

Development of the Total Engine Simulation System (TESS) and Its Application for System Investigation of Future Diesel Engine

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ABSTRACT

Complexity of the modern diesel engine has increased to meet the stringent future emission regulations especially for NO_x (nitrogen oxide) and PM (particulate matter). Air management system including exhaust gas recirculation (EGR), turbocharger and variable valve actuation (VVA) must be optimized of its design and control algorithm for combustion improvement coupled with precision control of fuel injection. As a matter of course, the optimization of aftertreatment system is extremely important for the exhaust emissions reduction. In addition, improvement of fuel consumption is very important from the standpoint of response to energy security and reduction of CO₂ (carbon dioxide) emission as the greenhouse gas. However an enormous amount of energy will be required to develop such kind of the complex engine system by conventional actual testing. Therefore, the total engine simulation system (TESS) with quasi real time processing and relatively high precision model for prediction of fuel consumption and exhaust emissions was developed in this study. The TESS consists of the zero-dimensional gas flow model and the aftertreatment model written by Simulink code. In addition, the zero-dimensional multi-zone diesel combustion model, HIDECS (Hiroshima University diesel engine combustion simulation) which was developed by Hiroyasu *et al.* is embedded in the TESS. Since modeling logic of the HIDECS is based on the phenomenism, prediction accuracy and calculation speed are well balanced. The premixed compression ignition (PCI) combustion will be a key technology for simultaneous reduction of exhaust emissions and fuel consumption. However, there are some problems to predict the PCI combustion on the original HIDECS. Therefore, modification of the HIDECS model to predict the PCI combustion was also

conducted in this study. Modified model uses pseudo method for consideration of mixing process that is strongly governed by oxygen concentration. Additionally, equation about ignition delay was also modified to fit the EGR rate changing. In this result, the modified HIDECS can predict exhaust emissions and fuel consumption on the PCI combustion. Finally, performance estimation of the most advanced diesel engine with multi-stage boosting, massive EGR and ultra high pressure injection was conducted by using the TESS including the modified HIDECS model. Experiment of single cylinder engine which has the VVA system was also conducted to make the TESS effectiveness clear and to get knowledge for further improvement of fuel consumption. In this result, effectiveness of the TESS for system investigation of the future diesel engine is clear. In addition, technological direction of fuel consumption improvement is indicated by the TESS and experimental result. This project was conducted as a part of the comprehensive technological development of innovative, next-generation, low-pollution vehicles program in the New Energy and Industrial Technology Development Organization (NEDO) of Japan.

INTRODUCTION

Further improvement of fuel consumption for the diesel engine is strongly required from the stand point of energy security and environmental protection on a global scale without mentioning about achievement of the stringent future emission regulations. Thus, the comprehensive technological development of innovative, next-generation, low-pollution vehicles program [1] which was organized by the NEDO was conducted from financial year (FY) 2004 to FY2008. This NEDO project has extremely severe target of fuel consumption and exhaust emissions as shown in Table 1.

Table 1. The NEDO project target on the JE05 (the Japanese new transient engine test cycle)

	NOx g/kWh	PM g/kWh	CO g/kWh	NMHC g/kWh	Improvement of Fuel Consumption %
NEDO Project Target	0.20	0.010	2.22	0.17	10
Ref. Japan NLT Regulation	2.00	0.027	2.22	0.17	Base

*NLT : New Long Term

Figure 1 indicates supposed engine system to meet the target of the NEDO project as follows in detail. High boosting technologies such as the multi-stage boosting is a key for simultaneous improvement of exhaust emissions and fuel consumption as well known [2,3,4]. Since high boost pressure can increase EGR rate under constant oxygen quantity, trade-off between NO_x and soot emissions can be improved. Alternatively, fuel consumption can be improved by injection timing advancement under same NO_x level. In addition, increase of the mass of the working gas by high boost pressure is also effective to improve fuel consumption by moderation of specific heat ratio declining during combustion.

