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On the Mechanism of Controlled Auto Ignition

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ABSTRACT

Controlled auto ignition, CAI, is a combustion form, which uses auto-ignited homogeneous air/fuel mixture but controlled by regulating internal EGR introduction. It offers superior fuel economy and significantly reduced pollutants potentials, but still a distance away from practical application due to lack of knowledge into the mechanism of such combustion. In this paper, using a fully variable valve train and a newly developed exhaust valves control strategy, we substituted EGR with hot nitrogen and hot air. We found that the internal EGR has two aspects of effect towards CAI combustion: thermal effect and chemical effect. Nitrogen is a chemically inertial gas. Although its temperature was raised up to the level of internal EGR during the test, no CAI combustion occurred. This indicates that EGR has a strong chemical effect towards CAI combustion. Oxygen in air is part of reactant of combustion. With its introduction, no CAI combustion occurred till its temperature ramped up to 120^{o}C. Such result proved that a minimum thermal condition of an added gas is required to generate auto-ignition. Comparing with EGR introduction, we found that nitrogen has the ability to delay the combustion ignition and smooth pressure increase rate while oxygen accelerates combustion and turned auto ignition combustion into an uncontrollable form normally experienced with knock. This explains the chemical effect of EGR's contribution towards CAI combustion since it contains a large amount of nitrogen as well as some chemical active species.

INTRODUCTION

Controlled auto-ignition, CAI, in an internal combustion engine fuelled with gasoline is a combustion phenomenon, which uses auto ignited homogeneous air and fuel charge but the combustion is controlled by regulating the quantity of internally re-circulated exhaust gas, EGR. Such combustion has grown in interest in recent years originally arising from works on 2-stroke engines [1-10] now has crossed to 4-stroke engines [11-18]. The reason for the interest in 4-stroke engines stems from the fact that CAI combustion holds considerable promise as a part-load throttle-less engine control strategy which is capable of yielding superior fuel economy and significantly reduced pollutants [19, 20]. It has been proved through our previous research results that such combustion phenomenon can be practically controlled in a certain engine operation range by controlling the quantity of re-circulated engine exhaust gas, EGR, using advanced active valve train, AVT, system [21,22].

Two exhaust valve control strategies have been successfully established in sustaining the CAI combustion in a single cylinder research engine [17]. Strategy one relies on trapping a pre-determined quantity of exhaust gasses by closing exhaust valves relatively early in the exhaust stroke. In strategy two, as the piston reaches BDC from that power stroke, exhaust valves are opened and all of the exhaust gas is expelled from the cylinder. As the piston commences the next induction stroke, both inlet and exhaust valves are opened simultaneously and both fresh charge and exhaust gas are drawn simultaneously into the cylinder. Once inlet and exhaust valves have closed, the piston begins to compress the mixture of fresh charge and trapped exhaust gas. There is a common feature of the two control strategies, which is the fact that the mixing between EGR and fuel/air fresh charge happens inside the combustion chamber. Hence, both of these two strategies can be regarded as internal EGR mixing process. Using these strategies, the EGR has little or no time to contact cold surfaces. Therefore, its temperature remains high. The EGR temperature using strategy one can not be measured directly, the measured temperature of the EGR using strategy two is 350 to 400^{o}C.

There is a third method to introduce the engine's EGR back into air/fuel fresh charge, which is to redraw the expelled exhaust gas back into the engine's inlet manifold. By doing so, the EGR will pre-mix with the air/fuel fresh charge before being introduced into the combustion chamber. Hence, this third method should be regarded as external EGR mixing process.

Through our research, we have found that the two different EGR mixing processes have distinct effects on initiating CAI combustion. In our early attempts to initiate

CAI, external EGR mixing process was used. High temperatures between 150 to 200^{o}C in routing EGR gas from the exhaust pipe to intake manifold were maintained. Although the volumes of the EGR were ramped up to approximately 70% of the engine cylinder volume, we found that the engine were unable to run in a true spark-less mode, which is the characteristic of CAI. In comparison, the CAI can be promoted with internal EGR mixing process as low as 36% of the engine cylinder volume.

If external EGR mixing process with EGR at temperature as high as 200^{o}C does not promote CAI, but internal EGR does, then why? Many researchers have attempted to resolve this problem and valuable details have been surfaced. However, great debate still ensues regarding the possible mechanism of CAI combustion, and the key to initiate such combustion. Such as the effect of chemical species the EGR contained, their molecular form and reactivity, and typically, the debate over how the pressure, temperature and chemical species influence the CAI combustion [23-31].

