that almost no increase in vaporization results from a change in the compression pressure. If the pressure prior to compression is 1 atm, and the polytropic exponent is 1.3, then a difference of around 2.3 will be produced in the

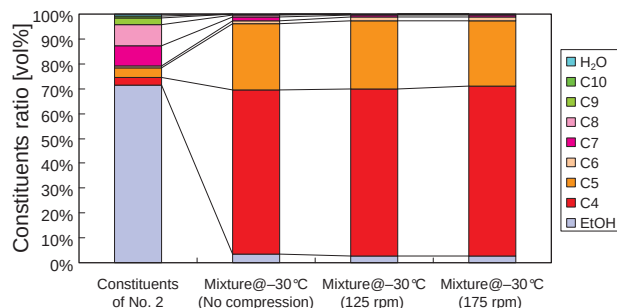


Fig. 12 Comparison of mixture constituents at 125 rpm and 175 rpm at -30 °C

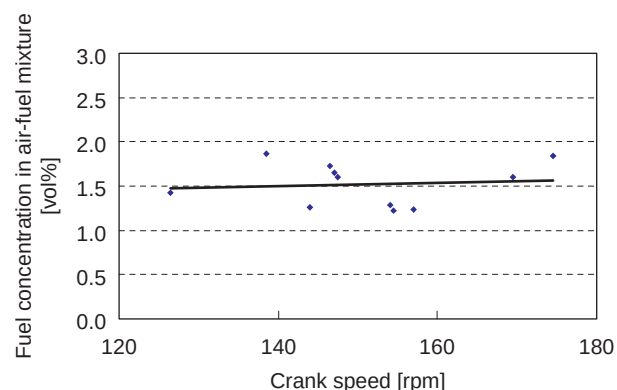


Fig. 13 Relationship between crank speed and fuel concentration in combustion chamber at -30 °C

compression ratio, which should result in a difference of 50 °C in the temperature at compression top dead center. The reason for the minimal effect of increasing the compression pressure can be considered as follows. Under low temperature conditions, the engine itself is at a low temperature, and heat generated by compression flows away to the engine without generating a substantial increase in temperature; or, even if there is an increase in temperature, because the thermal conductivity of the fuel droplets is low and only an instant is available for the droplets to absorb compression heat, they do not increase in temperature and fail to vaporize.

5.2. Effect of Cranking Speed

Figure 12 shows the constituent ratio of mixtures sampled at cranking speeds of 125 rpm and 175 rpm. Fuel and fuel injection quantity were identical to those employed in the study of the effect of the compression ratio. As in the case of the previous study, when cranking speed is varied, fractions for both mixtures are almost identical, and are similar to the fractions obtained from the simulation at -30 °C. Figure 13 shows the mixture concentration sampled at various cranking speeds, as in the previous tests. No increase in mixture concentration is observed as the cranking speed is varied. These results indicate that at low temperatures, increasing the compression ratio or cranking speed would have little effect in terms of increasing cold startability.

6. Effect of Increasing Fuel Injection Quantity

The results discussed in Chapter 5 showed that the fuel compositions of air-fuel mixtures sampled following compression were largely identical to those of mixtures sampled prior to compression. This suggests that the mixture concentration before the mixture enters the cylinder is important for cold startability. As Fig. 5 shows, increasing the fuel injection quantity is an effective method of increasing the mixture concentration before the mixture enters the cylinder. Figure 14 shows simulation

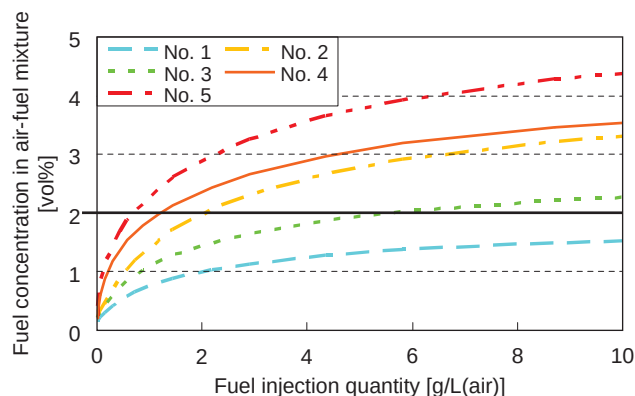


Fig. 14 Relationship between fuel injection quantity and simulated fuel concentration in mixture for test fuels at -30 °C