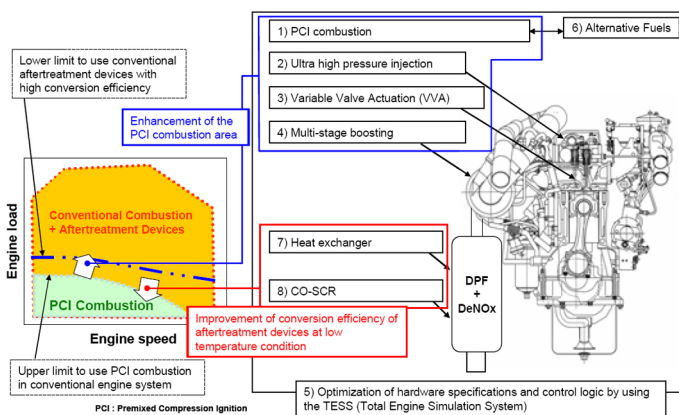


Figure 1. Supposed engine system to meet the target of the NEDO project

However, it was assumed that further effective items would be required to achieve the fuel consumption target of the NEDO project. Since increase of the expansion ratio can improve indicated thermal efficiency theoretically, investigation about high geometrical compression ratio was conducted in this study. But, exceeding the limitation of maximum cylinder pressure (P_{max}) is easily presumed in case of high compression ratio combined with high boosting system. It is concerned that fuel consumption cannot be improved due to injection timing retarding for maintaining the P_{max} limitation. Therefore, the VVA system was employed to control effective compression ratio by intake valve closing (IVC) timing for maintaining the P_{max} limitation. In this time, expansion ratio can be obviously kept high. And the degree of constant volume is also kept high.

Since advancement of IVC timing causes decrease of trapped gas mass simultaneously with reduction of effective compression ratio, aggravation of soot emission is concerned. High boosting technology is also effective to reduce soot emission. In addition, the ultra high pressure injection system which has capability up to 300 MPa of injection pressure was also prepared. Increase of injection pressure is also effective to improve the spray tip penetration under high ambient density condition which is generated by high boost pressure. This engine system is premised on using of a de-NO_x converter in order to meet the stringent target of NO_x emission. However the PCI combustion [5] must be used to reduce exhaust emissions at low load condition, because exhaust gas temperature do not reach the activation temperature of the de-NO_x converter. Effectiveness of the ultra high pressure injection coupled with micro-hole nozzle was already demonstrated to increase homogeneity of pre-mixture [6, 7]. In addition, the VVA can control the ignition timing of the PCI combustion to maintain the combustion phase at around top dead center (TDC) [8]. These two innovative devices can improve robustness and expand the region of the PCI combustion.

Then various innovative devices will be required to improve exhaust emissions and fuel consumption simultaneously, and the algorithm of integrated control about the complex engine system must be optimized. In addition, combustion mode switching between conventional combustion and the PCI combustion or utilization of exhaust gas enthalpy must be considered on various transient operation modes including emission test cycle. However an enormous amount of resources will be required to develop such kind of complex engine system by actual testing as in the past. Therefore, the TESS with quasi real-time processing and relatively high-precision model for fuel consumption and exhaust emissions prediction is strongly required as the novel approach for efficient development about the future diesel engine. Figure 2 shows the positioning of simulation software on engine development depending on the objective and calculation speed. There is no objection about effectiveness of numerical simulation applied to a broad range of engine development phase during basic research and control parameter calibration. Basically, objective phenomenon, demanded accuracy and computational time are strongly depending on the development phase.