In order to clarify the question among the effect of EGR on the mechanism of CAI, and to provide a potential platform for further development of CAI combustion into practical engine control strategy, we performed a series of experimental investigations. The results obtained have been presented and analysed in this report.

MECHANISM OF CAI COMBUSTION

In a theoretical investigation performed recently [32], we realised that all these debates about the effect of EGR on CAI combustion can actually be concluded into two aspects: thermal effect and chemical effect.

The thermal effect of EGR, or any kind of gas, contributes towards CAI combustion is due to its high temperature. After a hot gas being mixed with cool air/fuel mixture, the hot gas improves the temperature of entire engine inlet charge, therefore, increases the cylinder temperature uprising during compression process, and helps the engine charge overcome its activation energy. Similar to the technique to generate CAI combustion by increasing inlet temperature, hot EGR can initiate CAI combustion and advances ignition timing if more EGR is introduced.

The chemical effect of EGR is due to the contribution of certain chemical species it contained towards the chemical kinetics of CAI combustion. Different species has different chemical activity towards combustion reaction. Its presence in the EGR will therefore influence the contribution of EGR towards CAI combustion. The engine burned gas contains a large number of different chemical species. Some of them have been realised to be very active to combustion reaction for a long time. It therefore has a strong chemical effect in promoting CAI combustion.

In the early theoretical investigation, we substituted EGR with nitrogen and other independent gases. It was found that nitrogen has little effect on ignition timing but high impact on combustion heat release rate when it is heated to a sufficiently high level. Nitrogen is generally a chemical inertial gas. When it is introduced into the engine combustion chamber at hot state, its main contribution towards combustion is therefore thermal effect only. The more being introduced, the more the engine's charge is diluted, therefore, the lower the combustion heat release rate can be achieved no matter whether the CAI combustion can be maintained.

Different from nitrogen, oxygen is part of the reactant of combustion reaction. The simulated results showed that oxygen addition could advance the CAI combustion ignition timing, but with little effect on combustion heat release rate. The advances in ignition timing means that oxygen improves CAI combustion, while the little effect on heat release rate may due to the fact that the combustion is advanced so much, any dilution effect due to oxygen addition has been compromised by the advanced combustion.

EXPERIMENTAL INVESTIGATION

In order to confirm the understanding we have obtained, a series of experimental studies has been performed. In these works, we have deliberately separated the thermal effect and chemical effect of EGR by substituting it with pre-heated nitrogen and pre-heated air. The chemical effect is tested with hot nitrogen introduction. The thermal and the chemical effect is monitored with hot air. Pure oxygen is practically considered as a dangerous gas in the experimental environment.

Test Rig

To experimentally substitute EGR with nitrogen and air and study their effects on CAI combustion, a specially designed engine test rig has been used. The test rig consists mainly of a single cylinder engine, a research grade active valve train (AVT) system, and a partitioned exhaust port.

The engine used in this study is a 0.45L single cylinder research engine designed and developed in house. Its architecture, head, port and cylinder are representative to the geometry used in a standard 1.8L 4-cylinder multi-point fuel injection production engine in Europe today.

The engine is fitted with four electro-hydraulically driven valves. The opening and closing timing of each valve are independently variable and can be digitally controlled. Valve opening profiles can be selected and entered into the software by users, where the control software uses inputs from a crankcase encoder and valve linear displacement transducer to facilitate a closed-loop control to satisfy a desired versus actual position control until the required profile is achieved. Fine tuning of valve profiles, is accomplished using valve-specific gain controllers.

The exhaust port of the engine has been partitioned into two sub-ports, and connected to each exhaust valve independently. By tuning the timing of two exhaust valves separately, the partitioned exhaust port permits the two exhaust valves to be used either simultaneously or timed differently for different jobs. In this research, when nitrogen and air is used to substitute the EGR, one is timed to expel the exhaust and the other one is to intake independent gas.

Figures 1-3 show the details of the engine, and Table 1 gives additional information. In Figure 1, the partitioned exhaust ports can be seen at (a) and (b), where (a) is used for expelling the exhaust and (b) is used for nitrogen or air introduction in this case. (c) is the exhaust pipe. Figure 2 shows the single cylinder engine fitted with the research grade AVT at (a). Again, the hot nitrogen/air feed pipe can be seen at (b) and the exhaust pipe at (c). Finally, in Figure 3, the main heater used to elevate the temperature of the nitrogen or air can be seen at (b) with the exhaust clearly separate at (a).