results for the relationship between fuel injection quantity and mixture concentration at -30°C . The results show that increasing the fuel injection quantity enables cold season E85 (Fuel Nos. 2 and 3) to reach a mixture concentration of 2 vol%. As indicated in Section 3.2, when the fuel injection quantity was not adjusted, the test engine failed to start at -30°C when Fuel No. 2 was used. It was concluded in Section 4.2 that a mixture concentration of approximately 2.0 vol% would be necessary for engine start, but as Fig. 14 shows, increasing the injection amount of Fuel No. 2 would potentially enable engine start at -30°C . By contrast, even if the injection quantity of Fuel No. 1 was increased, the mixture would not reach a concentration of 2 vol%, and there would be little possibility of engine start at -30°C . This is because the mixture concentration as determined from the saturated vapor pressure at -30°C , 1.85 vol%, is the highest concentration that can be formed by this fuel. A simulation based on the maximum injection quantity possible in the test engine indicated that under these conditions Fuel No. 1 would reach a mixture concentration of approximately 1.2 vol%. Based on simulation results, therefore, increasing the injection amount of Fuel No. 1 would not enable engine start at -30°C using this fuel.

7. Verification in Actual Vehicle

Figure 15 shows the results of tests of cold startability

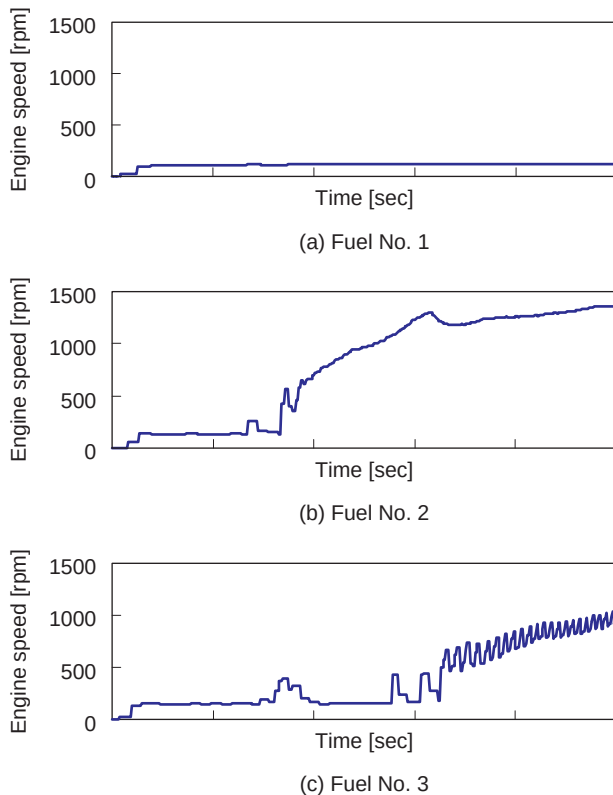


Fig. 15 Cold startability with optimized fuel injection quantity at -30°C

at -30°C using E85 fuels (Fuel Nos. 1, 2, and 3) at the fuel injection quantities that the simulation had indicated would produce a mixture concentration of 2 vol%. The simulation had indicated that Fuel No. 1 would not reach a concentration of 2 vol%, and therefore in this case the fuel was supplied in the highest quantity possible to the test engine. The engine took longer to start the lower the RVP of the fuel, but adjustment of the injection quantity of Fuel Nos. 2 and 3 enabled engine start at -30°C . The engine failed to start when Fuel No. 1, which the simulation had indicated could not achieve a combustible mixture concentration, was employed. The results indicate that increasing the fuel injection quantity is effective in increasing the mixture concentration, but that it is only effective for fuels that are able to reach the necessary engine start concentration when the injection quantity is increased.

8. Limit Temperatures for Engine Start using E85 Fuels

Figure 16 shows simulation results for mixture concentrations at -30°C for E85 fuels with various RVPs. The fuel injection quantity was the maximum amount that could be supplied to the test engine, 4.8 g

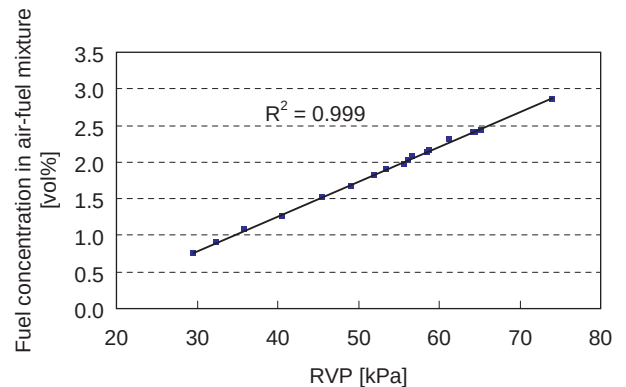


Fig. 16 Relationship between RVP and fuel concentration in mixture at maximum fuel injection quantity in test engine at -30°C

