

Construction of Hierarchical Scatter-band Data for Engine Specification Study in Model-based Development Realization

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ABSTRACT

Hierarchical scatter-bands were constructed to determine engine specifications in the early stages of development, and development efficiency was enhanced. The four elements of thermal efficiency and combustion stability, oil dilution, and soot, which conflict with thermal efficiency, were defined and the requirements of intermediate parameters were analyzed in order to link them to parts step by step. Using engine data, it was confirmed that the parameter linkages are generally correct. The issues of turbocharged direct injection engines and their causes were analyzed based on system characteristic analysis and requirement analysis using scatter-bands, thereby enabling efficient implement countermeasures. The in-cylinder flow was enhanced by changing the piston top to a shallow dish shape, which decreased the combustion period by 0.5 deg. and reduced the brake specific fuel consumption by approximately 0.6%. Countermeasures were also implemented for conflicting events, and the injection control was changed. This reduced the oil dilution rate by 2.6 wt% and allowed balancing of the performance demanded of the engine.

1. Introduction

Automotive regulations continue to become stricter year by year against backdrops such as global warming and air pollution. The Corporate Average Fuel Economy (CAFE) method is adopted in fuel economy regulations, making it necessary to enhance the average fuel economy of not only specific models but of all vehicles sold. In addition, Real Drive Emission (RDE) regulations have been introduced in emissions (EM) regulations, necessitating compliance with EM limit values even in real environments including low temperatures. To address these issues, gasoline engines use technologies such as mitigation of knock by direct injection (DI) and reduction of soot by high fuel pressure and multi-stage injection, etc. Thus, it is necessary to design engine specifications that satisfy multiple requirements under various conditions, making engine combustion design increasingly complex.

Automobile manufacturers are continuing to promote

higher development efficiency by using the MBD-V process, which combines the V-process and Model-Based Development (MBD). The MBD-V process is a means of establishing a design and verification process hierarchy and front-loading by using models in the design stage of each level⁽¹⁾. Advantages of applying MBD to development are that the accuracy of the main specifications of engines can be increased before prototyping in the early stages of development, the development period can be shortened, and the required performance can be achieved in a shorter period. Here, the models in MBD include control models such as engine control units, models of control targets, and CAE models of combustion, structural strength, sound vibration, etc.⁽²⁾

In application of CAE models to MBD, detailed and large-scale CAE entails time and cost. For this reason, CAE is repeatedly performed using engine specifications that do not meet performance target values, resulting in development reworking. The first example of reworking in engine development is the case when changing the

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intake port shape to enhance the in-cylinder flow due to the relationship between Brake Specific Fuel Consumption (BSFC) and steady-state tumble ratio (T/R). The target steady-state T/R may not have sufficient effect to reduce BSFC, making it necessary to re-examine enhancement of the in-cylinder flow. This is because it is a challenge to obtain the target engine performance with only target values at the parts level, requiring design of intermediate parameters that link the two. The second example of reworking occurs when changing to DI with the goal of mitigation of knock by cooling the intake air. DI provides effects to enhance thermal efficiency by mitigation of knock but may also reduce combustion stability due to inhomogeneous fuel distribution and increase the oil dilution rate and soot due to increased fuel adhesion on the in-cylinder wall surfaces. Therefore, in order to evaluate the impact of specification changes from multiple perspectives, it is considered necessary to use the same criteria among engines with multiple requirements and differing specifications.

Attempts are being made to use scatter-bands to increase the accuracy of engine specifications in the early stages of development to avoid reworking. For example, the certainty of specifications is increased by setting target values for turbulent intensity needed for EGR combustion^{(3), (4)}, reducing the fuel adhesion quantity to reduce the oil dilution rate⁽⁵⁾, and understanding the positioning of the intake port embedded in the cylinder head⁽⁶⁾. Here, scatter-band refers to a point cloud with a trend obtained by combining test and CFD data of engines developed in the past based on related parameters.

Conventional scatter-bands do not indicate in steps the parameters that link the performance targets demanded of engines with parts. In addition, the same criteria for comparing engines with different specifications may not be indicated. For this reason, conventional scatter-bands were considered inadequate to avoid the aforementioned reworking cases. The authors therefore constructed hierarchical scatter-band data that links engine performance and parts in steps in order to reduce reworking by increasing the certainty of engine specifications in the early stages of development. Furthermore, in order to evaluate the performance demanded of engines from multiple perspectives, the linkages of intermediate parameters between engine performance and parts were also clarified in a hierarchical manner for thermal efficiency, which is to be enhanced, and for multiple elements that conflict with thermal efficiency and thus call for confirmation. Parameter normalization was also performed in order to evaluate engines with different specifications using the same criteria. The constructed hierarchical scatter-bands were applied to promote the combustion of a turbocharged DI engine in order to verify the effectiveness, and this report describes these contents.

2. Examination of Hierarchical Scatter-band Data

2.1. Definition of Levels in V-process

Various engine phenomena such as intake and exhaust, fuel vaporization, and combustion proceed while interacting with each other, so engine performance such as power and fuel consumption is determined by many parameters. Therefore, in order to organize the parameters accumulated in scatter-bands, first the levels of the V-process in engine development were defined. Figure 1 shows the definition of the levels in the V-process. The left side of the V-process is Design, the right side is Verification, and the processes are divided into the five levels of L0: Vehicle, L1: Powertrain, L2: Engine, L3: Function, and L4: Parts. Here, L3: Function is defined as the function system (sub-system) comprising the multiple parts connecting L2: Engine and L4: Parts. For example, the combustion system consists of the cylinder head, piston, and injector (INJ), etc. Requirement parameters and target values are set in steps from L0: Vehicle to L1: Powertrain, L2: Engine, and then L4: Parts, and verification is performed by optical engines and actual engines of the same level.

Figure 2 shows a schematic diagram of scatter-band utilization in the development phase. The V-flow shown in Fig. 1 is applied to the three phases of research (hereinafter, R), pre-mass-production development (hereinafter, Pre-D), and mass-production development (hereinafter, D). The engine specifications are determined from R to the first half of Pre-D, and calibration of engine characteristics is performed from the latter half of Pre-D to D. It was thought that, since a scatter-band composed of engines already in mass production would facilitate judgment of the appropriateness of the examined specifications, data accumulation was performed in the D phase after the completion of calibration. In addition, the accumulated data is applied in the early stages of the R phase in which the next engine specifications are examined. It was assumed that scatter-bands would be used for characteristic analysis, positioning evaluation, and rough target value setting before performing large-scale CAE. To achieve this, the definitions and conditions to be accumulated as scatter-bands were examined from the following perspectives.

- Data that can be utilized in the early stages of development
- Definition and accumulation of parameters that interact with each other from L2: Engine to L3: Function and then to L4: Parts
- Evaluation can be performed using the same criteria even with different engine specifications such as displacement and natural aspiration (NA) or turbocharger (TC)

2.2. Examination of Engine Requirements (L2) and Operating Conditions

The engine requirements (L2) and operating conditions were examined in order to obtain data that can be utilized

