Research on Diesel Exhaust Aftertreatment System Modelling for Virtual Test Bed

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Abstract. With the increasing seriousness of environmental pollution, emissions regulations are being tightened and the design and manufacture of heavy duty diesel vehicles, diesel engine parts and post-processing systems cost more time and money. Virtual test bed can replace real engine and vehicle based on hardware-in-the-loop test system to deal with the vehicle development and calibration issues. In this paper, an exhaust aftertreatment system simulation model established method based on the AVL CRUISE\textsuperscript{TM} M of a diesel engine of China 6 applied to virtual calibration is presented. The results of thermal parameter, pressure parameter and emission parameter show that the model is of good quality and can be used in the research of virtual calibration development.

1. Introduction

With the increasing seriousness of environmental pollution, more and more attention has been paid to ecological environmental protection, and emission regulations have been further tightened [1]. In order to meet the national VI emission requirements of heavy diesel vehicles, diesel engine parts upgrading, post-treatment system selection and matching need a lot of human work and bench test support [2]. To deal with the problems of multi-scheme selection design and the increase of time and money cost caused by a large number of bench test, it is an effective solution to transfer part of bench test work to the office through virtual test bed [3].

Virtual test bed (VTB) is a vehicle virtual simulation bed based on hardware-in-the-loop test system which can replace real engine and vehicle [4]. It mainly includes software simulation model, hardware-in-the-loop test system and high-quality test data. Except ECU is real, other modules of VTB are simulated by simulation model [5]. The virtual calibration process mainly includes experiment design, virtual experiment, model construction, data optimization, MAP generation and calibration result test. Virtual calibration by VTB can greatly reduce the calibration cycle and workload, and thus reduce the cost of calibration [6-7].

In this paper, an exhaust aftertreatment system (EAS) simulation model established method based on the AVL CRUISE\textsuperscript{TM} M of a diesel engine of China 6 applied to virtual calibration is presented. The results of thermal parameter, pressure parameter and emission parameter show that the model is of good quality and can be used in the research of virtual calibration development.
2. CRUISE M software introduction

AVL Advanced Simulation Technologies announced in October 2015 that its vehicle system-level simulation platform software, AVL CRUISE™ M, is designed to facilitate the development of vehicles and subsystems. CRUISE™ M simulation platform designed specifically for the vehicle more physical system simulation, combining highly flexible and multi-level modeling method, and integrated the third-party tools standard interfaces of FMI, seamless system thermodynamic cycle engine, exhaust gas purification device, cooling and lubricating system, vehicle transmission system and control system integrated into a unified simulation platform [8].

In this paper, the CRUISE™ M Aftertreatment module was used to build the exhaust aftertreatment system model. CRUISE™ M can build models based on detailed physicochemical reaction mechanism and semi-empirical post-treatment system models. The former is an integrated exhaust gas post-treatment system model based on AVL Boost, while the latter is a semi-empirical post-treatment system model based on AVL database development (MoBEO EAS). Based on the post-treatment system model built by CRUISE™ M, steady and transient emissions can be predicted, carrier layout, size selection and control strategy development can be carried out.

3. Exhaust Aftertreatment System Modelling

3.1. Model Setup

China VI emission regulations have strict requirements on pollutant emission, mainly reflected in the control of NOx and particulate matter. Therefore, the current mainstream technical route of domestic engine plants is "EGR+DOC+DPF+SCR+ASC". In this route, the combustion chamber temperature is controlled by adjusting the EGR valve to reduce NOx emissions, and the HC, CO, NOx and particulate matter in the exhaust are significantly reduced through the combination of DOC, DPF and SCR catalytic convertors. Finally, ammonia in the exhaust is captured through the ASC catalytic convertor.

The EAS layout of this paper is shown in figure 1. During the modeling process, parameters of each pipe and catalyst included in the post-processing device should be set according to the EAS layout in CRUISE™ M. Table 1 shows the geometrical data and coating catalysts of EAS.

![Figure 1. EAS layout.](image)

| Material      | DOC | DPF | SCR | ASC |
|---------------|-----|-----|-----|-----|
| CPSI [1/in²]  | 400 | 300 | 400 | 400 |
| Wall Thickness [mil] | 4 | 9 | 4 | 4 |
| Volume [l]    | 3.13 | 5.21 | 5.73 | 3.14 |
| Diameter [mm/inch] | 228.6/9 | 228.6/9 | 228.6/9 | 228.6/9 |
| Length [mm/inch] | 76.2/3 | 127/5 | 139.7/5.5 | 76.2/3 |
| Zone Coating  | -   | -   | -   | -   |
| Coating Type  | -   | Cu  | -   | Cu  |
| PGM [g/ft³]   | 30  | 3   | -   | 3   |
| Pt/Pd/Rh      | 2:1:0 | 2:1:0 | -   | 1:0:0 |
| Insulation [mm] | 5   | 5   | 5   | 5   |
| Aging Status  | degreened | degreened | degreened | degreened |

Table 1. Geometrical data and coating catalysts.
The EAS model includes interface blocks, inputs, MoBEO EAS component, and sensors as shown in Figure 2. Interface blocks provide various interfaces, such as debug, ECU, sensors, engine-to-EAS, EAS-to-engine. MoBEO EAS property is configured according to the layout.

