

Prediction of In-Cylinder States under Multiple Injection Conditions Using a Reduced-Order Model Derived from 3D CFD

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1. Introduction

Improving development efficiency is essential to achieve high performance, fuel economy, and emission reduction within shortened development cycles. Multiple injection strategies can improve mixture formation and combustion stability; however, optimization of injection timing and fuel split ratios requires evaluating a wide range of injection conditions. Although three-dimensional CFD analysis is effective for assessing such phenomena, its high computational cost limits its application to large-scale parameter screening. Therefore, this study develops a Reduced-Order Model (ROM) derived from 3D CFD results to rapidly predict in-cylinder state variables under multiple injection conditions.

2. ROM Development

Figure 1 shows the ROM development process. The ROM predicts piston wetting, liner wetting, mixture homogeneity, and spark-plug equivalence ratio using time-series data obtained from 3D CFD simulations. Injection rate profile, cumulative fuel mass, crank angle, piston position, and piston velocity were used as input variables. LSTM(Long Short-Term Memory) and LightGBM models were compared, and LSTM was selected because it more accurately reproduced the CFD-derived state variables. Hyperparameter optimization and Early Stopping were applied to improve prediction accuracy and prevent overfitting.

3. Results and Discussion

Figure 2 compares ROM responses with CFD results under varying injection timing conditions. The ROM successfully reproduced the trends of piston wetting, liner wetting, and mixture homogeneity across a wide range of injection timings. These results demonstrate that the proposed ROM successfully reproduced the dependence of in-cylinder state variables on injection timing, supporting its use as a surrogate model for evaluating multiple injection conditions. Furthermore, trends predicted by the ROM agreed well with emission trends observed in engine experiments.

4. Conclusions

A CFD-based LSTM-ROM was developed to predict in-cylinder state variables under multiple injection conditions. The developed ROM successfully reproduced the effects of injection timing on in-cylinder state variables, suggesting its potential for efficient exploration and optimization of engine operating conditions.

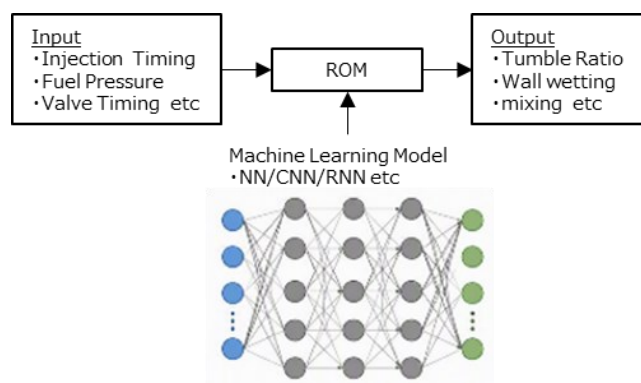


Fig. 1) Overview of the ROM development process

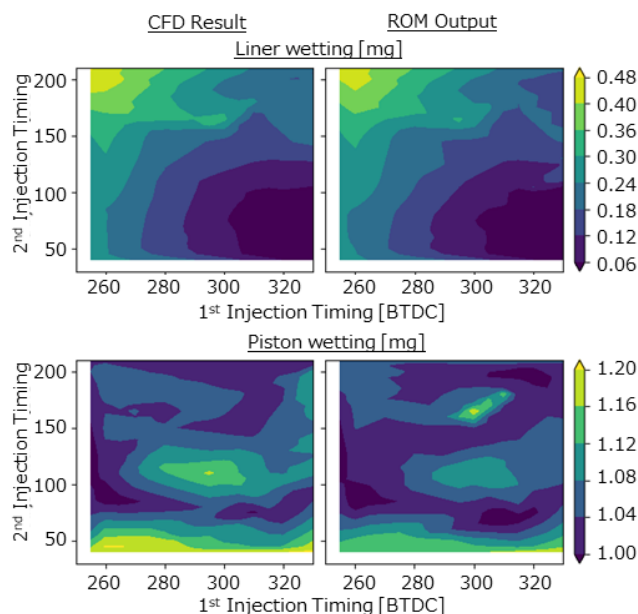


Fig. 2) ROM and CFD Responses to Injection Timing