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ENHANCEMENT OF STRATIFIED CHARGE FOR DISI ENGINES THROUGH SPLIT INJECTION

[1]SHAIK HUSSAIN, [2]T.RAMACHANDRAN, [3]A.RAVEENDRA

[1&3] Assoc.Professor, Department of Mechancial Engineering, Malla Reddy Engineering College (Autonomous), Maisammaguda(H), Gundlapochampally Village, Secunderabad, Telangana State -500100

[2] Professor, Department of Mechancial Engineering, Malla Reddy Engineering College (Autonomous), Maisammaguda(H), Gundlapochampally Village, Secunderabad, Telangana State -500100

The effect of split injection on the mixture characteristics of DISI (Direct Injection Spark Ignition) engines was investigated firstly by the Laser Absorption Scattering (LAS) technique. Through splitting the fuel injection process, two possible benefits were found: 1) High density liquid droplets piling up at the leading edge of the spray can be circumvented, subsequently the reduction of the spray tip penetration; 2) The quantity of "over lean" ($\varphi v < 0.7$, φv: equiv- alence ratio of vapor) mixture in the spray can be significantly reduced. These are believed to contribute to the reduction of the engine-out smoke and HC emissions. In order to clarify the mechanism behind the effect of the split injection, the spray-induced ambient air motion was investigated by the LIF-PIV technique. The strong ambient air entrainment into the tail region of the spray and a counter-vortex structure were found in both the single and split injections. In the case of the single injection, the spray develops in extending its length, subsequently a larger volume results and thus it is diluted to "over lean" by the ambient air entrainment. In contrast, in the case of split injection, the second spray is injected into the tail region of the first spray and its evaporation is promoted by the ambient air motion induced by the first spray. Hence the replenishment of the liquid fuel into the leading edge of the first spray is reduced. As a consequence, the high density liquid droplets piling up at the leading edge is avoided. Furthermore, a more compact spray results so that the ambient air motion plays a positive role on evaporating the spray into "more combustible" ($0.7 < \varphi v < 1.3$). This is especially true in the tail region of the spray and the region where the counter-vortex motion is occurring.

Key Words: Gasoline Engine, Direct Injection Spark Ignition (DISI) Engine, Fuel Injec- tion, Split Injection, Fuel Spray, Fuel Air Mixture, St Ratified Charge, Laser Diagnostics, Digital Image Processing

1.Introduction

It has been well known that most fuel economy of DISI (Direct Injection Spark Ignition) engines stem from the stratified charge operation at part load. The prepara- tion of the stratified charge in the vicinity of the spark plug is the key challenge for the combustion system de- sign of the DISI engine because there are very limited time between the fuel injection and spark ignition due to the late fuel injection during compression stroke. Most cur- rent production DISI engines adopt the wall-guided mix- ture preparing strategy for the stratified charge. The rel- atively high soot and HC emissions due to the spray-wall impingement are the issues. Nevertheless, a specially de- signed bowl-in-piston chamber for guiding the mixture to the ignition source is required. Thus, the increased com- bustion chamber surface area results in extra heat transfer losses and the reduced fuel economy. In contrast, ideally speaking, any spray-wall impingements should be avoided in the air- and spray-guided systems, and a flat or shallow- dish shape combustion chamber can be used. However, the well defined spray, such as proper spray penetration, droplet size and spray angle become more crucial. Re- cently, a “soft spray” was conceptually proposed by Yang et al.(1) The soft spray was featured by a shorter spray pen- etration, a wide cone angle and a spherical shape of fuel zone. In their study, however, the injector for the soft spray was not reported, and the soft spray was conceptually gen- erated using conventional swirl spray impinging upon a target for the spray characteristic study.