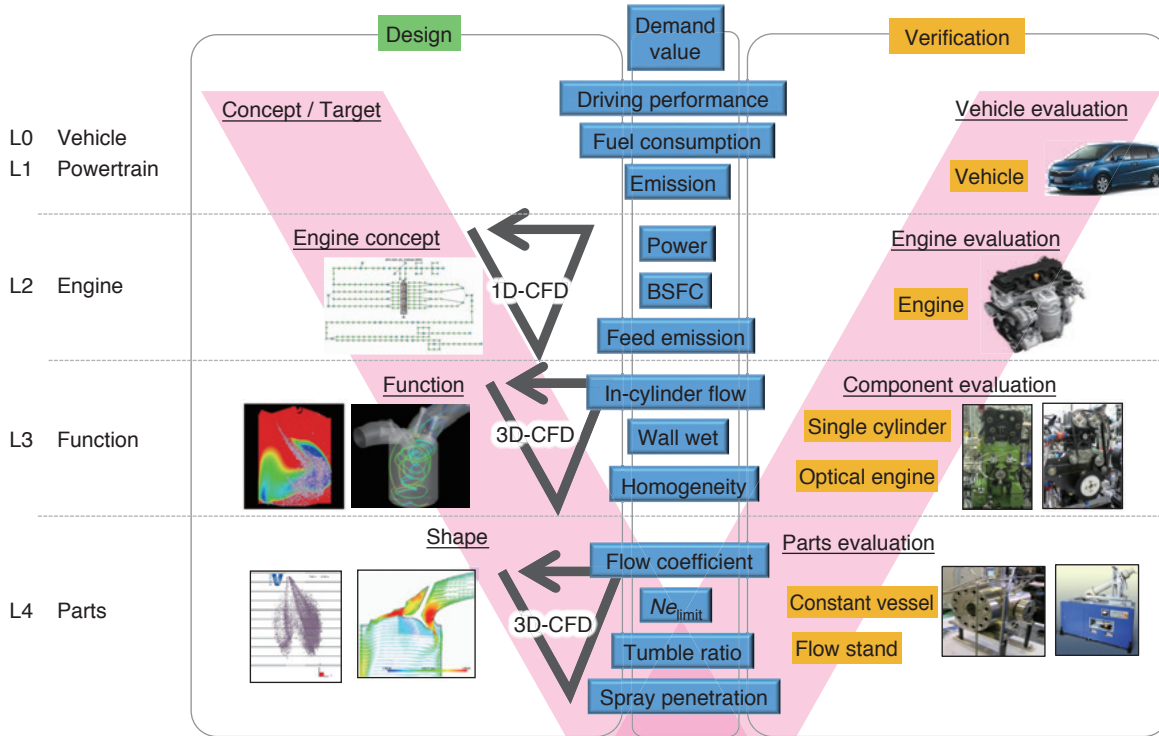


Fig. 1 Definition of each level in V-process for engine development

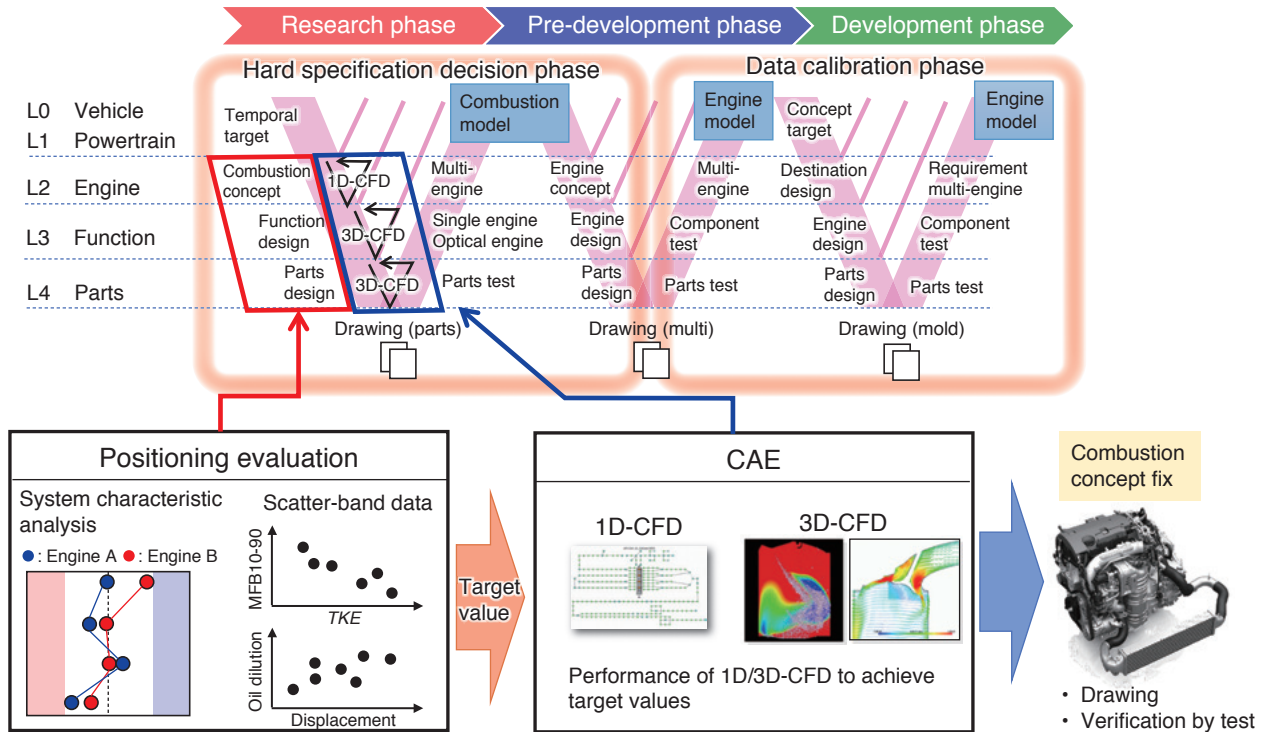


Fig. 2 Schematic diagram for utilization of scatter-band data in each development phase

in the early stages of development. The four elements of thermal efficiency, which is targeted for enhancement, and combustion stability, oil dilution, and soot, which conflict with thermal efficiency, were defined as engine requirements. In examination of operating conditions, eight types of average operating conditions were selected for engines mass-produced in the past ranging from inline 3-cylinder to V-type 6-cylinder engines with different bores, strokes, intake, and fuel supply systems. Table 1 shows the operating conditions, and Fig. 3 shows the schematic diagram. Here, N_e is the engine speed and T_w is the engine water temperature. In examination of thermal efficiency, $N_e = 1500$ rpm, and $T_w = 80^\circ\text{C}$ were set. Since thermal efficiency including friction is to be evaluated, the load was the Brake Mean Effective Pressure (BMEP), and three conditions were selected. In examination of combustion stability, the load was the Indicated Mean Effective Pressure (IMEP) in order to evaluate only the combustion state. From the viewpoint of vehicle drivability in the low engine speed, high-load range, IMEP was set to 1000 kPa for NA and 1600 kPa for TC. In examination of oil dilution, which tends to increase at low water temperatures, $T_w = 50^\circ\text{C}$ was set. With regards to soot, N_e , the load, and T_w were selected according to fast idle for early warm-up in the first half and extra-high vehicle speed in the second half of the mode in the Worldwide harmonized Light vehicles Test Cycles (WLTC). The air/fuel ratio (A/F) was the stoichiometric A/F for regular gasoline (RON91), and external EGR was 0%.

Table 2 shows the engine control conditions. The exhaust valve close (EVC) and intake valve open (IVO) timings were fixed in order to make the residual gas quantity in the cylinder as similar as possible. The valve lift curves set for each engine were used. The fuel injection timing θ_{inj} was set as the End Of Injection (EOI) for intake port injection (PI) and the Start Of Injection (SOI) for DI, and the average conditions for the aforementioned eight types of engines were selected. As the ignition timing θ_{ig} impacts the quality of combustion, the optimal ignition timing (Minimum advance for Best Torque: MBT) was

Table 1 Engine operating condition for scatter-band

Engine requirement (L2)		N_e [rpm]	Load [kPa]	T_w [°C]	A/F
Thermal efficiency		1500	BMEP 400 BMEP 600 BMEP 800	80	Stoichiometric
Combustion stability		2000	NA: IMEP 1000 TC: IMEP 1600	80	Stoichiometric
Oil dilution		2500	NA: IMEP 1000 TC: IMEP 1600	50	Stoichiometric
Soot (PM/PN)	Fast idle	1500	BMEP 200	40	Stoichiometric
	Extra high	2500	IMEP 1000	80	Stoichiometric

Table 2 Engine control conditions for scatter-band

Valve timing	IVO: -10 deg. BTDC EVC: -10 deg. ATDC
P_f	PI: 0.4 MPa DI: 12 Mpa
θ_{inj}	PI: -30 deg. BTDC (EOI) DI: -60 deg. BTDC (SOI)
θ_{ig}	MBT 10 deg. BTDC (fast idle)

used and θ_{ig} was fixed to -10 deg. Before Top Dead Center (BTDC) for fast idle. This control condition was applied to all the operating conditions shown in Table 1.