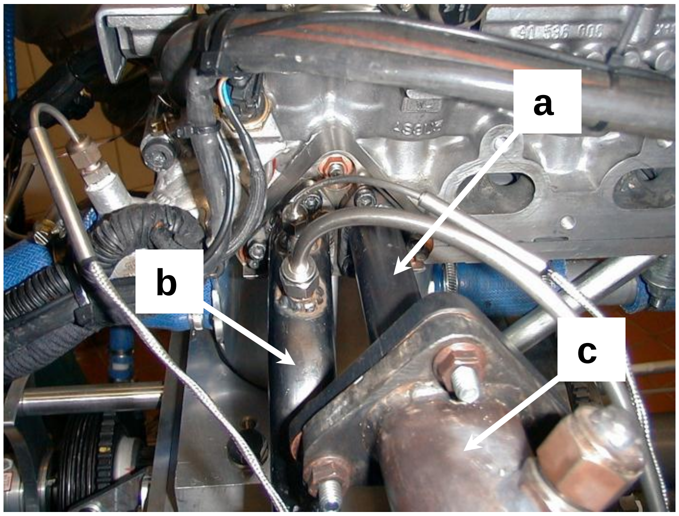


Figure 1 Side view of the engine cylinder head showing the partitioned exhaust port (a) and (b), and the exhaust pipe(c)

Table 1 Single cylinder engine specification

Bore	80.5mm
Stroke	88.2mm
Compression Ratio	10.5:1
Max speed	5000rpm
Number of valves	4
Fuel Injection	Port Fueled
Fuel	Gasoline (95RON)

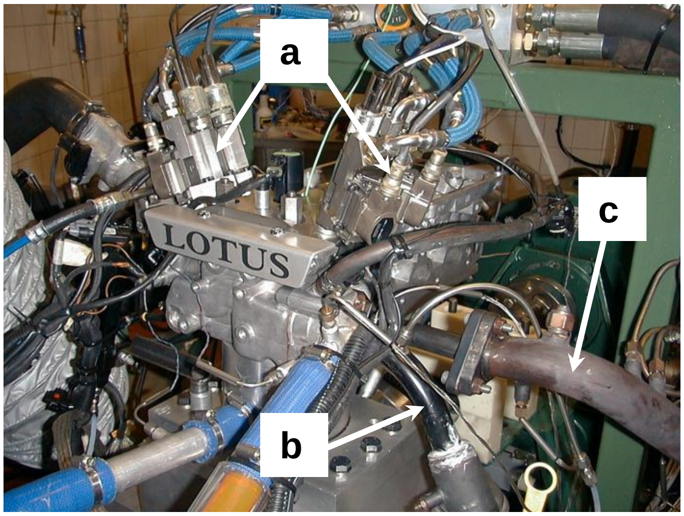


Figure 2 Side view of the engine showing the research grade active valve train (a), the nitrogen or air feeding pipe (b), and exhaust pipe (c)

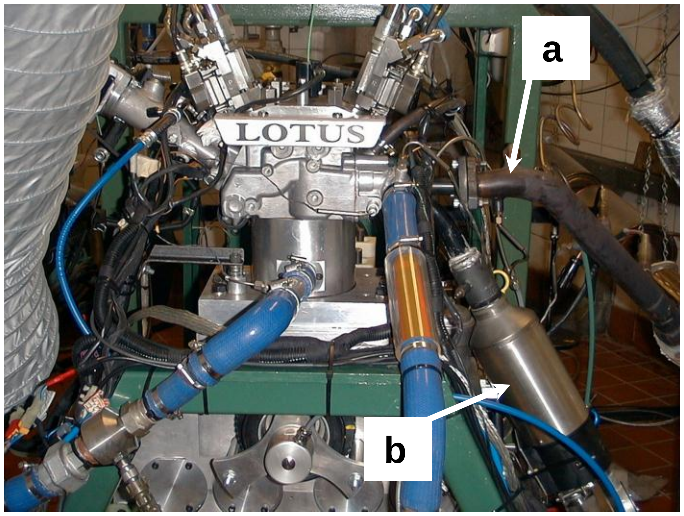


Figure 3 Front view of the engine showing the exhaust pipe (a) and electric heater (b)

Experimental Study on EGR

The first set of experimental studies on CAI combustion was completed with the second valve control strategy developed for promoting CAI combustion with EGR. Both exhaust valves were connected to exhaust pipe and controlled simultaneously. Figure 4 shows the timing for the valves. The engine's burned gas initially expelled through the two exhaust valves during exhaust process was then redrawn back into the chamber through the same valves during the following intake process. The engine speed was maintained at 2000rpm. The quantity of the EGR redrawn into the engine depends upon valve timing, and was tuned to approximately 45 to 50% of cylinder volume in this study.

