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# Multiple Injections study based on an advanced combustion investigation system

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**Abstract**

An advanced combustion investigation system was established in this paper. Based on this system, the multiple-injection spray development under various operating conditions was presented. The experiment result shows that the effect of ambient pressure and injection pressure on multiple injection spray are very conspicuous, especially the effect of injection fluctuation on multiple injections.


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Keywords: multiple injections, advanced combustion investigation system, spray, injection pressure.

## 1. Introduction

In the past twenty years, both spark ignition (SI) and compression ignition (CI) engines have been continuously improved for lower emissions and fuel consumption and higher power performance. Starting from the early research on HCCI (Homogeneous Charge Compression Ignition) for both gasoline and diesel fuels [1,2], amount of combustion concept researches followed, e.g. LTC (Low Temperature Combustion) [3], PCCI (Premixed Charge Compression Ignition) [4], PPC (Partially Premixed Combustion) [5] and RCCI (Reactivity Controlled Compression Ignition) [6,7]. During this process, various new type control strategies and technologies were proposed, such as multiple injections for fuel-air mixing [6], dual-fuel injections [8] and application of RIVCT and LIVC in premix combustion [9]. All these researches told us, in the process of developing a new kind of engine, the development of the combustion system which is the key part in an engine is becoming more and more important.

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So based on this purpose, several advanced combustion investigation systems were built in both engine company R&D centers and well-known colleges. National University of Singapore (NUS) is one of them. This paper presents an advanced combustion investigation system established in NUS. In this system, a completely new intelligent control system was established for both spray test and engine test, which provides the foundation for combustion investigation. With this intelligent electronic control system, all kinds of solenoid and piezo injectors, low and high pressure fuel pumps can be controlled to offer a range of flexible injection characteristics, e.g. accurate control of small amount of fuel injection, multiple injections, adjustable injection rate, and modulated even extremely high injection pressure. Also, most type of engines, which can get from current market, can be controlled and tested with this control system.

In this paper, based on this advanced combustion investigation system, the study on multiple-injection spray development was described. The relationship between multiple-injection and injection pressure fluctuation was experimentally studied. In addition, the effect of both ambient and injection pressure on multiple injection spray was visually investigated.

## 2. Advanced combustion investigation system

In order to make an improvement to the engine combustion system and to develop some new types of control strategies, an advanced combustion investigation system seems necessary. Fig.1 shows the structure of the advanced combustion investigation system which the authors have established and is composed of several subsystems.

- This structure is started with the purpose: to investigate a new alternative fuel (bio-fuels), to optimize an existing combustion system accessories (chamber, intake port, compression ratio...) or even to develop a whole new one and to propose a new type combustion control strategy.
- Fuel spray visualization system. In this subsystem, based on the spray injection and optical test equipment and a new control system, spray characterization can be done to get these very important information such as spray penetration, spray cone angle, spray momentum when subjecting to variable injection rate and multiple injections.
- Simulation for fuel spray study is closely linked with spray test. As for some microscopic spray characterization which is very hard to investigate by test, 3D simulation will become a necessary and useful mothed.