2.3. Definition of Intermediate Parameters (L3)

In order to construct scatter-bands with parameters that interact between each level from Engine (L2) to Function (L3) and then to Parts (L4), Function (L3) is divided into four parts as shown in Fig. 4. L3-1 is assigned factors to be enhanced such as indicated thermal efficiency η_i and volumetric efficiency η_v as well as factors to be reduced such as time loss. L3-2 is assigned factors that determine combustion characteristic such as in-cylinder pressure, and L3-3 is assigned factors just before combustion that realize combustion characteristics (L3-2) such as turbulent kinetic energy (TKE)⁽⁷⁾. L3-4 is assigned factors determined by combinations of multiple parts such as the surface/volume ratio (S/V) in the combustion chamber, and L4 is assigned single-part specifications and control parameters such as θ_{ig} and θ_{inj} .

Requirement analysis was performed to extract parameters step by step according to the definitions in Fig. 4. When performing requirement analysis, in order to emphasize simplicity and ease of intuitive comprehension, a method that links parameters considered to be empirically sensitive was selected. Figure 5(a) shows the requirement analysis for thermal efficiency.

The BSFC which is the requirement for engines is linked to the indicated thermal efficiency η_i and various losses such as time loss. Time loss is linked to the crank angle MFB50 with a mass fraction burnt (MFB) of 50% and then to the crank angle MFB10-90 with an MFB of 10% to 90%. Here, as MFB50 results in the highest thermal efficiency around 368 deg. ATDC, it is used to evaluate the

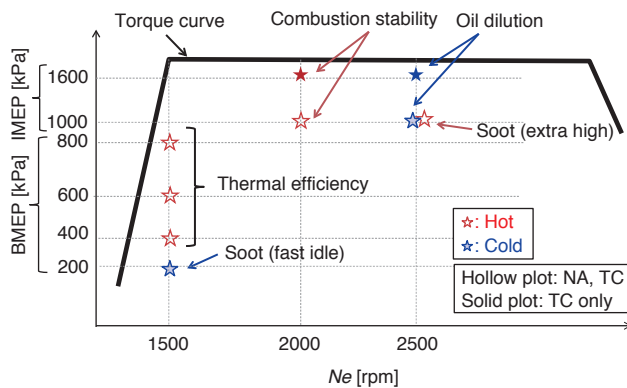


Fig. 3 Schematic diagram of engine operating condition for scatter-band

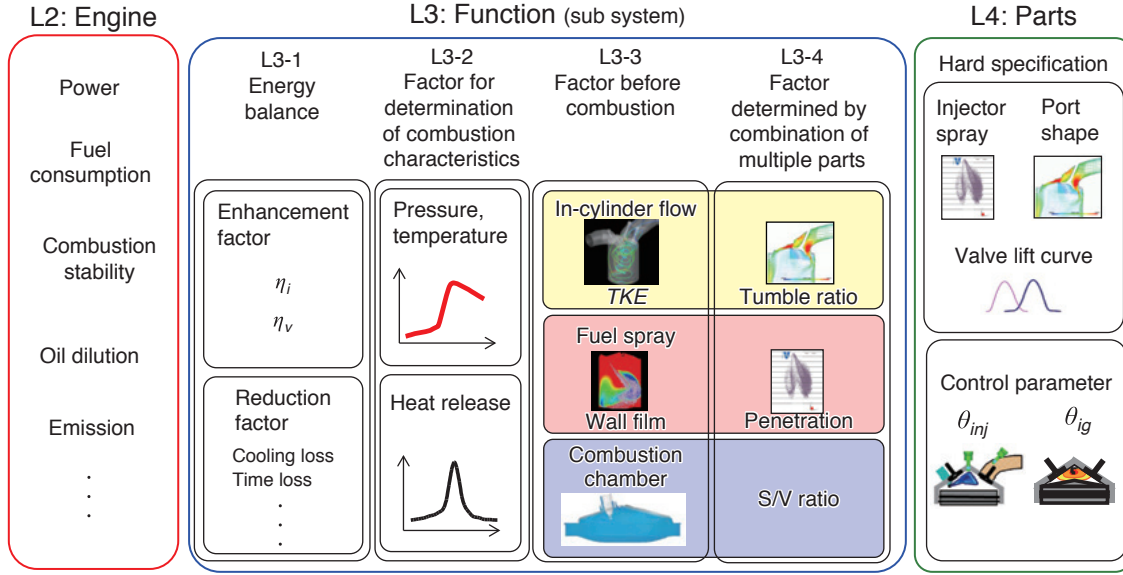


Fig. 4 Definition of parameters in L2: Engine; L3: Function (Sub system); L4: Parts

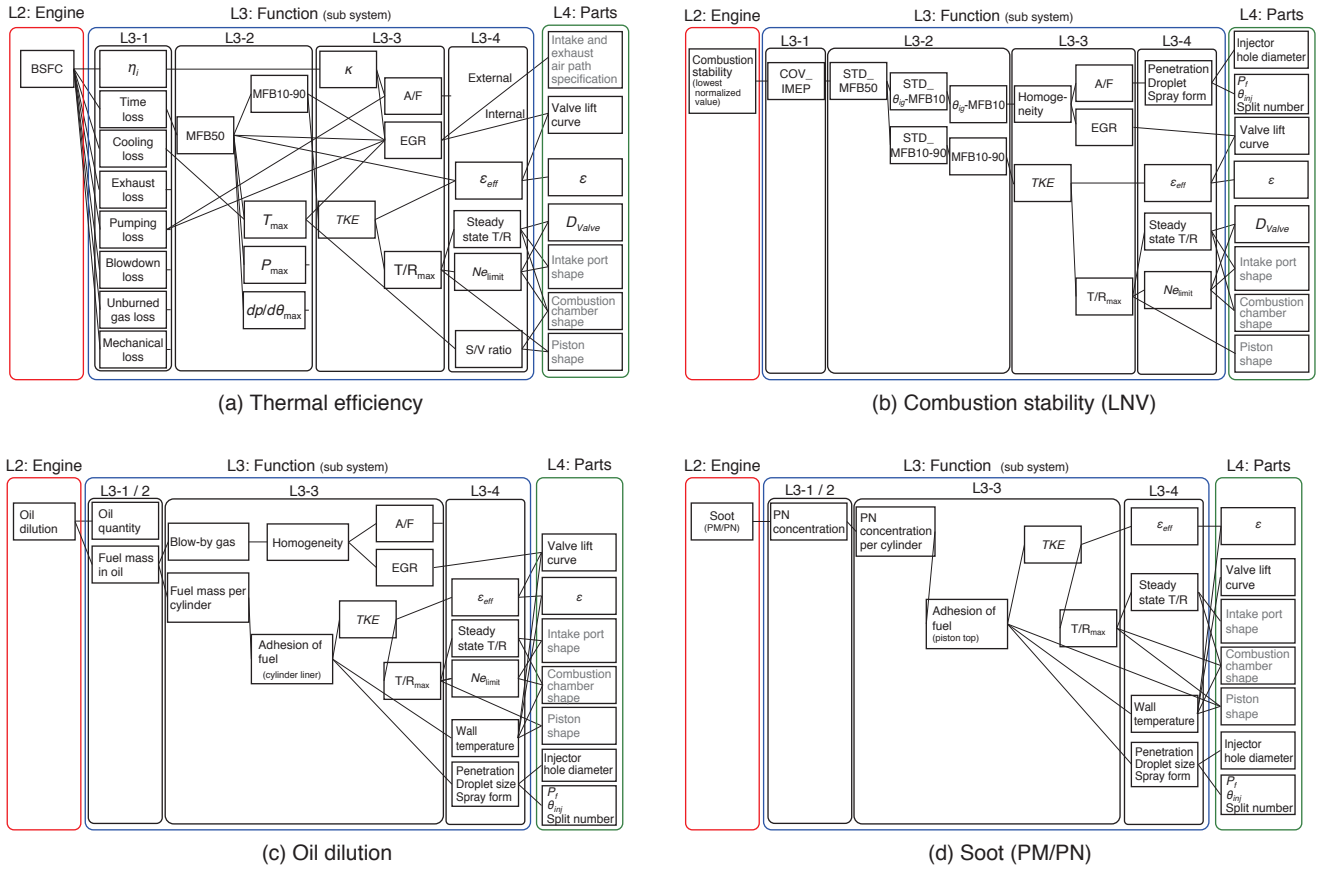


Fig. 5 Requirement analysis which were empirically linked with parameters

knock mitigation effect⁽⁸⁾. MFB10-90 is linked to TKE , T/R, and steady-state T/R in that order. Note that although data on parameters indicated in gray in the figure, such as intake port, has not been accumulated, however the need to change specifications and the direction of countermeasures can be determined based on the relationships shown.