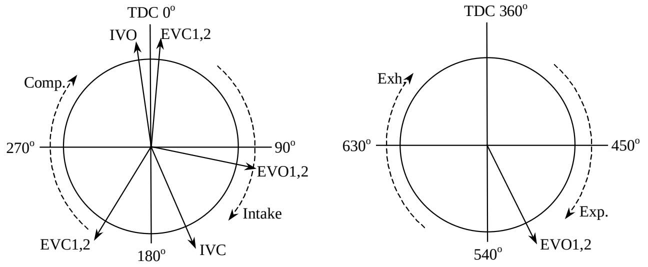


Figure 4 Valve timing for CAI combustion with EGR

Figure 5 shows the measured cylinder pressure data of 100 sequential cycles. Two cylinder pressure increases appeared, the first one with high peak values are the one with CAI combustion, and the second one with a peak pressure of approximate 4bar is an artefact of the trapped residual gas in-cylinder due to the valve overlap strategy. Clearly, this pressure pulse is completely separated from the main combustion event. It therefore has little if no effect on the main combustion.

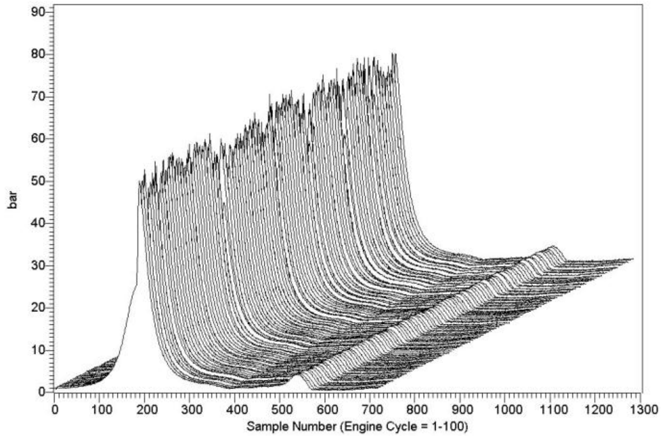


Figure 5 Pressure traces of CAI combustion using two exhaust valves [17].

Following the initial approach, one of the two exhaust valves was deliberately deactivated while the other one opening conventionally using the same strategy as shown in Figure 4. In this case, all the engine's exhaust gas has to be expelled out and redrawn back through a single valve. Due to the increased flow restriction, the EGR redrawn back into the cylinder could be slightly less than that with double valves. The other engine operation conditions were remained the same. We found that CAI combustion could still be generated and maintained. Figure 6 shows the measured cylinder pressure data.

Comparing both CAI combustion results, it can be seen that the overall pressure signature is similar, despite the peak pressures are slightly noisier, and pressure uprising timings are slightly delayed with single exhaust valve in operation. The peak pressure noise may mainly due to the fact that deactivating one of the two exhaust valves restricts the gas exchange mixing process, so a required degree of pre-mixing is pushed toward a threshold (or minimum gas exchange) condition. The slightly delay may due to less EGR have been redrawn by the single valve, since less EGR introduction delays ignition timing [17]. However, the key feature of the test shown in Figure 6, is the fact that, despite minor differences in the combustion event, the CAI combustion can also be obtained using single exhaust valve with same operation strategy to that with double exhaust valves.

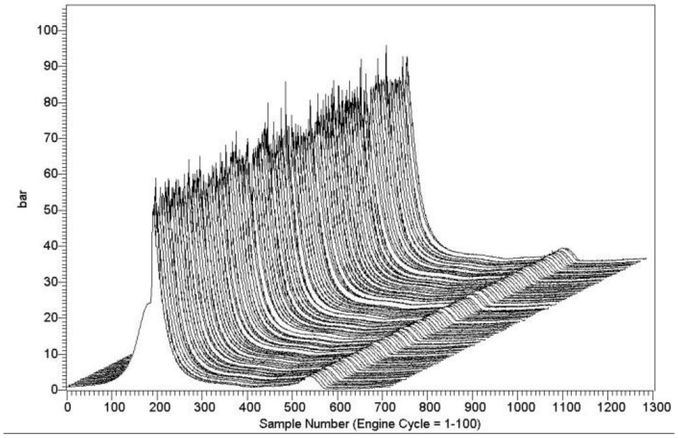


Figure 6 Pressure traces of CAI combustion using one exhaust valve

Nitrogen and Air Substitution

With the knowledge that CAI combustion can be initiated using single exhaust valve with a same control strategy to that of double valves, we now have a platform to experimentally differentiate between the effects of true exhaust gas, and hot nitrogen and air substitutes on CAI combustion.

