論文の要旨

題　目　CHARACTERIZATION OF DIESEL SPRAY AND MIXTURE FORMATION PROCESSES UNDER SMALL INJECTION AMOUNT CONDITION

（微小噴射量条件下のディーゼル噴霧と混合気形成過程の特性に関する研究）

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Fuel spray and mixing process play an important role in modern automotive engines, which are affected by the internal flow of the nozzle and directly related to the subsequent in-cylinder combustion and emission generation. Studies focused on the spray during quasi-steady condition, in particular when the injection rate profile reaches steady condition; while rare research has been conducted on the spray with small injection amount which the entire injection rate profile are under transient.

In the dissertation, the fuel atomization and mixing process under the condition of small injection amount is investigated by experimental methods, including high-speed video observation and tracer laser absorption and scattering (LAS) technique. High-speed video observation was performed for near-field spray behaviors of single-hole and multi-hole injectors under non-evaporating conditions. LAS experiments were conducted to measuring the parameters in mixture process (equivalence ratio, etc.) under different injection amounts for both single-hole and multi-hole injectors. Moreover, LAS technique was also employed to analyzing the divergence between various dwell times as well as the split ratio of split injection strategies for a multi-hole injector. In addition, the flow state inside the nozzles was numerical investigated by commercial software AVL Fire (2014) to illustrate the different in spray evolution between single-hole and multi-hole injectors under different injection amount and rail pressure.

Chapter 1 introduced the research background including the energy and environmental issues, common rail systems, diesel injectors and factors affecting the spray behavior, as well as previous works on nozzle internal flow, spray characteristics. Specially, the development of LAS technique and research based on LAS technique were introduced in detail.

In Chapter 2, the experimental apparatuses and investigation methods are introduced. The apparatuses include constant volume chamber (including the chamber cap specially designed), photograph systems of microscopic and LAS technique, fuel injection system and measurement system of injection rate. The main investigation method adopted in the research is the experiment of LAS specially developed for measuring vapor and liquid phases distributions under evaporating conditions, the principle of which has been described detailly. Meanwhile, the diffused background illumination used for high-speed observation and numerical models are presented.

In Chapter 3, An experimental study was introduced to investigate the spray characteristics of single -hole and multi-hole injectors including microscopic measurement under non-evaporating spray conditions and mixture formation process under evaporating spray conditions. LAS technique was implemented for measuring the mixture concentration. Three injection amounts, 0.5, 2.5, and 5.0 mg/hole, were selected to observe the effects of the transient and quasi-steady state injection spray.

The sprays of single-hole and multi-hole injectors show a higher instability in terms of injection rate, spray cone angle and spray angle when the injection amount is small enough (0.5 mg). Moreover, for the spray of multi-hole injector, the variation on spray angle and spray cone angle are much more obvious.

The spray cone angle was wider, and the boundary of the spray showed higher turbulent structure for multi-hole injector. However, as the injection amount increased, the spray cone angle difference between two injectors became small. The quasi-steady state injection as the injection amount increased reduced the difference between two injectors. The spray angle of multi-hole injector became greater again at the vicinity of end-of injection (EOI) timing, where the needle lift became smaller again.

The macroscopic spray (evaporating) of both injectors under large injection amount exhibited a similar spray structure, with a 'time shift' for multi-hole injector. The initial development process of vapor penetration was faster for single-hole injector; however, the gap between two injectors remained constant as far as the injection entered into quasi-steady state. The spray angle of the multi-hole was greater than that of single-hole injector at the vicinity of SOI timing. However, the spray angle also converged into a similar value for both injectors when the injection became steady. The differences of two injectors were more pronounced as the injection amount decreased, where the transient process dominated over the entire injection event, as shown in the result of 0.5 mg condition.

The mixture formation process (equivalent ratio, evaporation ratio) based on the LAS experiment also showed similar results for both injectors under large injection quantity condition (2.5 mg). Since the quasi-steady state injection dominated over the entire injection process, the mixture formation during the injection were similar for both injectors. The main difference was the initial spray development process during the sac pressure build-up period.