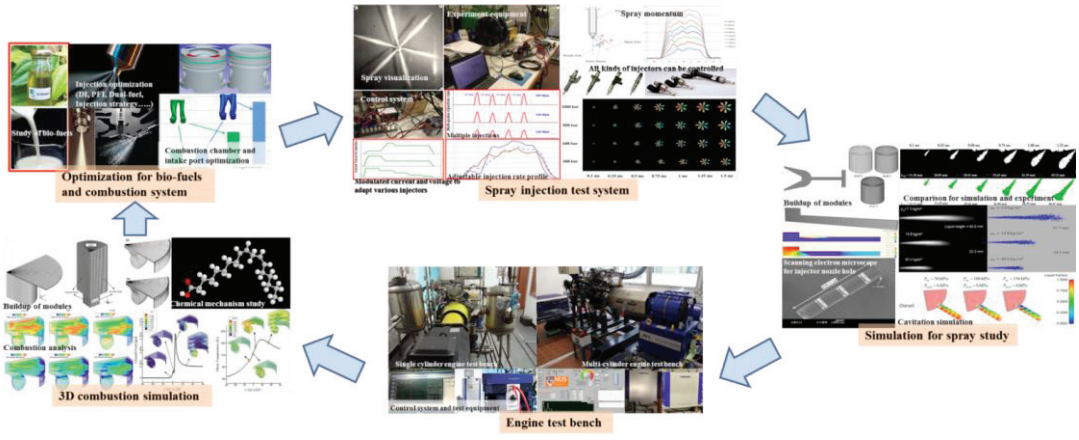


Fig.1 structure of the advanced combustion investigation system

- Engine test (both single cylinder and multi-cylinder engine test) is the most crucial link in the whole system. All the process for developing new combustion control strategies and new combustion systems can be carried out in the single cylinder engine test, which has unique advantages, such as easy modifications, simple realization of control and easily adjustment of boundary conditions. After that, multi-cylinder engine test will be a key validation in the aspects of emissions, fuel consumptions and power performance.
- In order to study the microscopic combustion characteristic and to explain some results from engine test, CFD (computational fluid dynamics) has been proved to be an effective method. Based on accurate simulation models, the distribution of temperature and concentration can be visualized, the process of flame propagation can also be studied visually. Actually, most of the time, engine test and combustion simulation are closely linked.
- When one process comes to an end, we have to return to our purpose. If the research purpose is proved to be satisfied and even better, the process is over. If not, an adjustment should be made to continue with a new cycle.

## 3. Study of multiple-injection spray based on advanced combustion investigation system

With the development of engine combustion system and control strategy, multiple-injection is becoming more and more crucial both in CI and SI engines. Even all kinds of advanced combustion technologies prefer multiple injections. For PCCI, multiple injections were used to create a better air-fuel mixing charge with least wall-wetting; for RCCI, the researchers used multiple injections to ignite the mixed low activity fuel maintaining low knocking intensity. In this paper, based on an advanced combustion investigation system, the multiple-injection spray was investigated phenomenally.

### *3.1 Effects of multiple injections on common rail pressure*

Fig.2 shows the spray momentum, rail pressure and spray optical images in a two-split injection. The initial injection pressure is 100MPa and ambient pressure is 2MPa. The control current signals for the two-split injections are kept the same as 0.5ms, and the dwell time between the two split injections is 1.5ms.

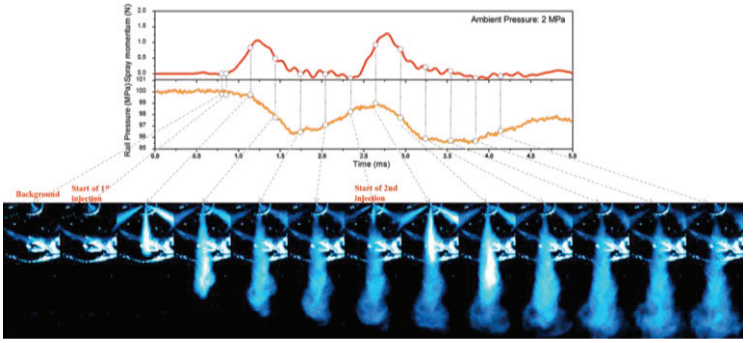


Fig.2 Spray momentum, injection pressure and optical images of split injections

These two sprays are so close so that the second spray appears while the first one hasn't dispersed and in the end the two sprays even merge into one. It is obvious that when injections happen, it will be accompanied by a rail pressure drop. The pressure fluctuation starts from the first injection and continues until the second injection happens. After the second injection, the pressure fluctuation caused by these two injections will continue to affect the next one if there is. So it is clear that in a real engine, the

injection pressure for a close multiple injections is hard to maintain accurately even using a common rail with large volume. It is hard to get two identical injections with the same control electric current. The following injections will be affected by not only the electric current but also the pressure wave caused by the previous ones. And due to different designs and applications of high pressure fuel pipes, the characteristic of pressure fluctuation will also have a slight different. That is why the calibration is so crucial in the development process of a completely new engine.