Figure 5(b) shows the requirement analysis for combustion stability. The lowest normalized value (LNV) obtained by dividing the smallest IMEP in the cycle by its mean is linked to IMEP coefficient of variation (COV), STD_MFB50, which is the standard deviation of MFB50, and then to STD_θ_{ig}-MFB10, which is the standard deviation of the crank angle θ_{ig}-MFB10 at which the MFB from θ_{ig} is 10%. It is then further linked to the A/F homogeneity, the spray penetration and droplet size, and the INJ hole diameter and fuel injection pressure P_p etc., showing that the A/F homogeneity impacts combustion stability. On the other hand, STD_MFB50 is also linked to TKE , and the flow also impacts combustion stability.

Figure 5(c) shows the requirement analysis for oil dilution. Oil dilution is linked to fuel in the blow-by gas that escapes from the combustion chamber to the oil pan, and to fuel adhesion to the cylinder liner. Adhesion of fuel on the cylinder liner wall surface is linked to penetration and P_p etc. On the other hand, it is also linked to flow-related parameters such as T/R_{max}, showing that the in-cylinder flow impacts oil dilution.

Soot requirement analysis is performed for the Particle Number (PN) shown in Fig. 5(d), but the same trend is also seen for the Particulate Matter (PM) mass. The PN per cylinder discharged from each cylinder is mainly linked to fuel adhesion to the piston top, and then further connected to the spray penetration, etc.

The reworking cases described in Chapter 1 were analyzed as a method of utilizing factor analysis. The requirement analysis in Fig. 5(a) shows that combustion design of TKE is needed for the main intermediate parameters of BSFC and steady-state T/R in the first reworking case. In the second reworking case, Fig. 5(b) confirmed that INJ specifications (L4) impact combustion stability via A/F homogeneity (L3-3).

2.4. Examination Related to Normalization of Accumulated Parameters

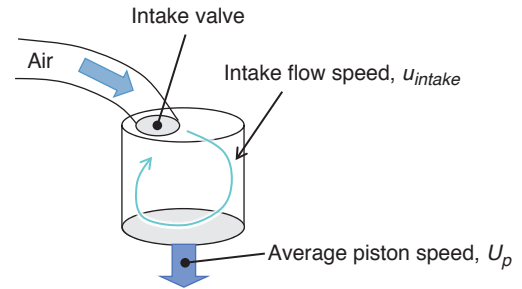
Normalization is needed in order to evaluate different engine specifications using the same criteria. For example, BMEP and η_v are normalized by displacement, enabling comparison of different engine specifications. This section describes normalization of TKE as an example. The flame structure in an engine in-cylinder is considered to be classified as a wrinkled laminar flame regime, and enhancement of the turbulence is known to increase the burning velocity⁽⁹⁾. Here, even if the specifications impacting the in-cylinder flow such as the intake port shape are the same, the burning velocity increases together with Ne ⁽¹⁰⁾. Also, even if the turbulent intensity is the same,

if the bore diameter differs, the combustion period will not be the same due to the different flame propagation distance. An attempt was therefore made to correct TKE so that even data obtained with different Ne and bore diameters can be compared using the same criteria. Figure 6 shows the approach to corrected TKE . First, correction by engine speed Ne was examined. In an engine with the same intake system specifications, the average piston speed U_p is obtained from the stroke L_s and the engine speed Ne as shown in Eq. (1). As shown in Fig. 6(a), when U_p increases, the difference between the intake port pressure and the in-cylinder pressure increases, also increasing the intake flow speed u_{intake} . The in-cylinder flow is enhanced by the increase in intake flow speed u_{intake} , also increasing turbulent intensity u' . Note that TKE can be obtained from u' by Eq. (2).

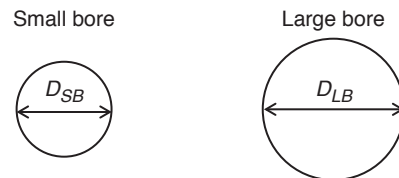
$$U_p = \frac{L_s}{60 / (Ne \times 2)} \propto u_{intake} \quad (1)$$

$$u_{intake} \propto u' = \sqrt{\frac{2}{3} TKE} \quad (2)$$

As U_p is proportional to Ne , it is thought that the turbulent intensity can be corrected by the ratio of Ne . Next, correction by bore diameter was examined. On the left side of Eq. (3), the combustion characteristic time is calculated by dividing MFB10-90 by $Ne/60$. It is thought that when the spark plug is positioned in the center of the bore, this characteristic time is equivalent to the time for the flame



(a) Correction by engine speed



(b) Correction by bore diameter

Fig. 6 Method of corrected turbulent kinetic energy, TKE_{corr}

kernel generated near the spark plug to propagate over the bore radius $D/2$. The time for the flame to propagate varies according to turbulent intensity u' , so the combustion characteristic time on the left side of Eq. (3) is assumed to correlate with the value obtained by dividing the $D/2$ shown in the center of Eq. (3) by u' . Next, in order to make the combustion characteristic time obtained by dividing the small-diameter bore D_{SB} shown in the center of Eq. (3) by u'_{SB} and the combustion characteristic time of the large-diameter bore D_{LB} shown on the right side of Eq. (3) the same, it is necessary to increase u'_{LB} as the bore diameter increases.

$$\frac{MFB_{10-90}}{Ne/60} \sim \frac{D_{SB}/2}{u'_{SB}} \approx \frac{D_{LB}/2}{u'_{LB}} \quad (3)$$

Here, the subscript SB indicates the small-diameter bore, and the subscript LB indicates the large-diameter bore. The corrected TKE_{corr} based on the above concept is shown in Eq. (4).

$$TKE_{corr} = TKE \times \left(\frac{Ne_{ref}}{Ne} \right)^2 \left(\frac{D_{B_{ref}}}{D_B} \right)^2 \quad (4)$$

The numerators of the second and third terms on the right side are respectively the reference engine speed Ne_{ref} and the reference bore diameter $D_{B_{ref}}$, and were set to $Ne_{ref} = 2000$ rpm and $D_{B_{ref}} = 73$ mm, which correspond to the intermediate positions, according to Table 1 and Table 3 described hereinafter. Also, in consideration of the turbulent intensity unit m/s and the TKE unit m^2/s^2 , the second and third terms on the right side were each squared. For example, for a bore diameter of 91 mm, the third term on the right side of Eq. (4) becomes approximately 0.64, and the corrected TKE exhibits a smaller value than the original TKE . Therefore, it can be estimated that in order to obtain the same combustion period as that of a bore diameter of 73 mm, a TKE approximately 1.55 times (inverse of 0.64) that of a 73 mm bore is needed.

In order to verify the effect of TKE correction, Fig. 7 shows the correlation between TKE and MFB10-90. The horizontal axis of Fig. 7(a) shows the uncorrected TKE at the compression TDC, and Fig. 7(b) shows the TKE_{corr} corrected by Eq. (4). When TKE and MFB10-90 are approximated by a quadratic function, the coefficient of determination R^2 is $R^2 = 0.56$ without correction and $R^2 = 0.86$ with correction. R^2 is enhanced, confirming the effect of the TKE correction method.