Split injection strategy has been adopted in the pro- duction of DISI engines. In the first generation of produc- tion DISI engines by Toyota Motor Corporation, split in- jections were used to obtain a smooth transition between light and heavy load operations. With the two-stage in- jection (one during the intake stroke and the other during the compression stroke), semi-stratified charge was real- ized and continuous torque output without smoke genera- tion was reported(2). Engineers in Mitsubishi Motor Cor- poration used double pulsed injections during the intake and compression strokes respectively to suppress cylinder knock in the low speed range and to reduce soot emis- sions(3). Furthermore, with a strategy of one injection dur- ing the compression stroke and the other during the ex- pansion stroke, an increased exhaust gas temperature was realized for the quick warm-up of the catalyst(4). In the study of Yang et al.(5), a detailed mechanism of higher volumetric efficiency and lower knocking tendency im- proving engine torque output was clarified. To improve the volumetric efficiency, fuel injection during the intake stroke is required. In contrast, to reduce the tendency to knock, fuel injection during the latter stage of the com- pression stroke is required. As a result, a split injection strategy was proposed as a compromise to meet the two competing requirements and to further increase the engine torque output. Stiesch et al.(6) made a conceptual study by using computational fluid dynamics to investigate the pos- sible benefit of split injections. Double pulse injections with each pulse being 50% of the total fuel mass were proposed. The simulation results suggest that both the fuel economy and NOx emissions would be improved by the double pulse injections. However, with regard to the research for spray and mixture characteristics of DISI en- gines, most of the numerical and experimental works were focused on the sprays by single injection. Detailed infor- mation about the characteristics of DISI

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engine sprays by split injection is rarely reported in trade journals although this information is extremely important to optimize the de- sign of DISI engines.

In this study, the effect of split injection on the mix- ture formation process of DISI engines was investigated by employing the LAS technique. As a result, it was found that through splitting the fuel injection, two benefits for the preparation of the stratified charge can be obtained: 1) High density liquid phase spray piling up at the leading edge of the spray can be circumvented; 2) The quantity of "over lean" ($\varphi v < 0.7$) in the spray can be significantly re- duced. These are believed to contribute to the reduction of the engine-out smoke and HC emissions. Then, in order to clarify the mechanism behind the effect of the split in- jection, the spray-induced ambient air motion was studied by the LIF-PIV technique. It was found that the ambient air motion play a role in diluting the spray by single in- jection whereas it has positive effect on evaporating the second spray in the split injection. This gives the reason of the benefits of the split injection for the stratified charge formation.

2. Experimental Setup

2. 1 Laser Absorption Scattering (LAS) technique

The LAS technique is based on the measurement of the relative extinction of the two wavelength (ultraviolet and visible) lights by an evaporating spray. The necessary condition is that the extinction of ultraviolet light is due to the absorption of vapor phase spray and both the scatter- ing and absorption of liquid droplets whereas the extinc- tion of visible light is due to only the scattering of liquid droplets. In a dispersed cloud droplets like DISI gasoline spray (mean diameter larger than 7 μm), the extinction ef- ficiency tends to be the same regardless of the wavelength of incident light(7). Thus, from the extinction difference, the vapor concentration distribution can be obtained ac- cording to the Lambert-Beer's law. Furthermore, based on the light scattering theory and the definition equation of Sauter mean diameter, the liquid phase concentration can be obtained. Figure 1 shows the schematic of the experi- mental setup for the LAS measurement. In this study, the Nd:YAG laser, which can provide both ultraviolet (wave- length 266 nm) and visible (532 nm) lights, was used as the light sources. P-xylene, which has similar physical properties to gasoline, was selected as the test fuel. The fuel injector was a high-pressure swirl-type one. The in- jection pressure was 5 MPa. The ambient pressure and temperature were 1.0 MPa and 500 K. For the detailed information of the LAS technique and the pressure-swirl injector, readers can refer to the published paper of the authors(7).

2. 2 LIF-PIV technique

The LIF-PIV technique is a measure combining the features of the Laser Induced Fluorescence (LIF) and Par- ticle Image Velocimetry (PIV) techniques. The PIV tech- nique is based on measuring the displacement of particles in two images obtained by two-exposure imaging with a very short interval. In order to obtain a

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measurement of air motion, tracer is generally necessary.