However, the mixture formation process was better for single-hole injector than that of multi-hole injector under small injection quantity condition. Under this condition, the spray penetration was higher for single-hole injector, while the spray angle was wider for multi-hole injector. The single-hole injector was able to achieve similar mixture distribution with its higher spray penetration despite its narrow spray angle compared to the multi-hole injector. The experimental results revealed that the mixture was leaner for single-hole injector throughout the injection process, and it was considered to be attributed to the following two reasons - evaporation ratio and the air entrainment wave after EOI timing. A slower evaporation rate of single-hole injector at EOI timing might have contributed in leaner vapor mixture at the vicinity of the EOI timing. After the fuel was fully vaporized, it was considered that the stronger air entrainment wave induced by shorter injection duration and faster ramp-down features in the injection rate of the single-hole injector yielded faster liquid recession and leaner mixture formation after EOI.

More importantly, the spray under small injection amount has a slower evaporation AEOI due to the small momentum and less ambient entrainment from the spray tail. However, faster dilution rate of equivalence ratio presented under the same condition caused by the larger surface-volume ratio. That means combustion and emission characteristics will be much different when the operation condition changed in a real engine. Furthermore, these differences should be considered carefully in a multiple injection system because that small and large injection amounts exist simultaneously.

In Chapter 4, the mixture formation process of fuel spray was observed for single-hole and multi-hole injectors. According to Chapter 3, the spray behavior of single-hole injector has much different with that of multi-hole one under small injection amount condition. In Chapter 4, the thinking had been breaking down and changed to control the hole exit velocity. The spray evolution with small injection amount under same injection pressure (100 MPa for both injectors) or similar injection rate condition (30 MPa for single-hole, and 100 MPa for multi-hole injector) were observed, respectively. The laser absorption scattering (LAS) techniques were implemented to measure the equivalence ratio of the vapor phase of the fuel spray.

Under the same injection pressure condition, the vapor penetration is greater for single-hole injector than that of multi-hole injector, due to the faster pressure build-up process inside the sac volume. For similar injection rate condition, the spray tip penetration has been controlled by adjust the rail pressure and achieved a decrease of the variable numbers.

The spray angle is larger for multi-hole injector than that of single-hole injector under both same rail pressure and similar injection rate conditions. That is probably due to the complex nozzle internal flow which will be discussed in Chapter 5.

The mixture formation of single-hole injector is slightly better than that of multi-hole injector under same injection rate condition. The entire injection event of small injection quantity took place under transient condition. The greater spray tip penetration caused by the faster pressure build-up process inside the sac volume yielded greater air entrainment rate and amount for the single-hole injector. However, the difference in air entrainment rate and amount as a function of axial distance can be eliminated for both injectors under the same injection rate condition, since their vapor penetrations are similar to each other. The mixture formation process for single-hole injector then become worse than that of multi-hole injector. The narrow spray angle and dense liquid core of the single-hole injector caused a lower evaporation ratio at the EOI timing. The overall equivalence ratio moves towards lean side for the multi-hole injector as the time elapsed. However, since the single-hole injector no longer has any advantages on the vapor penetration, the evaporation rate is slow, and the mixture is not able to lean out quickly due to continuous portion of liquid core evaporating into vapor, maintaining the rich mixture. The mixture starts to lean out after the vapor was fully evaporated.

Regarding the same injection pressure condition, the vapor penetration plays an important role in the air entrainment and evaporation rate, thus improved the lean mixture formation process, despite of its smaller spray angle of the single-hole injector. When the vapor penetration becomes similar (by means of controlling the injection pressure) for both injectors, the mixture formation becomes worse for single-hole injector due to its smaller spray angle and dense liquid core.

In Chapter 5, nozzle internal flow and near-field spray behaviors have been numerical investigated by employing the commercial software AVL Fire (version 2014). In the simulation, the flow characteristics inside the nozzles of single-hole and multi-hole injectors were compared under both same rail pressure and similar injection rate conditions.

The increase rate and the peak of the sac pressure was greater for single-hole injector than that of multi-hole injector under same rail pressure condition. Therefore, the spray axial velocity calculated at 1 mm downstream of the nozzle exit showed that, the velocity profile for single-hole injector was higher than that of multi-hole injector.