In order to substitute EGR with hot nitrogen and air while remain other engine parameters unchanged, both exhaust valves were activated, but timed differently for two jobs during the test. Number one exhaust valve, which was connected to nitrogen and air supply, was timed to intake hot nitrogen into the combustion chamber during intake process. Number two valve was connected to exhaust pipe, and was timed to expel the exhaust gas from cylinder during exhaust process. Figure 7 shows the valve timing. Therefore, combining the two valves together, a new valve control strategy, which is equivalent to the one used in previous EGR test with single valve, has been developed. Using this new strategy, we then could substitute EGR with hot nitrogen and hot air.

Since the aim of the experiments is to investigate the thermal and chemical effects of EGR separately, the thermal condition of the added gas should be maintained close to that of engine's EGR to isolate the chemical effect. This has been achieved by pre-conditioning the added gas. Two pre-condition parameters have been concerned here. One is the temperature. The added gas was pre-heated by two electric heaters. The first heater heated the gas to a temperature of 100^{o}C, and the second heater to further increase the temperature up to 400^{o}C. The other parameter is the heat capacity of the added gas. It should be reasonably close to that of engine exhaust gas. This has been achieved by introducing water vapour into the added gas. The quantity of the water introduced into the substitute is about 15% in mass.

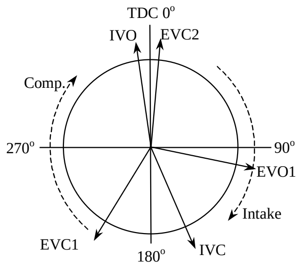


Figure 7 Valve timing for EGR substitution

The first set of substitution tests used hot nitrogen. During the test, the nitrogen is derived from a high-pressure cylinder, then pre-conditioned by the two electric heaters to a temperature up to 400^{o}C and fed into a cylinder at a pressure of approximately 0.4bar. The cylinder is then connected to one of the partitioned exhaust manifolds.

Figure 8 shows the measured cylinder pressure data with nitrogen introduction. The temperature of the nitrogen used was 400^{o}C. It can be seen that the pressure signals are rather similar to those presented in Figure 5 and 6. However, there is a fundamental difference in between, which is the fact that during the test with nitrogen introduction, the combustion process can only be maintained under spark-ignition conditions. No CAI combustion has been achieved.

Figure 9 shows part of the cylinder pressure history during the experiment with nitrogen introduction: (a) combustion under spark assistance; (b) the period when spark plug being switched off and re-enabled; (c) the combustion after spark plug was re-enabled. From (b), it can be seen that the data is consisted of three parts. The first part is spark-assisted combustion following (a) with nitrogen introduction. When we switched off the spark plug, the combustion distinguished. The engine was simply driven by the motor as shown in the middle part. In the third part, we re-enabled the spark plug. The combustion was restarted again. There is a distinct cylinder pressure spike as the spark is re-enabled. This large pressure spike arises from the combustion of the fuel entrained within the cylinder since the spark was disabled. Following this pressure peak, the engine again begins to run normally with nitrogen introduction but under spark ignition conditions as shown in (c).