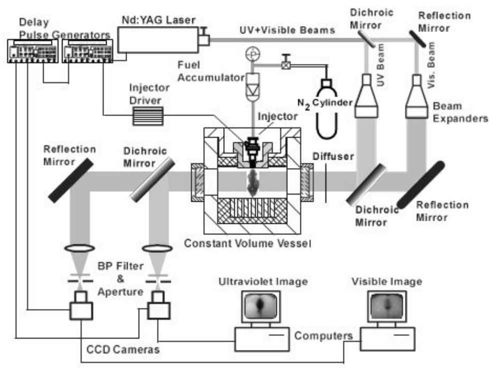

Fig. 1 Experimental setup for Laser Absorption Scattering (LAS) measurements

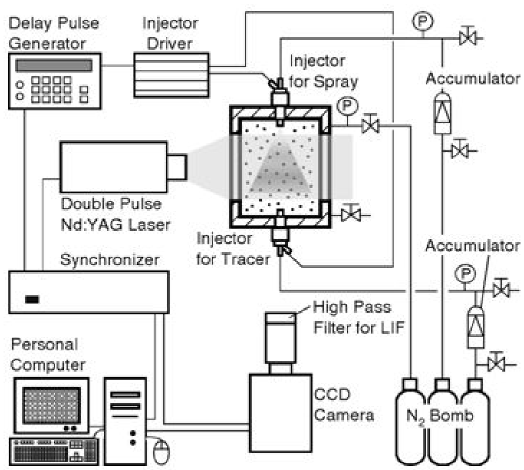

Fig. 2 Experimental setup for LIF-PIV measurements

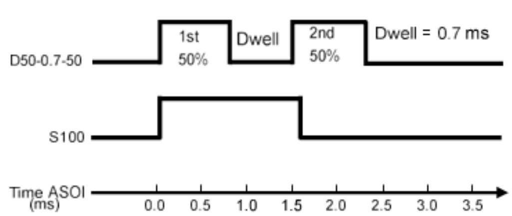

Fig. 3 Timing chart for the two different injection patterns

In order to ensure the tracer droplets as small as possible, injector pressure for tracer was set as 9.0 MPa that is the design limit of the injector. The injection timing for tracer was 800 ms before the start of fuel injection so that the ve- locity of the tracer was in the range of less than absolute 0.1 m/s at the start of fuel injection. In addition, based on the calculation of the terminal velocity, the tracing veloc- ity of the tracer can exceed 90% of the ambient air veloc- ity in 0.5 ms. In Ref. (8), the detailed information about the LIF-PIV technique can be found.

3.Results and Discussion

3. 1 Effect of split injection

Figure 3 shows the timing chart for the split and sin- gle injections. In the split injection (D50-0.7-50), the total injection quantity was 9.4 mg, and 50% of the fuel was injected in each pulse of a width of 0.8 ms. The dwell be- tween the two pulses was 0.7 ms. In the single injection (S100), in order to keep the same injection quantity, injec- tion duration was set as 1.62 ms.

Figure 4 shows the spatial equivalence ratio distribu- tions of liquid and vapor phase in the sprays by the sin- gle and split injections at 3.3 ms after the start of injection (ASOI). The digits in each figure denote the value of the equivalence ratio contours

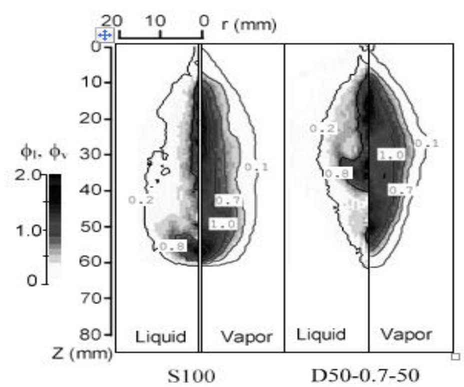

Fig. 4 Spatial equivalence ratio distributions of liquid and vapor phase in the sprays by single injection and split injection at 3.3 ms (Fuel: p-xylene; P_{inj} = 5.0 MPa; Q_{inj}=9.4 mg; P_a=1.0 MPa; T_a=500 K)

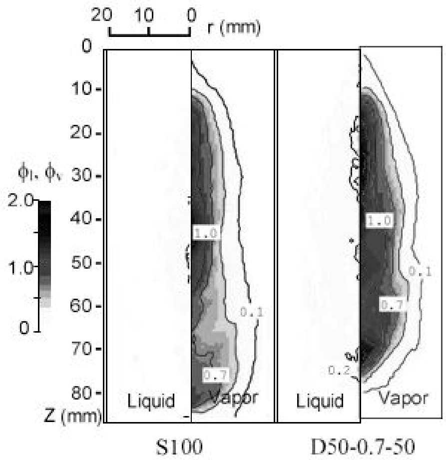

Fig. 5 Spatial equivalence ratio distributions of liquid and vapor phase in the sprays by single injection and split injection at 5.8 ms (Fuel: p-xylene; P_{inj} = 5.0 MPa; Q_{inj}=9.4 mg; P_a=1.0 MPa; T_a=500 K)