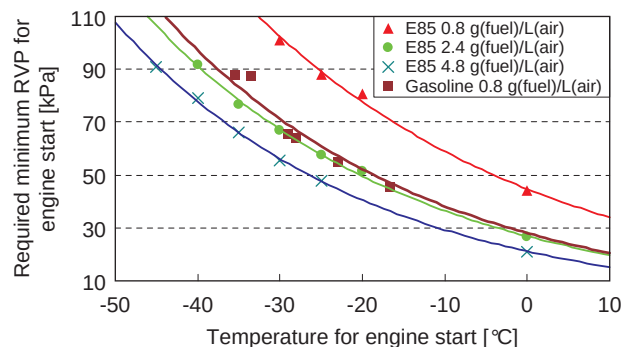


Fig. 17 Estimation of required RVP for cold engine start

per 1000 cm³ of air. While there is some variation due to the fuel composition, there is an almost exact correlation between RVP and the mixture concentration. At an RVP of 55 kPa, E85 reaches a mixture concentration of 2 vol%. It was therefore predicted that the test engine would start at -30 °C using E85 with an RVP of 55 kPa or more at the maximum injection quantity. The RVPs at which the engine would start at various temperatures and injection quantities were also estimated. The results are shown in Fig. 17. Figures for gasoline are also included for purposes of comparison. The results indicate that the minimum temperature for engine start using E85 is dependent on RVP and fuel injection quantity, as it is in the case of gasoline. Comparing the fuels at the same injection quantity (0.8 g per 1000 cm³ of air), it would be necessary to set the RVP of the E85 30-35 kPa higher than the gasoline in order to achieve engine start. If the injection quantity was to be increased, it would be necessary to increase the quantity of the E85 by three times when ASTM Class 3 fuel is used, and by six times when CWA Class B fuel is used, against the gasoline.

9. Discussion

The results of the project discussed here show that E85 displays lower vaporization characteristics, and thus inferior cold startability when compared to the gasoline with an identical RVP. This is because the fuel concentration in the mixture formed by the E85 is lower than that of the mixture formed by the gasoline, even when the RVP of the fuels is identical. At low temperatures, light HCs with carbon numbers of C4 and C5 are the main HC components of the air-fuel mixture, and it is therefore important to increase the concentration of these HCs. The results of this project have shown that increasing the fuel injection quantity is an effective means of doing so. This is because increasing the supply of fuel increases the absolute volume of C4 and C5 HCs. However, there are drawbacks to increasing the fuel injection quantity, such as the fact that fuel efficiency declines when the fuel injection quantity is increased⁽¹⁴⁾. In addition, unless the fuel has a specific vapor pressure, increasing the fuel injection quantity will not have any effect. An alternative method is to increase the RVP of the fuel. This method is able to increase the mixture concentration, and is therefore a certain method of increasing cold startability. However, it would be necessary to increase the RVP of the E85 by 30-35 kPa against that of gasoline. If the RVP is increased to some extent, it may result in vapor lock. Given this, the achievement of a balance between the fuel injection quantity and fuel properties is important from the perspective of cold startability, and it will be necessary to sufficiently research these parameters in order to enable practical use of high-ethanol gasoline.

10. Conclusion

The research discussed in this paper studied the relationship between the vaporization characteristics and the cold startability of high-ethanol gasoline. The following results were obtained:

- (1) When E85 and gasoline with identical RVP values were compared, the E85 displayed less vaporization than the gasoline, and its cold startability was inferior to that of the gasoline.
- (2) When the fuel concentration in the E85 air-fuel mixture was made equivalent to that of the gasoline mixture, the E85 displayed equivalent startability to gasoline. A mixture concentration of approximately 2.0 vol% would be necessary for engine start at low temperatures.
- (3) The main fuel components of the mixture at low temperatures are HCs with carbon numbers of C4 and C5.
- (4) Increasing the fuel injection quantity and increasing the RVP of the fuel are both effective methods of increasing the mixture concentration.
- (5) In order to achieve equivalent startability to gasoline, it would be necessary to increase the quantity of the E85 by three times when ASTM Class 3 fuel is used, and by six times when CWA Class B fuel is used, against the gasoline.

11. Afterword

The current U.S. ASTM D5788-06 and EU E85 specification CWA-15293 stipulate minimum RVPs for cold season E85 of 66 kPa and 50 kPa, respectively. Based on these values, for cold startability at -30 °C and below, the respective injection quantities required for the fuels would be, respectively, three times and six times that of gasoline (ASTM D4814-06 Class D, RVP83), as discussed in Chapter 10. Revision of the RVP specifications would therefore be desirable from the perspective of realizing more efficient cold startability.

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