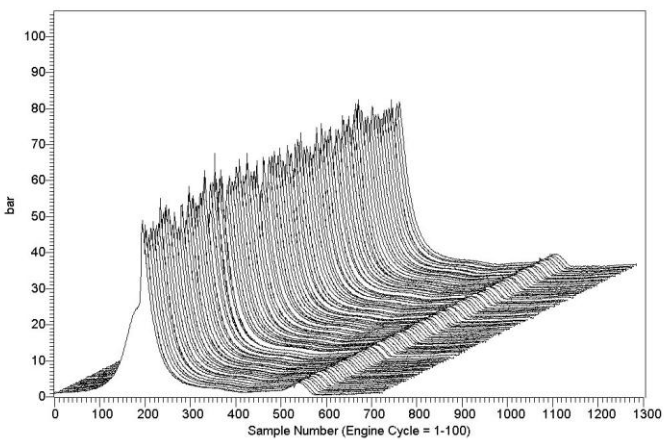
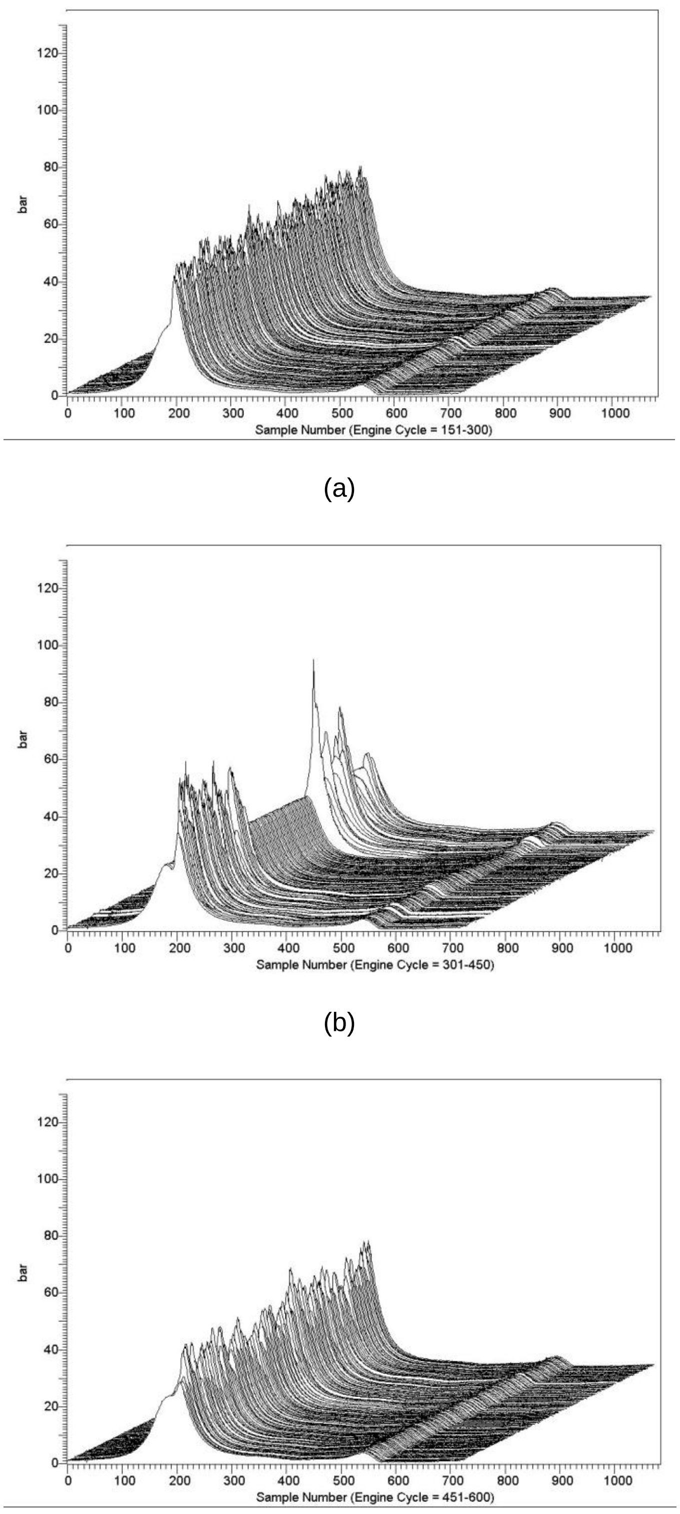


Figure 8 Pressure traces of N_2 introduction, no CAI combustion achieved

As we have clarified that nitrogen is generally a stable chemical species. The experimental results clearly indicated that pre-conditioning it to a thermal condition equivalent to that of real EGR showed no sign of CAI combustion. As we know, approximately 43cm^3 will remain as final clearance volume, which contains the trapped exhaust gas in a 450cm^3 single cylinder engine. If there is any chemical species, which may be responsible for CAI combustion, in the engine exhaust gas, their concentration will be negligibly low due to the relatively large quantity of nitrogen introduction. It is clear that when a hot, but basically free from active chemical species inertial gas is substituted for hot real exhaust gas, although the thermal contribution is similar to that of EGR, the CAI combustion cannot be sustained. This indicates that certain chemical species inside engine exhaust gas do play a critical role in approving CAI combustion.

Oxygen is part of the combustion reactant. From our previous theoretical study, we found that oxygen has the potential to improve fuel oxidation reaction, and therefore accelerate the fuel auto-ignition reactions. Air contains about 21% of oxygen. It was used as the substitute to EGR in the study due to safety reasons. During the experiments, both thermal and chemical effects have been investigated. The thermal effect was judged by ramping the air temperature, and the chemical effect is monitored by whether the CAI combustion can be achieved. The thermal capacity of the air was maintained close to that of EGR, again, by water introduction. Similar to that has been done during nitrogen substitution, about 15% of water has mixed with the hot air. The valve control strategy and other engine parameter were remained the same to those with nitrogen introduction.