In the case of the single injection, the high density liquid phase fuel (φl > 0.8, φl: equivalence ratio of liquid) piling up at the leading edge of the spray can be found. In contrast, when splitting the injection process, the high density liquid phase fuel distributes at some distance from the leading edge of the spray. As a consequence, the spray tip penetration can be reduced(9) (This can also be found in Fig. 5). In a wall-guided combustion system, this can help reduce the possibility of the formation of fuel film attaching on the wall, because when a small amount of liquid fuel impinge upon a hot wall like the surface of piston cavity, it will evaporate soon; whereas a large amount of liquid fuel impinging upon and continually re- plenishing into the cavity cause the fuel film forming more possibly. The fuel film may be the major source of the engine-out smoke emissions in the wall-guided type DI gasoline engine. Nonetheless, the benefit of reducing the spray penetration becomes more pronounced in the air- or spray-guided combustion systems because any unintended spray-wall impingement should be avoided in these en- gines.

With regard to the vapor phase spray, the single in- jection shows more vapor of equivalence ratio below 0.7 (over lean) than the split injection. This becomes more pronounced in the sprays at 5.8 ms ASOI as shown in Figs. 5 and 6. At this time, there shows very little liq- uid phase fuel in both the single and split injections, and the spray by the split injection shows apparently shorter penetration than the single injection.

For a further analysis, the mass frequency distribu- tions of both the liquid and vapor phase sprays at 5.8 ms are drawn as shown in Fig. 6. In both the cases, the liquid phase mass in the sprays show almost the same distribu- tion, that is, there is very little liquid phase fuel distributed in the low equivalence ratio region. This indicates that about 84% of the fuel has evaporated. As for the vapor phase fuel, most of the vapor mass in the case of the single injection shift to the "over lean" region, and in contrast, the peak of vapor mass in the case of split injection occurs in the region of "stable operating limit". The "stable op- erating limit" is defined by the range of 0.7 = φv = 1.3 as a reference for the evaluation on "over lean" or "over rich" of the mixture in this study.

It has been described in the introduction section that most of the fuel economic benefits of DI gasoline en- gines stem from the super-lean stratified combustion at light load due to the reduction of pumping loss. How- ever, to determine the spark ignition

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timing is quite dif- ficult for the stratified charge compared to the homoge- neous charge. The constraint on the spark ignition tim- ing presumably results from two phenomena: 1) Ignition of the stratified charge requires that the spark plug gap is located in the flammable mixture at the time of ignition. Because the fuel-air mixture is moving and diluting after fuel injection, the acceptable range of ignition timing is constrained. 2) Flame propagation in the fuel-lean mix- ture at the edge of the main mixture zone is slow. If peak of heat release occurs after TDC (Top Dead Center), com- bustion in the lean mixture can be even later. The piston is moving down, and temperature is dropping due to ex- pansion. Hence, the flame propagating through the lean mixture can be quenched; higher UBHC (Unburned Hy- drocarbon) emissions results. Advancing the spark igni- tion timing can move the combustion timing of lean mix- ture closer to TDC; higher mixture temperature can help the burnout of UBHC in the lean mixture. However, peak heat release probably occurs before TDC, resulting in sig- nificant increases in heat transfer loss

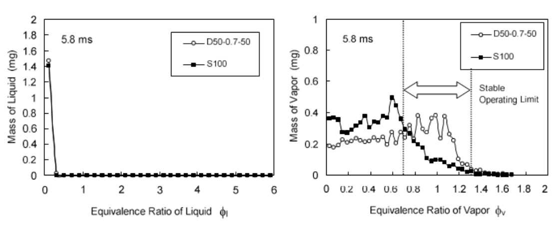

Fig. 6 Mass distributions of liquid and vapor phase in the sprays by single injection and split injection at 5.8 ms (Fuel: p-xylene; P_{inj} = 5.0 MPa; Q_{inj} = 9.4 mg; P_a = 1.0 MPa; T_a =500 K)

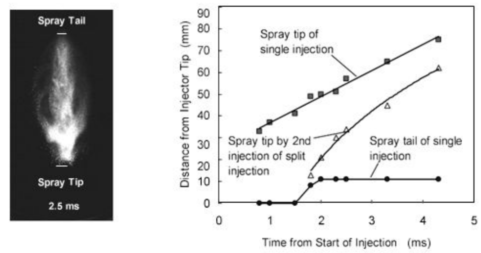

Fig. 7 Variations of the positions of spray tail and tip by single injection and spray tip by second injection of split injection (Fuel: dry-solvent; P_{inj} = 4.6 MPa; Q_{inj} = 9.4 mg; P_a=0.6 MPa; T_a =300 K)

4.Conclusions

In this study, the effect of split injection on the mix- ture characteristics of DISI engines have been investi- gated by the Laser Absorption Scattering (LAS) tech- nique. Through splitting the fuel injection process, two possible benefits to the stratified charge of DISI engines were found:

(1) High density liquid phase spray piling up at the leading edge of the spray can be circumvented; subse- quently, the spray tip penetration can be reduced.