2.5. Engine Specifications and Analysis Method

Testing and CFD analysis were performed using the scatter-band conditions defined in Table 1 and Table 2 in order to construct scatter-bands. Table 3 shows the main engine specifications. A total of nine inline 3-cylinder,

Table 3 Engine specifications for scatter-band validation test

Engine type	In-line 3-cylinder			In-line 4-cylinder					V6
Engine No.	1	2	3	4	5	6	7	8	9
Displacement [L]	0.66	0.66	0.66	1.5	1.5	1.5	2.0	2.4	3.5
Bore [mm]	64	64	60	73	73	73	86	87	91
Stroke [mm]	68.3	68.3	77.6	89.4	89.4	89.4	85.9	99.1	89.5
Intake system	NA	TC	NA	NA	NA	TC	TC	NA	TC
Fuel supply system	PI	PI	PI	PI	DI	DI	DI	DI	PI/DI

inline 4-cylinder, and V-type 6-cylinder engines were used. Engines with differing specifications were selected, such as displacement from 0.66 L to 3.5 L, NA and TC intake systems, and PI and DI fuel supply systems. The in-cylinder pressure and the intake and exhaust pressure pulsation were measured, and the obtained in-cylinder pressure was subjected to combustion analysis with the first model of thermodynamics.

In-cylinder 3D CFD analysis was performed to obtain parameters such as TKE and the quantity of fuel adhering to the wall surface, which cannot be obtained from actual engine test results. The commercial 3D fluid analysis software VECTIS (Ricardo PLC) was used, and the standard $k-\varepsilon$ model was applied as the turbulence model. Also, in order to calculate the boundary conditions of 3D CFD, the commercial 1D engine analysis software GT-SUITE (Gamma Technologies, LLC) was used to calculate the mass flow rate of the intake and exhaust. In construction of the scatter-band, the obtained actual engine test data was applied from L2 to L3-2 and the CFD data was applied from L3-3 to L3-4.

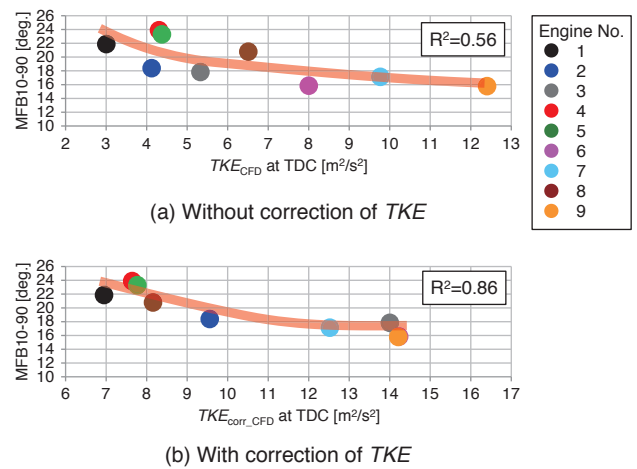


Fig. 7 Effect of correlation between combustion duration (MFB10-90) and TKE at $Ne=1500$ rpm, $BMEP=800$ kPa, $T_w=80^\circ C$

3. Validation of Hierarchical Scatter-bands

3.1. Scatter-band for Thermal Efficiency

Figure 8 shows the scatter-band data for thermal efficiency. The operating conditions are $N_e = 1500$ rpm, BMEP = 800 kPa, and $T_w = 80^\circ\text{C}$. Figure 8(a) shows the relationship between BSFC and indicated thermal efficiency η_i in L3-1. Overall, BSFC tends to decrease as η_i increases. Here, engine No. 6 exhibits an η_i of 35.8%, which is a higher value than the 33.6% of engine No. 8, but BSFC is roughly the same value of approximately 244 g/kWh. Engine No. 6 is TC and was confirmed to have higher friction due to increased strength in order to withstand high in-cylinder pressure. Next, Fig. 8(b) shows the energy balance. Engine No. 6 exhibits a time loss of 3.1%, which is a lower value than the 3.7% of engine No. 8. This confirmed that engine No. 6 promotes more rapid combustion by the enhanced in-cylinder flow. As described above, the magnitude of the various losses can be perceived from the energy balance. In addition, by understanding the positioning based on the system characteristic analysis described in Section 4.1., the data can be used to set rough target values before performing large-scale CAE.

Figure 9 shows an example of a scatter-band for time loss. This shows that time loss is generally correlated with MFB50 [Fig. 9(a)]. From there, MFB50 is correlated with MFB10-90 [Fig. 9(b)], MFB10-90 is correlated with TKE_{corr} [Fig. 9(c)], TKE_{corr} is correlated with the maximum value of the transient tumble ratio T/R_{max} [Fig. 9(d)], and then T/R_{max} is correlated with the steady-state T/R. For example, at a time loss of 4%, MFB50 is approximately 377 deg. ATDC, and MFB10-90 at that time is approximately

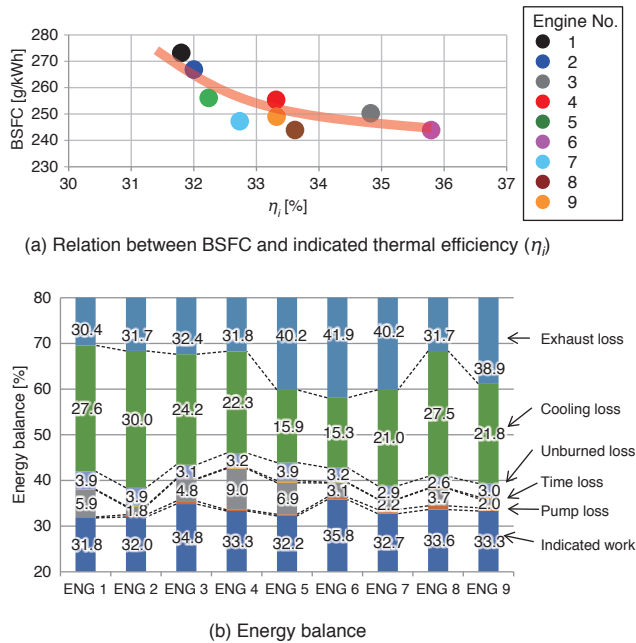


Fig. 8 Scatter-band data in L3-1 at $N_e=1500$ rpm, BMEP=800 kPa, $T_w=80^\circ\text{C}$

20 deg. In this way, the levels can be followed downward to eventually arrive at a steady-state T/R of approximately 0.8. The parameter shown on each vertical axis is the same as that shown on the horizontal axis of the upper level. This confirmed that if the steady-state T/R of the cylinder head can be obtained by testing or CFD, the approximate combustion period can be predicted without actual engine testing by advancing and replacing the parameters in order from the lower levels.

3.2. Scatter-band for Combustion Stability

Figure 10 shows the scatter-band data for combustion stability, demonstrating that LNV, which indicates combustion stability, is correlated with combustion fluctuation COV_IMEP [Fig. 10(a)]. From there, COV_IMEP is correlated with the MFB50 cycle variation STD_MFB50 [Fig. 10(b)], STD_MFB50 is correlated with the MFB10-90 cycle variation STD_MFB10-90 [Fig. 10(c)],

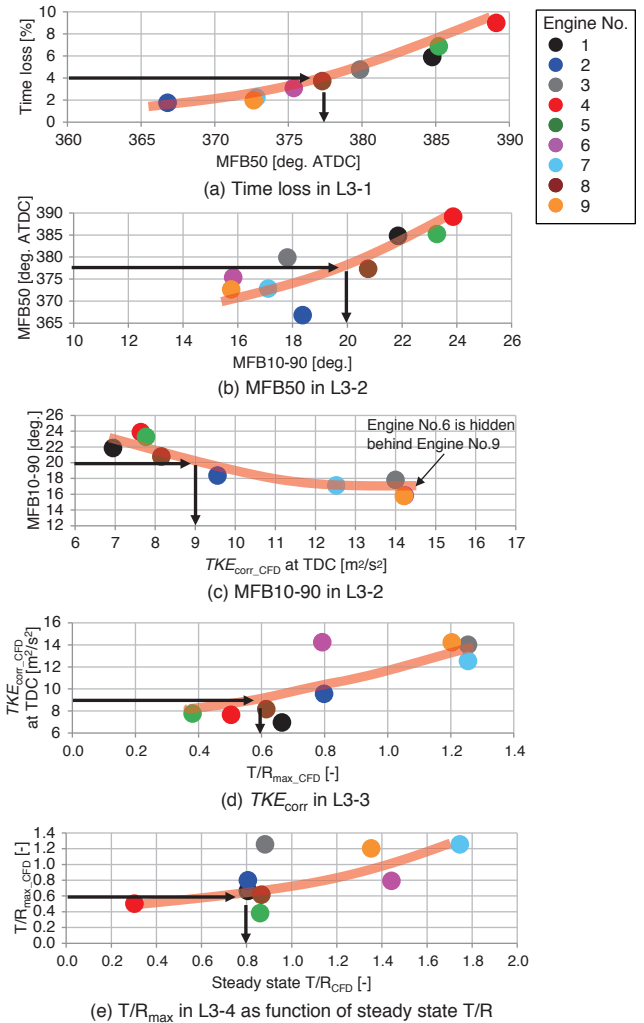


Fig. 9 Scatter-band data related time loss for thermal efficiency at $N_e=1500$ rpm, BMEP=800 kPa, $T_w=80^\circ\text{C}$