(a)

(b)

(c)

Figure 9 Pressure traces with N_2 introduction with and without spark-assistance

We started the tests with air from room temperature. The engine could not run without spark assistance. No CAI combustion can therefore be achieved. When the temperature was gradually increased to 120^oC, a dramatic effect has been found. Combustion was sustained without the need of spark ignition, but becomes extremely violent. The usual form of controllable auto-ignition experienced with EGR introduction has been displaced by an uncontrollable violent auto-ignition normally experienced with knock. When temperature of the humid air is further increased to 130^oC, the auto-ignition becomes so violent that the test lasted only for a very limited period before the piston and valves were damaged as a consequence of such combustion. Figure 10 shows a set of data collected with the introduction of hot humid air at 130^oC. It can be seen that the peak cylinder pressures were nearly doubled comparing to those with EGR or nitrogen introduction.

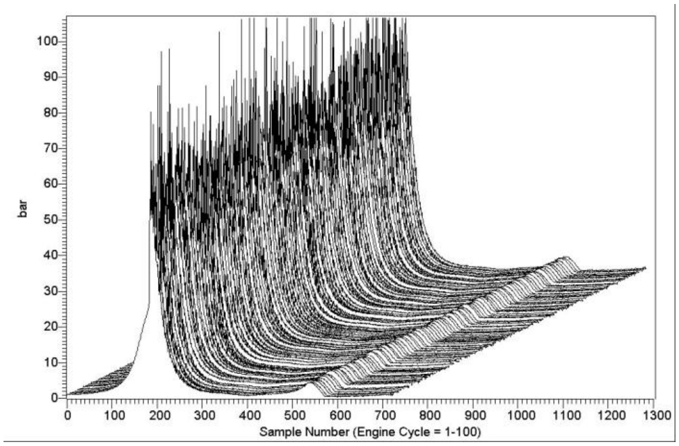


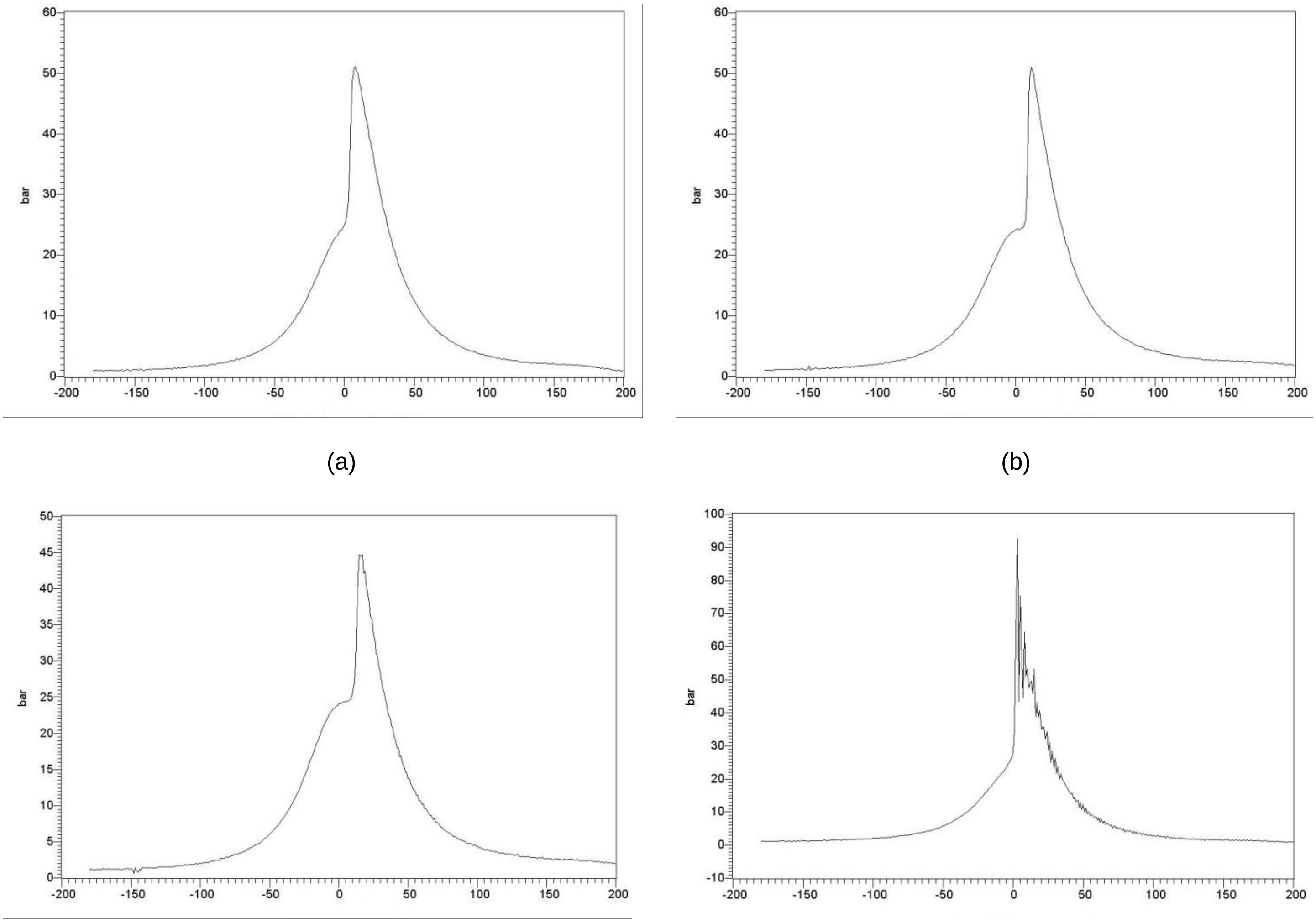
Figure 10 Pressure traces with air (at 130^oC) introduction