![Figure 2. EAS generic model.](image)

### 3.2. Syngas Test Bench

Syngas test bench is required to meet arbitrary mix and control syngas flow, the accuracy of syngas mass flow rate is controlled within ±5°C, and at the same time be able to produce steady state conditions and maintain sufficient uniformity in order to get high experimental reproducibility. Syngas test bench measured data with a sampling rate of 1 Hz, and measure the composition of syngas upstream and downstream of the catalyst sample by FTIR (Fourier Transform Infrared Spectroscopy) or similar devices. Temperature of the syngas stream upstream the catalyst sample should be controlled in a range from 100°C - 600°C with an accuracy of ±10°C. For SCR catalysts at least NO, NO₂ and NH₃ have to be provided with an accuracy of ±15 ppm and O₂ and H₂O with an accuracy of ±0.5%.

Different syngas test bench measurements such as NH₃ only, NH₃ and O₂ are needed as a basis for the EAS Wizard. See Table 2 for detailed test description.

| Name             | Description                                                                 |
|------------------|-----------------------------------------------------------------------------|
| NH₃ only         | SGB experiments with a constant level of NH₃ should be performed at different temperatures. |
| NH₃ and O₂       | SGB experiments with a constant level of NH₃ and O₂ surplus at different temperatures. |
| NH₃, O₂ and NO   | SGB experiments with a constant level of NH₃, NO and O₂ surplus at different temperatures. NO2/NOX level should be around 0%. |
| NH₃, O₂, NO and NO₂ | SGB experiments with a constant level of NH₃, NO, NO2 and O₂ surplus at different temperatures. NO2/NOX level should be around 50%. |
| NH₃, O₂ and NO₂  | SGB experiments with a constant level of NH₃ and NO2 with O₂ surplus at different temperatures. NO2/NOX level should be around 75%. |
3.3. Engineering Enhanced EAS Wizard

With the engineering enhanced solution in CRUISE™ M default settings for EAS, detailed concept investigations can be performed. The modeled outputs will qualitatively resemble a similar EAS based only on a few basic parameters defining the geometry and the types of catalysts (EAS) which are used. When it comes to performing tasks such as EAS calibration, a higher level of accuracy is required. Therefore, tools for automated parameter refinement based on measurement data named engineering enhanced EAS wizards, are included in engineering enhanced solution in CRUISE™ M.

The EAS wizards are designed to minimize the divergence between the modeled outputs and those of the real EAS. Therefore, they automatically adjust numerous model parameters to increase the model accuracy. Figure 4 shows EAS wizards setting interface.

3.4. Engine Test Bed Measurement

For validation of simulation quality for the full system, experiments included stationary operating points, load-steps, transient cycles, relevant legal cycles and requested customer cycles on the engine test-bed are needed. To obtain the necessary data out of these tests, emission measurement up/down-stream each component as well as over the whole EAS (EO/TP) repeated cycles with different emission measurement configurations. And the tests were performed with defined preconditioning procedures.
4. Results

The coupled model was achieved by replacing the generic transfer EAS module in the engine model with the established EAS model to verify the accuracy of the thermal parameter results, pressure parametrization results, and emissions parameterization results.

Figure 5 shows the results of thermal parametrization under WHSC (World Harmonized Steady-state Cycle) and WHTC (World Harmonized Transient Cycle) conditions. The red line represents the simulation results, while the blue line represents the measurement results. It can be seen that mean substrate model temperature are good match with measured temperature in ETB, only soak phase in mean ASC substrate temp is mismatch.

![Figure 5. Thermal parametrization results.](image1)

In figure 6, the black line represents the input of model, the red line represents the simulation results, and the blue line represents the measurement results. It is obvious that the coupled model pressure has a good match with measured ETB pressure under WHSC and WHTC conditions.

![Figure 6. Pressure parametrization results.](image2)

The emission parametrization results include DOC, DPF, SCR, ASC and EAS full system. Figure 7 shows different emission results under WHSC and WHTC. The coupled model showed good correlation between measurement and simulation as shown in figure 7 except NH3 slip downstream SCR was
underestimated. However, the timing and shape of the slip showed a good correlation with measurements, this effect may be due to uniformity issues in EAS layout, which may lead to high slip.

5. Conclusion
In this paper, an exhaust aftertreatment system simulation model established method based on the AVL CRUISE™ M of a diesel engine of China 6 applied to virtual calibration is presented. The results of thermal parameter, pressure parameter and emission parameter show that the model is of good quality and can be used in the research of virtual calibration development.

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