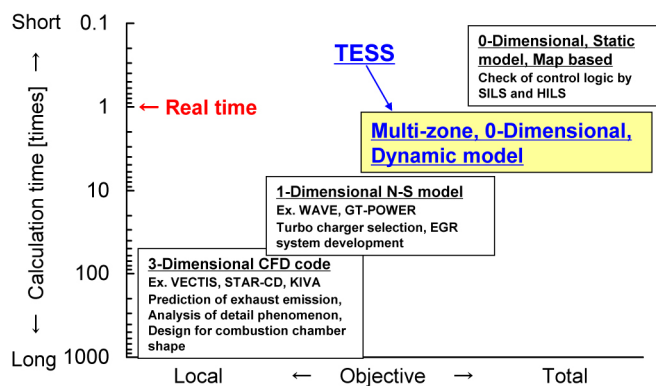


Figure 2. Positioning of simulation software for engine research and development

Detailed information about fluid dynamics, mixture formation and chemical reaction can be solved by using the three-dimensional computational fluid dynamics (CFD) software. Analysis of in-cylinder physics and optimization of the combustion chamber shape and the nozzle configuration are conducted efficiently by using this kind of software [9]. However cyclic simulation is impractical due to extremely high calculation load. Meanwhile the one-dimensional gas dynamics software can be used for selection of the turbo charger specification and investigation of EGR path [10]. Since calculation time about this kind of software requires more than 100 times of real time, approximately one week of calculation time will be needed for simulation of whole the JE05 mode (the Japanese new transient engine test cycle). Therefore, calculation on steady state condition or partial transient condition about representing operation conditions is only conducted. On the other hand, the simplified engine simulator applied for the model based controller or hardware in the loop simulation (HILS) is developed [11]. This kind of software can be applied for real time simulation. However prediction of exhaust emissions and fuel consumption is impossible, because there is no combustion model. As mentioned above, there is no simulation software for system investigation and performance prediction at the beginning of development phase of the future diesel engine. Therefore, the TESS was developed, and investigation of future engine system that can meet the target of the NEDO project was also conducted in this study.

DEVELOPMENT OF THE TESS

Operating variable of all actuators including new devices such as the VVA must be considered in the diesel combustion model of the TESS. In addition, both high calculation speed and relatively high accuracy of prediction about exhaust emissions and fuel consumption are strongly required for the diesel combustion model too. Therefore, zero-dimensional diesel combustion model is desired. The diesel combustion model is also the fundamental model to output exhaust gas

composition, mass flow rate and temperature for the co-simulation of aftertreatment devices.

Regarding the zero-dimensional diesel combustion model, Austen *et al.* [12] approaches that heat release rate is directly estimated by rate of injection. If ignition delay is estimated precisely, high accuracy of prediction of heat release rate will be expected in this model. Since this model cannot predict distribution of temperature and equivalence ratio, however, prediction of NO_x emission as well as soot emission is impossible. Meanwhile Hiroyasu *et al.* [13] develops the phenomenological based, zero-dimensional multi-zone diesel combustion model HIDECS. Numerous packages along with fuel spray growth are generated depending on injection rate and prescribed spray angle. Air entrainment, evaporation, ignition, heat release and combustion products are calculated for each package independently based on experimental results of detailed optical observation of diesel spray and combustion. Komninos *et al.* [14] develops the zero-dimensional multi-zone model specialized for the homogeneous charge compression ignition (HCCI) combustion.

Each zone is segmented by dimensional factor of in-cylinder volume. This kind of combustion model is effective for prediction of the PCI type of combustion with high homogeneity on equivalence ratio distribution. Since this model cannot predict about the conventional diesel combustion that is strongly governed by physics of fuel and air mixing, however, investigation of combustion mode switching between the conventional combustion and the PCI combustion is impossible. Thus the HIDECS was employed as the diesel combustion model for the TESS in consideration of calculation speed, adaptation for prediction of the conventional diesel combustion and evolvability for prediction of the PCI combustion with moderate homogeneity on equivalence ratio distribution that was generated direct injection near TDC. The HIDECS was embedded to the gas flow model which was written by Simulink code as a zero-dimensional mean value model.

The configuration overview of the TESS that consists of gas flow model, diesel combustion model and aftertreatment model is indicated in Figure 3. This figure is an example model of the diesel engine with three-stage boosting system. In the aftertreatment model, catalyst temperature, catalytic reaction and pressure loss caused by catalyst structure and accumulated soot are calculated with giving consideration to the catalyst thermal capacity and the heat transfer with ambient air. Since the HIDECS can not predict the detailed phenomenon involved in three-dimensional gas flow and inertia of fluid, calculation of the HIDECS is conducted for a single cylinder which was representative of multi cylinder. Finally, number of cylinders is multiplied to the calculation result of single cylinder calculation. When the TESS

calculation is executed, embedded engine controller that has the same logic with actual engine control unit (ECU) outputs injection quantity, injection timing, common rail pressure and valve timing of the VVA to the HIDECS. The HIDECS also receive the information about intake gas composition, temperature and pressure from upstream of the gas flow model. Then the HIDECS calculation is executed and output such as exhaust gas composition, temperature, mass flow, torque and in-cylinder pressure to the downstream of gas flow model and the control model.

