Thesis Title「Study on Combustion Modeling for Diesel Engines with Multi-Stage Injection Strategies」
（多段噴射を用いたディーゼル機関の燃焼モデルに関する研究）

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Abstract

In order to satisfy the growing demand for the reduction of fuel consumption and pollutants emissions, various technologies have been employed in diesel engines. In particular, with common-rail fuel injection systems getting practical, the multi-stage injection strategies have been paid more attention in combustion control for the latest engines due to its potential to obtain low emissions and high fuel efficiency under different operating conditions. Thus, to obtain the proper multi-stage injection strategy, the primary work of this thesis focuses on the development of a phenomenological combustion model with NO_x and soot calculation for realizing parametric studies on multi-stage injection strategies. In addition, the experimental study on smoke reduction effect by post injection is conducted in this thesis with the aim for selecting post injection parameters properly. These researches are specified in 6 chapters as follows.

Chapter 1 is the introduction expounding the research background, present research status, and research objectives. First of all, the increasingly severe situations of energy and environment and consequential reduction requirement of fuel consumption and emissions for vehicles powered by internal combustion engines were introduced. Then, based on the statements of the problem of diesel engines, relevant emission standards, and the barriers of aftertreatment technologies, the importance of further improvements on in-cylinder combustion was indicated. Furthermore, the technologies of in-cylinder combustion improvement and their problems were demonstrated, and the conclusion revealed that the multi-stage injection is a potential approach to realize low NO_x and PM emissions and high fuel efficiency in diesel engines. However, combustion process operating with multi-stage injection is complicated due to the interactions between different injections, and thereby leads to incomplete understanding on pollutants production process during combustion when varying injection conditions. That results in difficult selection of proper injection strategy from numerous parameters, especially

the post injection strategy for smoke reduction has not been revealed clearly. Thus, developing a practical combustion model for simulating diesel combustion with multi-stage injection, which can be used for parametric study on multi-stage injection strategies, was proposed as the main objective of this thesis. Moreover, further research about the post injection effects on smoke reduction for post injection parameters selection was another purpose of this thesis.

Chapter 2 shows experimental work undertaken to study the smoke reduction effect of post injection under three-stage injection conditions. In this chapter, the experiments were performed with varying the pilot and post injection conditions including the injection quantity and timing in a single-cylinder DI-diesel engine under high load conditions, and the dwells between main and post injection were restricted in a small region. The results show that small post injection quantity with early post injection timing causes less smoke emission. And larger pilot injection quantity and later pilot injection timing lead to higher smoke emission. Then, to comprehend and explore the smoke reduction mechanism by the post injection combined with the pilot injection, the experimental results of three-stage injection conditions were compared to those of two reference cases, which only included pilot and main injection, and the interaction between main spray flames and post sprays was applied for analysis. Based on the comparative analysis, the larger smoke reduction effect of post injection was observed with the larger pilot injection quantity, while it was not greatly influenced by pilot injection timing. In addition, the smoke emission can be reduced considerably by increasing the injection pressure, however the smoke reduction effect of post injection was attenuated. And all of these tendencies were able to be interpreted by considering the intensity variation of the interaction between main spray flames and post sprays.

Chapter 3 covers the development of the phenomenological combustion model for diesel engines with multi-stage injection. The phenomenological combustion model was developed based on the stochastic combustion model which has been developed for simulating diesel combustion with single-stage injection. To extend the stochastic combustion model for the case of multi-stage injection, at first, new model concepts were proposed considering the relative positions of the sprays from sequent injections observed from the shadowgraph images of two-stage injection in a constant volume combustion chamber. Then, in order to realize the new model concepts, a zero-dimensional spray propagation model including the spray evolution after the end of injection and the calculation of spray tail penetration were developed based on the latest fundamental studies on the turbulent spray behavior, and the interaction between the sprays from sequent injections was modeled by taking account of the spray tail position and the spray entrainment behavior.

Chapter 4 presents the validation and improvements of the developed combustion model. In this chapter, the combustion model developed in the Chapter 3 was validated against the experimental data from a single-cylinder DI diesel engine for pilot/main two-stage injection, in which the pilot injection conditions were varied with fixed main injection timing, and some discrepancies of heat release rate between the simulation and experiment were observed. Based on the analysis of heat release rate, entrainment rate, and probability density functions of equivalence ratio, the improvements were carried out on three stages to reproduce the experimental heat release rates. The lower fuel-air mixing rate was considered when the spray flows into the squish region after the wall impingement to capture the decrease tendency of pilot spray's heat release with advancing pilot injection timing as it in experiments. The enhancement of main spray entrainment rate by wall impingement was introduced to raise and advance the peak of calculated heat release rate during mixing-controlled combustion phase of main injection. However, high entrainment rate also made combustion ended early, which leaded to more rapid decrease of the calculated heat release rates than that of experimental data during late combustion period. Thus, the suppression of entrainment rate by interaction between adjacent sprays was employed in order to reproduce the heat release rate during late combustion period. Finally, after the improvements above, fairly well predictions of heat release rate when varying the pilot injection timing and quantity has been achieved using the developed combustion model.

Chapter 5 is aimed at embedding the NO_x and soot calculations into the developed combustion model. From the results obtained in Chapter 4, the calculated heat release rates in the larger pilot injection quantity cases showed lower peaks phase than those of experiment data during mixing-controlled combustion, which were needed to improve for reasonable emission calculation results. Thus, in this chapter, the effects of swirl flow on the interaction between sprays from sequent injections were taken into account for improving the prediction of heat release rate at first. Following this work, NO_x and soot calculations were embedded into the model to predict exhaust emissions. NO_x was calculated by the extended Zeldovich mechanism and soot model was referred to the Patterson's model. The calculated results were compared with experimental data from the single-cylinder test engine for pilot/main two-stage injection, and the experimental conditions were same with those in Chapter 4. The results showed the well prediction of heat release rates, in-cylinder pressures, and NO_x emissions, however, the soot emissions obtain an inverse tendency with increasing pilot injection quantity to that of measured data. Then based on the analysis of soot histories, the improvements of soot model, which includes decreasing the soot oxidation constants of Patterson's model and using more detailed soot model proposed by Moss et al instead of Patterson's model, were conducted subsequently. The results indicated that the measured tendency of soot emissions with increasing pilot injection quantity was captured by Moss's soot model. That was caused by the smaller soot oxidation rate relative to fuel-air mixing rate according to the comparison analysis of soot production information between Patterson's model and Moss's model, including soot histories, soot mass distributions along equivalence ratio. However this phenomenon also resulted in overestimation of the soot emissions in earlier pilot injection cases especially in the cases of larger pilot injection quantities. Thus the soot oxidation rate relative to fuel-air mixing rate was indicated to be paid attention for the improvement of soot calculation.

Chapter 6 contains the conclusions summarized from all the researches in this thesis and recommendations for future research.