At low needle lift condition, the drastic direction change in the internal flow induced higher turbulent intensity inside the sac volume and the hole of the multi-hole nozzle. Thus, although the violent vortexes also appeared inside the sac volume of single-hole nozzle, higher radial velocity vectors were created in the spray, resulting in higher dispersion angle for the multi-hole injector, as expressed in Chapter 3.

The results of nozzle flow simulation under similar injection rate show that there were greater portion of radial velocity term at the nozzle exit for multi-hole injector than that of single-hole injector at the transient period (low needle lift condition). It can be attribute to the drastic direction change in the internal flow and uneven velocity distributions inside the hole of multi-hole nozzle. These might yield a high spray angle for multi-hole injector with small injection quantity, either under the same rail pressure or similar injection rate conditions. In addition, the large values of turbulence kinetic energy in the liquid core and ambient gas regions enhanced the mixture formation process and evaporation for the spray of multi-hole injector.

In Chapter 6, the mixture formation process of split injection strategies (positive and negative dwells) were investigated in a constant volume chamber under evaporating conditions. A commercial multi-hole injector was used in the study to eliminate any possibilities of differences in spray structure from a single-hole injector. Laser absorption scattering (LAS) technique was utilized to measure the fuel concentration. The split ratios and the dwell times (interval) between two split injections were varied to observe their effects on the mixture formation. Three split ratios of 3:7, 5:5, and 7:3 were selected, while the dwell times were varied from the negative value of -50 μs to maximum of 840 μs. The total amount of injected fuel quantity was fixed to 5.0 mg per hole. The split injection strategies were also compared with the single injection result.

The vapor penetrations of the split injections were shorter than the single injection due to the discontinuity of the injection momentum. The penetration of the second injections were shifted temporally and aligned with the first injections to observe the effects of first injections on the second ones. The vapor penetration development of the second injections were faster than the first ones' due to the slipstream effect. This slipstream effects were reduced as the dwell time between two injections increased. The vapor penetration of the second injection surpassed the first one under the split ratio of 3:7 obviously, due to the greater amount of fuel mass for the second injection. The effect of slipstream was not obvious under the split ratio of 7:3, because the injection quantity for second injection was small and the spray soon lost its momentum after the end of injection.

Regarding the mixture formation process, the split ratio of 7:3 exhibited the best performance among the conditions conducted in the current study. The ambient air/fuel mixture created from the first injection was entrained into the second injected spray; therefore, leaner the mixture formed from the first injection was advantageous. The air entrainment wave after the end of injection of the first injection yielded rapid formation of lean mixture at the downstream of the nozzle. In addition, the split ratio of 7:3 provided an appropriate amount of fuel amount to penetrate into the lean region of the first injected fuel mixture, thus creating an overall leaner mixture than any other two split ratio conditions. The split injection strategies were not as good as the single injection in terms of the mixture homogeneity due to decreased penetration, since the penetration plays an important role in the total amount of air entrainment. Moreover, the small injection amount of the second injection can provide an enhanced penetration and faster dilution rate forming a lean mixture at same time with the first injection. However, this conclusion can only be drawn with a free spray, and the optimum conditions may vary when considering an impinging spray, such as in a combustion chamber of a real engine.

The dwell time of 120 μs was reasonable from the mixture preparation perspective for positive dwell conditions. The greater the dwell time indeed provided time for creating leaner mixture from the first injection, thus provided chance to entrain leaner mixture into the second injected spray. However, the improvement magnitude was small, because the mixture formation of the second injected spray could already achieve lean mixture even with the minimum dwell time of 120 μs. In addition, the split injection with minimum dwell time would be advantageous in terms of engine efficiency due to the degrees of constant-volume combustion. The optimum dwell time requires further investigation when taking the combustion and emission formation into account.

A shorter penetration represented for the split injection with negative dwell time due to the impingement of the second part on the low momentum part of the spray. The low-momentum spray region with large density blocks the development of the second injection at the hole outlet, while the low-momentum spray is driven by the second injection to spread around and its momentum dissipates rapidly. However, the split injection with negative dwell time still has a better lean mixture process comparing with the single injection strategy. This makes it possible to improve the combustion and avoid wall impingement inside the cylinders of small engines without reducing the injection pressure.