### *3.2 Effects of injection pressure fluctuation on multiple-injection sprays*

Fig.3 shows spray momentum and injection pressure of two split-injection cases (case1 and case2) and one single injection case. In the three cases, all injections' control Current Durations (CD) are 0.5ms while the two split-injection cases have different dwell times (DT). It is clear that even case1 and case2 have the same control current duration, their spray momentums are different. In case1, the second spray momentum is higher than the first one; however in case2, the second injection spray momentum is tangibly lower. The reason should mainly come from the pressure fluctuation. Compared with injection pressure of single injection, in case1, the second injection appeared near the pressure wave crest of single injection (Position 1 in Fig.2) where the pressure is relatively high. Oppositely, in case2, the second injection appeared near the pressure wave trough of the single injection (Position 2) where the pressure is lower. It is also obvious in Fig.4 that with higher momentum the second injection spray in case1 will be faster than that in case2.

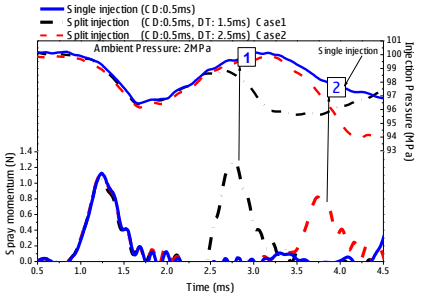


Fig.3 spray momentum and injection pressure of split injections

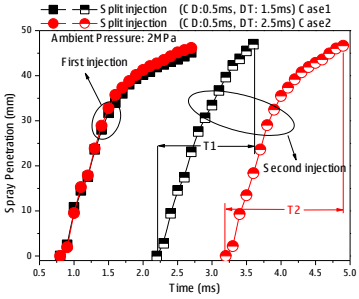


Fig.4 Spray penetration of split injections

### *3.3 Effects of ambient pressure on multiple-injection sprays*

Fig.5 shows split-injection spray penetration under different ambient pressure. It is obvious that when the ambient pressure is increased from 2 to 6MPa, both the first and second injections are becoming slower. With ambient pressure of 6MPa, the second injection is also faster than the first one and the trend is more obvious than lower ambient pressure of 2MPa, which is also due to injection pressure fluctuation.

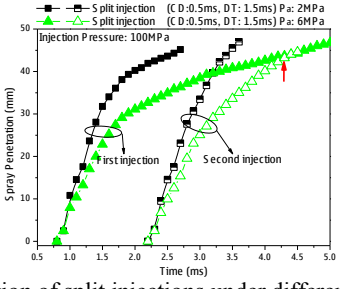


Fig.5 Spray penetration of split injections under different ambient pressures

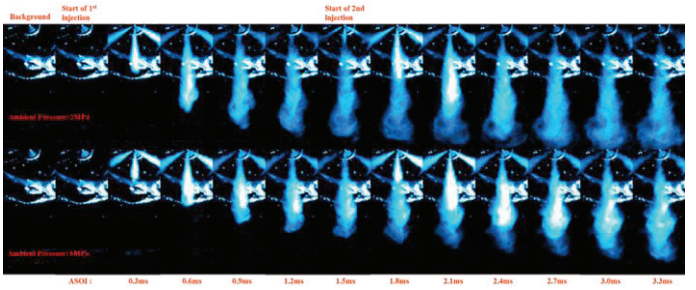


Fig.6 Spray development of split injections under different ambient pressures

Spray development in Fig.6 indicates that with higher ambient pressure injection penetration is obviously reduced and spray angle becomes bigger. It can also be discovered that, for the case with ambient pressure of 6MPa, the second injection spray is much faster than the first one, even when the penetration is increased to about 43mm, the second injection spray catch up the first one and these two sprays are merged into one.