STD_MFB10-90 is correlated with MFB10-90 [Fig. 10(d)], and then MFB10-90 is correlated with TKE_{corr} [Fig. 10(e)]. This confirmed that combustion fluctuation can be reduced by enhancement of the turbulent flow to promote combustion.

3.3. Scatter-band for Oil Dilution

Figure 11 shows the scatter-band data for oil dilution. The oil dilution rate is correlated with the oil dilution quantity divided by the oil quantity [Fig. 11(a)]. From there, the oil dilution quantity is correlated with the oil dilution quantity per cylinder [Fig. 11(b)], and the oil dilution quantity per cylinder is correlated with the highest fuel adhesion quantity on the cylinder liner [Fig. 11(c)]. Here, the highest fuel adhesion quantity was the highest value of the fuel adhering to the cylinder liner in one cycle obtained by CFD. This confirmed that the oil dilution rate can be reduced by reducing fuel adhesion to the cylinder liner.

The linkages between the parameters of the scatter-

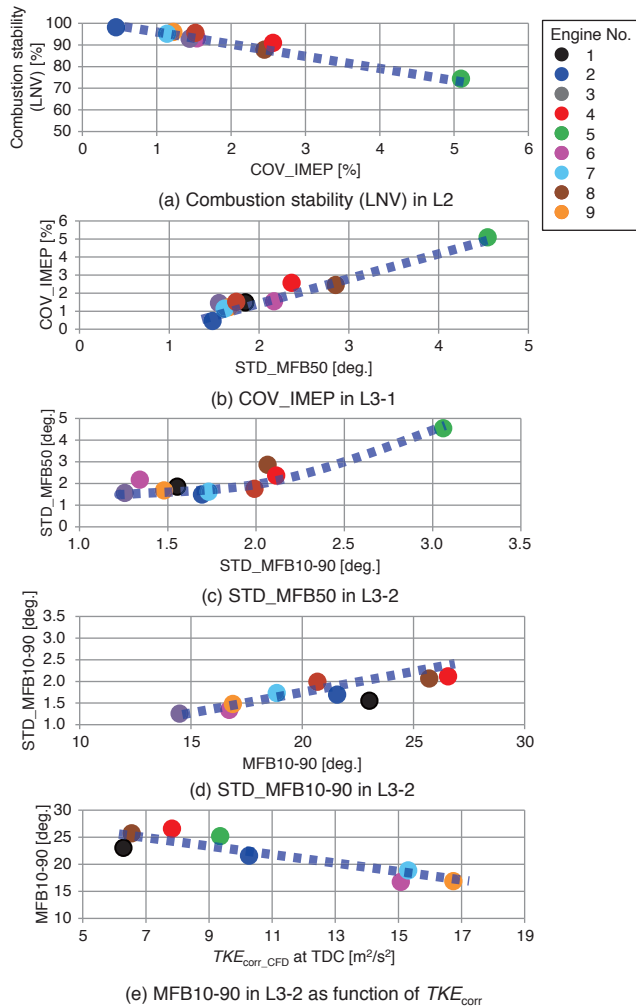


Fig. 10 Scatter-band data for combustion stability at $N_e=2000$ rpm, IMEP=1000 kPa, $T_w=80^\circ\text{C}$

bands for thermal efficiency, combustion stability, and oil dilution were confirmed in order to verify the validity of the constructed scatter-bands. The results confirmed that the parameter linkages examined in Fig. 5 are generally correct.

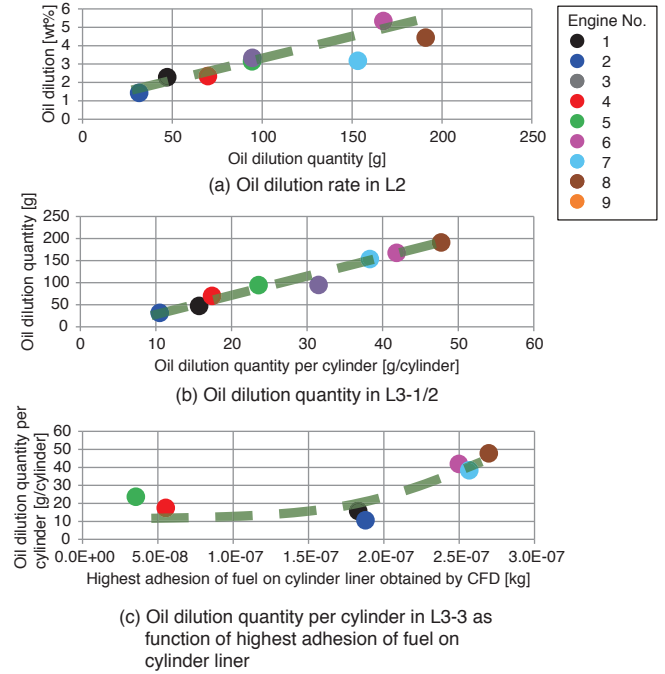


Fig. 11 Scatter-band data for oil dilution at $N_e=2500$ rpm, IMEP=1000 kPa, $T_w=50^\circ\text{C}$

4. Application to Study of Engine Specifications

In this chapter, the hierarchical scatter-bands constructed in Chapter 3 are applied to promote the combustion of a 2.0 L TC DI engine in order to verify the validity. First, Section 4.1. describes analysis of the current situation and the causes of issues and examination of countermeasures by system characteristic analysis that analyzes the positioning of the parameters in each level from an overall viewpoint. Next, Section 4.2. describes enhancement of the in-cylinder flow by the piston top shape in order to address the issues. Lastly, Section 4.3. describes examination of injection control to decrease the oil dilution rate, which calls for confirmation as a conflicting element.

4.1. Analysis of Current Situation by System Characteristic Analysis

Figure 12 shows the results of comparing the thermal efficiency of the 2.0 L TC DI engine No. 7 with that of the similar 1.5 L TC engine No. 6 as base engines for examining specifications. System characteristic analysis here shows the positioning of the parameters to be analyzed

in the range from -1 to 1, where the upper limit value of each parameter is 1 and the lower limit value is -1⁽⁶⁾. For example, as a higher indicated thermal efficiency η_i is better, the highest value of η_i in the accumulated data is expressed as 1 and the lowest value as -1. Conversely, as a lower time loss is better, here the lowest value is expressed as 1 and the highest value as -1. Note that the magnitude of the various losses relative to η_i differs as shown in Fig. 8(b), so misjudgment of enhancement methods may occur. Therefore, the ratio of the mean value of each loss to the mean value of η_i was obtained and weighting was performed by multiplying each loss by that ratio. The η_i of the base engine No. 7 was approximately -0.7, which was a low position overall. One factor for this is thought to be that the exhaust loss is large according to the energy balance.

Next, MFB50 and MFB10-90 are positioned well and TKE_{corr} and T/R occupy high positions, demonstrating that the engines promote combustion by enhancement of the in-cylinder flow. The η_i of engine No. 6 is near the scatter-band upper limit, and there was also no large difference in MFB10-90 between the engines. However, TKE_{corr} was positioned low even though the T/R of engine No. 7 is larger than that of engine No. 6.