(2) The quantity of “over lean” (φv < 0.7) in the spray can be significantly reduced. These results are believed to contribute to the reduction of the engine-out smoke and HC emissions.

In order to clarify the mechanism behind the effect of the split injection, the spray-induced ambient air mo- tion has been investigated by the LIF-PIV technique. The results are as followings:

(3) When splitting the injection process, the second spray is injected into the tail region of the first spray and it distributes some distance from the leading edge of the first spray. As the spray-induced ambient air motion helps evaporate the second spray, the second spray loses its mo- mentum quickly, hence it will not pile up at the leading edge.

In addition, with the less injected fuel quantity, the spray can evaporate more quickly. As a result, the liquid fuel piling up at the leading edge of the first spray can be reduced to some degree compared to the single injection. Therefore, the total high density liquid phase fuel piling up at the leading edge is circumvented.

(4) In the single injection, the spray develops in con- tinually extending its length and subsequently a large vol- ume of the spray. Thus, the spray-induced ambient air mo- tion including the ambient air entrainment into the tail re- gion and the vortex structure at some distance downstream could play a role in diluting the spray into "over lean". In the split injection, the second spray is injected into the tail region. Due to the avoidance of liquid fuel piling up at the leading edge, the spray formed a more compact struc- ture. The interaction between the second spray and the first spray-induced ambient air motion helps accelerate the evaporation of the spray in such a compact structure. As a result, the more combustible mixture results.

References

(1) Yang, J. and Kenney, T., Some Concepts of DISI En- gine for High Fuel Efficiency and Low Emissions, SAE Technical Paper, No.2002-01-2747, (2002).

(2) Harada, J., Tomita, T., Mizuno, H., Mashiki, Z. and Ito, Y., Development of Direct Injection Gasoline Engine, SAE Technical Paper, No.970540, (1997).

(3) Kuwahara, K., Ueda, K. and Ando, H., Mixing Control Strategy for Engine Performance Improvement in a Gasoline Direct Injection Engine, SAE Technical Pa- per, No.980158, (1998). Subramanyam Pavuluri https://orcid.org/0000-0002-2703-2358

(4) Kuwahara, K., Yamamoto, S., Iwachidou, K. and Ando, H., Two-Stage Combustion for Quick Catalyst Warm-up in Gasoline Direct Injection Engine, Proc. 4th COMODIA 98, (1998), pp.293–298.

(5) Yang, J. and Anderson, R.W., Fuel Injection Strate- gies to Increase Full-Load Torque Output of a Direct- Injection SI Engine, SAE Technical Paper, No.980495, (1998). . https://orcid.org/0000-0002-2703-2358

(6) Stiesch, G., Merker, G.P., Tan, Z. and Reitz, R.D., Modeling the Effect of Split Injections on DISI Engine Performance, SAE Technical Paper, No.2001-01-0965, (2001).

(7) Yamakawa, M., Takaki, D., Li, T., Zhang, Y. and Nishida, K., Quantitative Measurement of Liquid and Vapor Phase Concentration Distributions in a D.I. Gasoline Spray by the Laser Absorption Scattering (LAS) Technique, SAE Trans. J. Engine, Vol.111, No.3 (2002), pp.2194–2206.

(8) Nishida, K., Li, T., Onoe, T., Lee, J. and Hiroyasu, H., Effect of Injection Splitting of D.I. Gasoline Engine Spray on Ambient Air Flow, Proc. 12th ILASS-Japan, (in Japanese), (2003), pp.265–270.

(9) Li, T., Zhang, Y., Nishida, K. and Hiroyasu, H., Char- acterization of Mixture Formation Processes in DI Gasoline Engine Sprays with Split Injection Strategy via Laser Absorption and Scattering (LAS)

Technique, SAE Trans. J. Fuels Lubricants, Vol.112, No.4 (2003), pp.2296–2306.