### *3.4 Three injections under different injection pressures*

As can be seen from Fig.7 that fuel injection pressure has a crucail effect on spray momentum. The three injection spray momentum at 100MPa injection pressure are much higher than that at 50MPa within the same injection duration. However it is also abvious that the injection pressure has little effect on injection duration. With higher injection spray momentum, caused by high injection pressure, all the three sprays' penetrations become longer within a fixed period of time and this means the spray velosity is higher, which can be seen in Fig.8.

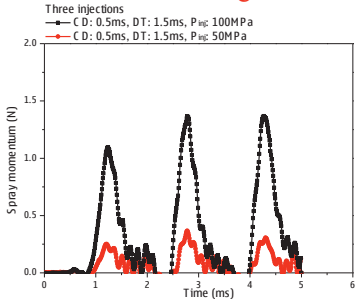


Fig.7 spray momentum for different injection pressures

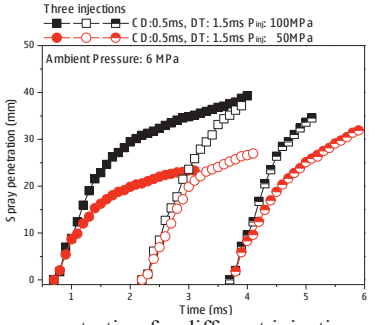


Fig.8 spray penetration for different injection pressures

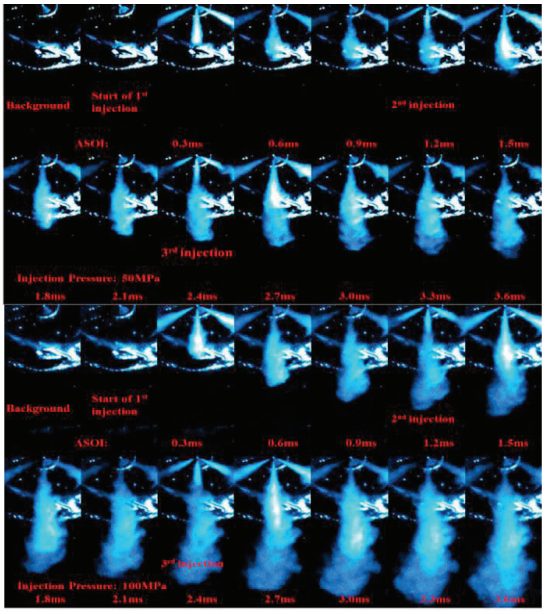


Fig.9 three injections spray optical study with different injection pressure

It can also be found that even the same control current duration is used for every injections, the actual three sprays' momentum are not identical that is mainly because of the injection pressure fluactuation, which will also be reflected by the different three spray penetrations. The optical study in Fig.9 visually shows that the spray grows slowly with higher injection pressure and the second injection spray can catch up the first one in a very short period, especially for the lower injection presure

## 4. Conclusions

This paper gives a brief introduction on an advanced combustion investigation system established in NUS and shows the findings of multiple injection based on this system. The experiment result shows that the effects of ambient pressure and injection pressure on multiple injection spray are very conspicuous, especially the effects of injection fluctuation on multiple injections. That is why the engine calibration is becoming more important. Actually, there are much more infuluence factors in a real engine, such as temperature, swirl ratio, compression ratio, geometry of combustion chamber, etc. which will be our next research objectives.

## Copyright



## Acknowledgements

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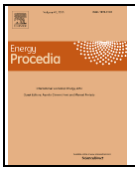


### Biography

Dr. Wenbin Yu now is research fellow in NUS.