The intake port performance of engines No. 7 and No. 6 in the steady-state condition was compared in order to analyze the relationship between T/R and TKE_{corr} . Figure 13(a) shows the velocity distribution of the cylinder liner cross-section at the position of half the bore diameter from the gasket surface as measured by particle

image velocimetry (PIV). Comparison with the velocity distribution of engine No. 6 confirmed that in engine No. 7, the flow from the intake side is suppressed and the intake port is designed so that air flows to the exhaust side [red circles in Fig. 13(a)]. Figure 13(b) show the steady-state T/R and the limit engine speed $Ne_{limit}^{(11)}$. Here, Ne_{limit} is a characteristic value obtained from the average flow coefficient of the intake port, and the larger the value, the more air that can be sucked into the cylinder. Compared to engine No. 6, the Ne_{limit} of engine No. 7 was roughly the same at approximately 4000 rpm, but the steady-state T/R exhibited a higher value of approximately 2.4. The above results confirmed that, although the intake port provides adequate flow performance, flow formation is poor due to the piston shape. In addition, use of factor analysis and scatter-bands enabled efficient analysis of causes and implementation of countermeasures.

4.2. Enhancement of In-Cylinder Flow by Piston Top Shape

Figure 14(a) shows the piston top bowl shape and the in-cylinder velocity distribution obtained by CFD, and Fig. 14(b) shows the relationship between MFB10-90 and

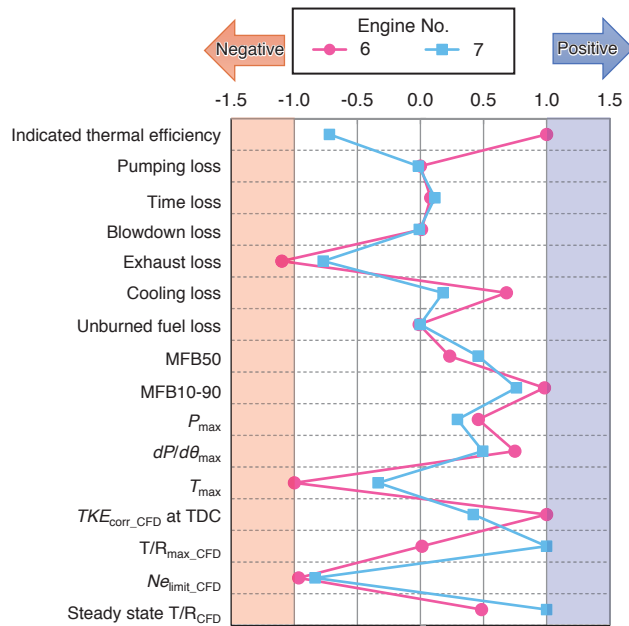
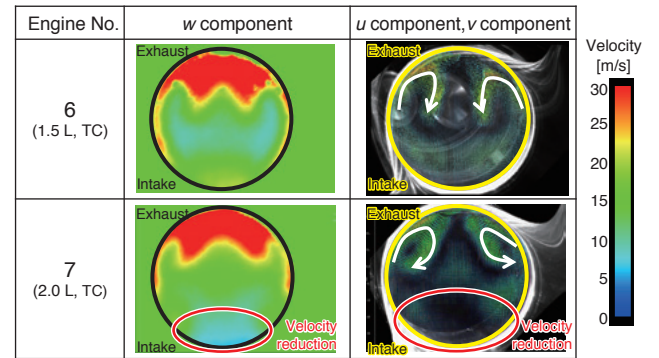
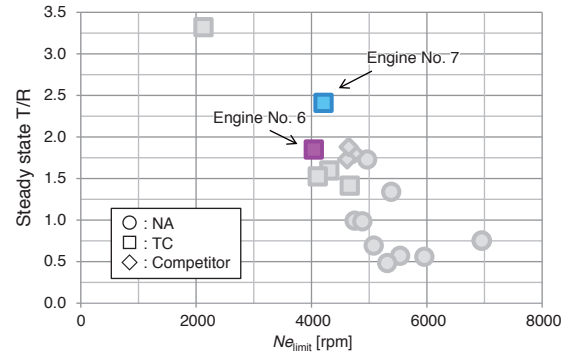


Fig. 12 System characteristic analysis for thermal efficiency by comparison of base engine, No. 7 (2.0 L, TC) with similar specification engine, No. 6 (1.5 L, TC) at $Ne=1500$ rpm, BMEP=800 kPa, $T_w=80^\circ\text{C}$



(a) Velocity distribution of cylinder liner cross section at 1/2 bore diameter position from gasket surface obtained by stereo-PIV



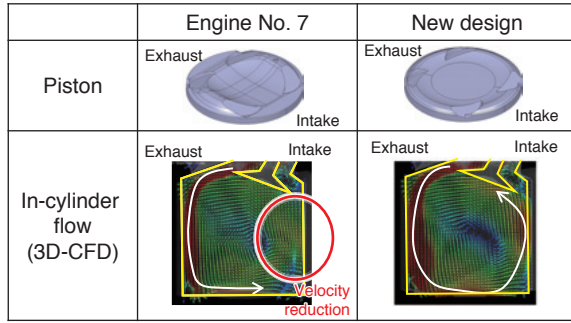
(b) Relation between steady state T/R and Ne_{limit}

Fig. 13 Comparison of intake port performance of Engine No. 7 (2.0 L, TC) with Engine No. 6 (1.5 L, TC) in steady state flow

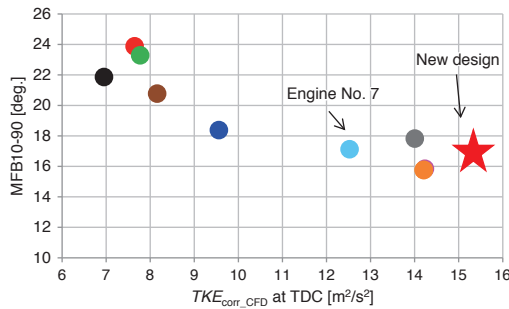
TKE_{corr} . Here, the velocity distribution is the 2D distribution of the bore center cross-section. From Fig. 9(a), the time loss of engine No. 7 was 2.2% and MFB50 = 373 deg. ATDC. Assuming a tentative goal of reducing time loss by 1%, it is sufficient to design combustion so that MFB50 is 370 deg. ATDC and MFB10-90 is 15 to 16 deg. Thus, the tentative target for flow is $TKE_{corr} = 14$ to $15 \text{ m}^2/\text{s}^2$. With the base shape of engine No. 7, while the flow from the intake port was converted to an upward flow by the piston bowl, a decrease in velocity was observed [Fig. 14(a) left figure]. This is consistent with the tendency to judge quality by the system characteristic analysis in Fig. 12. As shown in the right figure of Fig. 14(a), the bowl shape of the piston top was changed to a shallow dish shape in order to smoothly convert the flow into the cylinder to an upward flow, enabling increase of the rising velocity on the exhaust side. As shown in Fig. 14(b), changing from the base shape to a shallow dish shape resulted in a TKE_{corr} of approximately $15.2 \text{ m}^2/\text{s}^2$, so the flow could be enhanced by the bowl shape of the piston top. In addition, when a piston of the same shape was confirmed in an actual engine, MFB10-90 decreased by 0.5 deg. from 17.1 deg. to 16.6 deg. and was generally positioned on the extension of the trend, enhancing BSFC by approximately 0.6%.