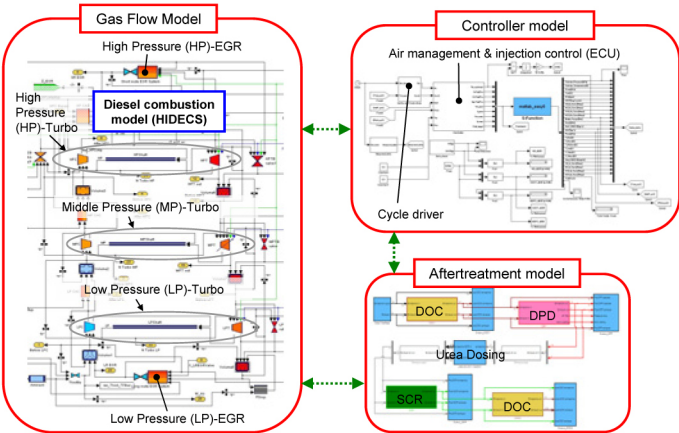


Figure 3. Configuration overview of the TESS

OUTLINE DESCRIPTION OF THE HIDECS AND ITS EVALUATION

As mentioned above, the HIDECS can simulate the distribution of temperature and equivalence ratio by generated numerous packages along with the fuel spray growth depending on injection rate and prescribed spray angle even though the HIDECS as a zero-dimensional model has no dimensional factor. Each package penetrates depending on the equation of spray tip penetration that is proposed by Hiroyasu *et al.* [15]. The momentum of the package during transfer is preserved and the ambient air corresponding to the attenuation of the package speed is entrained that this concept is known as the momentum theory proposed by Wakuri *et al.* [16]. However quantity of air entrainment in case of wall impingement or ignition is corrected by the model constant so called the air entrainment coefficient. Evaporation of fuel droplet is occurred by ambient gas entrainment with high temperature, and ignition delay is calculated by Livengood-Wu integral [17]. Then vaporized fuel and oxygen in the package equivalent to stoichiometric ratio is combusted. Afterward, combustion proceeds depending on air entrainment rate or fuel evaporation rate. NO_x is formatted depending on calculated temperature and gas composition in the package by using extended Zeldovich mechanism [18]. Soot is calculated by using soot generation and oxidation equation that was

proposed by Hiroyasu *et al.* [13]. Finally, bulk information such as in-cylinder pressure and engine-out emissions are obtained by summation of all package data.

Next, influence of EGR rate including the PCI combustion condition was evaluated to check the accuracy of the HIDECS. Engine specifications and operating conditions is indicated in Table 2. Calculation result of the HIDECS is indicated in Figure 4 in addition with experimental result. In this case, the HIDECS which was modified [19] to obtain strictness of the momentum theory in case of adaptation of the air entrainment coefficient was used. All of model constants including the air entrainment coefficient are fixed regardless of calculation condition.

Table 2. Engine specifications and test conditions

Engine Type	4-Stroke Single Cylinder
Bore × Stroke	115 mm × 125 mm
Swirl Ratio	1.29
Injection Nozzle	φ 0.16 mm × 8 holes, β 125°
Combustion Chamber	Shallow Dish
Compression Ratio	16.5
Fuel	JIS2D
Engine Speed	1000 rpm
Fuel Flow	30 mm ³ /st.
Injection Pressure	90 MPa
Injection Timing	33.3 deg.BTDC
Boost Pressure	NA
EGR Rate	Parameter