4.3. Reduction of Oil Dilution Rate by Injection Control

Figure 15(a) shows the oil dilution rate as a function of the engine displacement V_s , indicating that the oil dilution



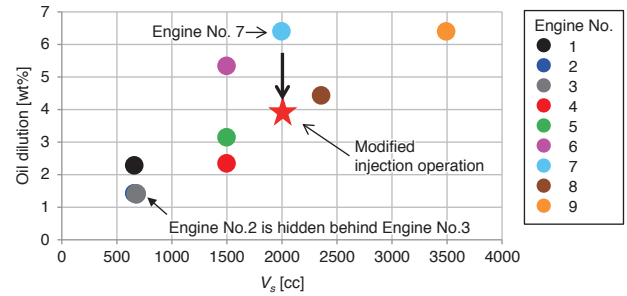
(a) Comparison of in-cylinder flow by piston top bowl shape



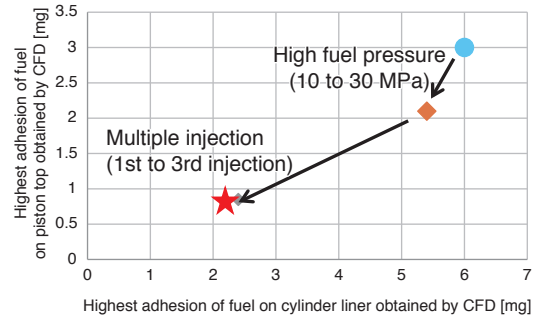
(b) Relation between MFB10-90 and TKE_{corr} of Engine No. 7 (2.0 L, TC)

Fig. 14 Effect of piston top bowl shape at scatter-band condition, $N_e=1500 \text{ rpm}$, BMEP=800 kPa, $T_w=80^\circ\text{C}$

rate tends to increase together with engine displacement. The fuel injection quantity increases in accordance with the displacement at the same IMEP, so the relative increase in the quantity of fuel adhering to the in-cylinder wall surfaces, such as the cylinder liner, is thought to be a factor. The oil dilution rate of engine No. 7 is positioned near the upper limit of the trend due to the aforementioned increase in displacement. There was a concern that enhancement of the in-cylinder flow would increase the oil dilution rate, so an attempt was made to reduce the oil dilution rate by injection control. Figure 15(b) shows the highest fuel adhesion quantity on the cylinder liner and piston obtained by CFD. By increasing the fuel injection pressure P_f from the base condition of 10 MPa to 30 MPa and increasing the number of injections from one time to three times, the quantity of fuel adhering to the wall surfaces of both the cylinder liner and the piston were reduced. This is due to atomization of the fuel droplets and reduction of the spray penetration by high fuel pressure and multiple injection. As a result, the oil dilution rate of engine No. 7 could be reduced by 2.6 wt%, from 6.4 wt% to 3.8 wt% [Fig. 15(a)].



(a) Comparison of oil dilution as function of engine displacement



(b) Comparison of highest adhesion of fuel on cylinder liner and piston top

Fig. 15 Effect of injection operation at $N_e=2500 \text{ rpm}$, IMEP=1000 kPa, $T_w=50^\circ\text{C}$

5. Systemization of Data Accumulation and Utilization

Figure 16 shows the trend in the yearly accumulation of engine and steady-state flow intake port test data. The

amount of engine data when constructing the scatter-bands was equivalent to that for nine engines. By continuously accumulating data and incorporating data from the benchmarking project of the Research Association of Automotive Internal Combustion Engines (AICE), data equivalent to 26 engines had been accumulated as of 2022. As examples of utilization, scatter-bands have been applied to set target values for in-cylinder flow and to examine the combustion chamber S/V ratio to reduce cooling loss. It is thought that utilization in the early stages of development has enabled smooth transition to combustion design and CAE analysis and reduced reworking in engine development.

From the above, the original goal of applying scatter-bands in the initial examination stage of engine development and indicating the direction of development was achieved. However, as the engine control conditions were fixed as shown in Table 2, the optimal control conditions for each engine may differ. Going forward, it is also necessary to accumulate data under the optimal control conditions for each engine, and to expand the range of utilization to understand the sensitivity of control parameters and examine the optimal values. It is also necessary to increase the number of parameters to be controlled in order to further enhance the environmental performance of engines.

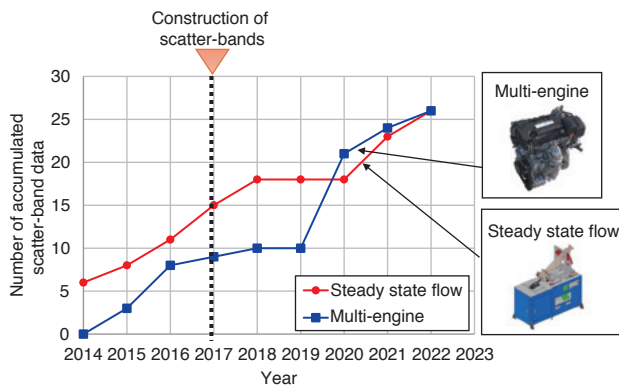


Fig. 16 Yearly accumulation of engine and steady flow test data

6. Conclusion

Hierarchical scatter-bands were constructed in order to determine engine specifications in the early stages of development with the goal of increasing development efficiency by reducing reworking. The constructed scatter-bands were applied to promote the combustion of a TC DI engine, the validity was verified, and the following conclusions were obtained.

- (1) The four elements of thermal efficiency and combustion stability, oil dilution, and soot, which conflict with thermal efficiency, were defined in the engine requirements (Level 2), and requirement analysis was performed for the intermediate parameters (Level 3) in order to link them hierarchically to Parts (Level 4). The

results of verification using the data of nine engines confirmed that the parameter linkages are generally correct.

- (2) Parameter normalization was performed in order to evaluate different engine specifications using the same criteria. As an example, when the turbulent kinetic energy was normalized by engine speed and bore diameter, the correlation with the combustion period was enhanced.
- (3) The issues of a TC DI engine were analyzed using scatter-bands. System characteristic analysis and requirement analysis found that in-cylinder flow formation was not good due to the piston shape and enabled efficient analysis of causes and implementation of countermeasures.
- (4) In order to reduce the oil dilution rate, which is given as a conflicting event with enhancement of the in-cylinder flow, the quantity of fuel adhering to the in-cylinder wall surfaces was reduced by injection control. High fuel pressure and multiple injections enabled reduction of fuel adhesion and balancing of the performance required of the engine.
- (5) It is thought that the continuing accumulation and utilization of scatter-band data can reduce reworking in engine development. Going forward, it will be necessary to increase the number of parameters to be controlled in order to further enhance the environmental performance of engines.

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DI	Direct Injection
EGR	Exhaust Gas Recirculation
EM	Emission
EOI	End Of Injection
EVC	Exhaust Valve Close
IMEP	Indicated Mean Effective Pressure
INJ	Injector
IVO	Intake Valve Open
LNV	Lowest Normalized Value
MBD	Model-Based Development
MBT	Minimum advance for Best Torque
MFB	Mass Fraction Burnt
NA	Natural Aspiration
PI	Port Injection
PIV	Particle Image Velocimetry
PM	Particulate Matter
PN	Particle Number
RDE	Real Drive Emission
SOI	Start Of Injection
STD	Standard deviation
T/R	Tumble Ratio
TC	Turbocharger
TDC	Top Dead Center (BTDC: Before TDC, ATDC: After TDC)
WLTC	Worldwide harmonized Light duty vehicles Test Cycle

List of Symbols

A/F	Air/Fuel ratio [-]
D	Bore diameter [mm]
N_e	Engine speed [rpm]
P_f	Pressure of fuel [MPa]
L_s	Stroke [mm]
S/V	Surface/Volume ratio [m^2/m^3]
T_w	Temperature of water [$^{\circ}C$]
TKE	Turbulent Kinetic Energy [m^2/s^2]
U_p	Mean piston speed [m/s]
u_{intake}	Velocity of intake flow [m/s]
u'	Turbulent intensity [m/s]
V_s	Displacement [L]
θ_{ig}	Ignition timing [deg. BTDC]
θ_{inj}	Injection timing [deg. BTDC]
η_i	Indicated thermal efficiency [%]
η_v	Volumetric efficiency [%]

List of Abbreviations

AICE	the research association of Automotive Internal Combustion Engines
BMEP	Brake Mean Effective Pressure
BSFC	Brake Specific Fuel Consumption
CAE	Computer Aided Engineering
CAFE	Corporate Average Fuel Efficiency
CFD	Computational Fluid Dynamics
COV	Coefficient Of Variation

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