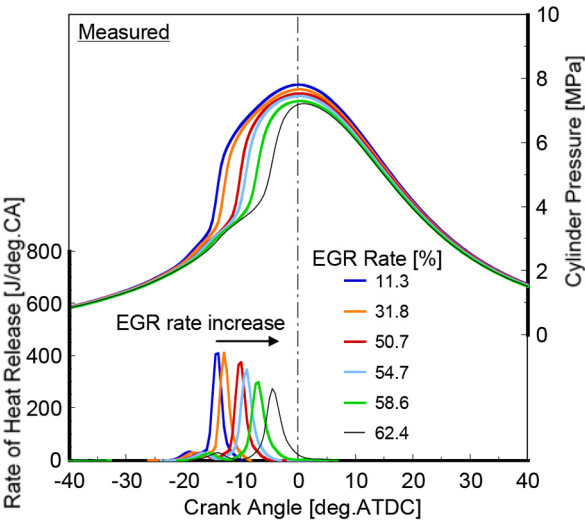


Figure 4. Evaluation result of the original HIDECS under EGR rate change

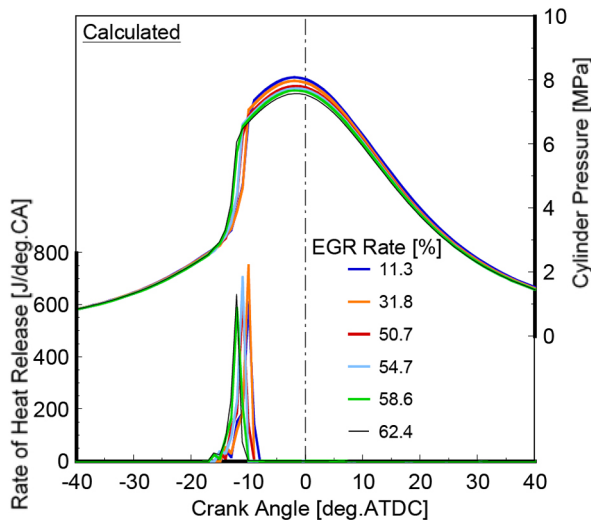


Figure 4 (cont'd). Evaluation result of the original HIDECS under EGR rate change

From this result, the HIDECS cannot predict about delay of ignition timing and elongating of combustion duration that was caused by increase of EGR rate. Ignition timing is advanced by increase of EGR rate rather than retarding as shown in experimental result from detailed observation of the calculation result. Here, ignition delay in the original HIDECS is given in Eq. (1).

$$\tau = A \cdot P^{-2.5} \cdot \phi^{-1.04} \cdot \exp\left(-\frac{B}{T_z}\right) \quad (1)$$

τ : Ignition delay, P : Pressure

ϕ : Equivalence ratio, T_z : Package temperature

A, B : Model constant

As already indicated in Eq. (1), Livengood-Wu integral is forwarded by increase of equivalence ratio. Therefore, shift of equivalence ratio in the package toward rich side by EGR rate increase causes reduction of ignition delay. Additionally, influence of EGR rate to the heat release rate cannot be observed and heat release rate is very steep regardless of EGR rate as indicated in Figure 4. Vaporized fuel and entrained oxygen equivalent to stoichiometric ratio in the package is combusted during one calculation step in the original model. Thus when ignition delay is almost the same, heat release at the premixed combustion phase is also almost the same. Exhaust emissions and fuel consumption cannot be predicted obviously. From evaluation result, the original HIDECS had issues of prediction accuracy of ignition delay and heat release rate under EGR rate changing. It is expected that the issue of ignition delay prediction will be solved by fine adjustment of model constants and modification of

factors in Eq. (1). But the issue of prediction of heat release rate cannot be solved directly, because this phenomenon strongly depends on the fuel-air mixing physics that is obtained by calculation of unconsidered factor in the HIDECS such as fluid dynamics. Since calculation of the fluid dynamics requires high computational load, however, pseudo method for consideration of mixing process is desired.

MODIFICATION OF THE HIDECS FOR PREDICTION OF THE PCI COMBUSTION

Improvement of prediction accuracy especially for torque, NO_x , soot and exhaust gas temperature without aggravation of calculation speed are required from the standpoint of the objectives of the TESS as mentioned at the beginning. Therefore, process of the low temperature oxidation is ignored due to non-dominant process for heat release. Then improvement of prediction accuracy about ignition timing and combustion duration of high temperature oxidation is only focused in model modification. Prediction about THC (total hydrocarbon) and CO (carbon monoxide) emissions are also required for co-simulation with aftertreatment model. Then, model modification was conducted as follows.

Modified processing flow is indicated in Figure 5 in addition with the processing flow of original model. Models for air entrainment and fuel evaporation are same with the original HIDECS. However it hypothesizes in the modified model that vaporized fuel is isolated with entrained gas at the beginning. Next, mixed (combustible) fuel vapor is generated depending on pseudo mixing rate. The mass of mixed (combustible) fuel vapor is implemented to the Livengood-Wu integral for ignition delay calculation as a new factor. When ignition is determined by modified Livengood-Wu integral, quantity of heat release during one calculation step is obtained by using reaction rate that is calculated by gas temperature and equivalence ratio in the package. Regarding of equation establishment on above mentioned method of the HIDECS modification, previous research work by Jung *et al.* [20] that approach improvement of prediction accuracy of heat release rate focused on conventional combustion is referred.