DISCUSSION

Figure 11 depicts the typical pressure traces from the four reported tests: (a) CAI standard combustion with EGR redrawn by both exhaust valves; (b) CAI combustion with EGR redrawn by one exhaust valve; (c) SI combustion with nitrogen introduction at 400^oC, no CAI combustion can be sustained; (d) uncontrollable form of auto-ignition combustion with hot air introduction at 130^oC. Table 2 summarised some key parameters obtained from these four tests.

From (a) and (b), it can be seen that although one of the exhaust valves was deactivated, CAI combustion could be sustained despite a few minor differences. The temperatures of these EGRs were about 350 to 400^oC. The minor differences may due to the restrictions caused by valve deactivation.

To prove the chemical effect of EGR on CAI combustion, nitrogen at similar thermal condition to that of EGR at 400^oC has been used as a substitute. No CAI combustion could be sustained. The clear message is that EGR does have a strong chemical effect towards CAI combustion. Comparing the cylinder pressure showed in (b) and (c) and the information given in Table 2, it can be seen that the ignition timing has been delayed by 4^oCA and the maximum pressure rise time has increased by 45% due to nitrogen introduction. Also,



(a) (b)

(c) (d)

Figure 11 Typical pressure traces obtained from four experiments

Table 2 Combustion type and pressure data for the combustion event

	(a)	**(b)**	**(c)**	**(d)**
Angle of maximum pressure (°)	**8° ATDC**	**12° ATDC**	**16° ATDC**	**3° ATDC**
Maximum pressure (bar)	**51**	**51**	**44.5**	**74**
Angle of maximum pressure rise (°)	**4° ATDC**	**9° ATDC**	**13° ATDC**	**1° ATDC**
Combustion type	**CAI**	**CAI**	**SI**	**AI**

the peak pressure has been reduced by about 13%. It is clear that although nitrogen can not ignite the combustion at the thermal condition equivalent to that of EGR, it can smooth the combustion due to its inertial nature and dilution effect.

Oxygen is part of reactant of combustion. With its introduction, no CAI combustion occurred till its temperature was ramped up to 120°C. The reason behind such observation is that the thermal energy the air contained at low temperatures was not sufficiently high to help the engine's charge to overcome its activation energy. There is a threshold temperature level with a certain quantity of air addition, which appears to be 120°C in this case. When the air temperature was raised higher than 120°C, auto ignition starts, but uncontrollably violent as shown in (d) and Table 2. It can be seen that the combustion ignition timing has been advanced by 9°CA and the peak cylinder pressure increase rate was about 13 times higher than that with EGR introduction. A clear message we can draw from the phenomenon is that oxygen advances auto ignition timing and accelerates the combustion reaction rate. However, despite its chemical contribution, its thermal condition to combustion initiation appears to be essential.

Comparing the results of air and EGR introduction, it can be seen that air addition has converted the auto ignition combustion into an uncontrollable form normally experienced with knock. EGR contains a large portion of nitrogen and a large number of reactive species include oxygen. Its chemical effect towards CAI combustion is therefore come from two sides: the reactive species make the auto ignition easier so the combustion can be initiated at relatively low temperature, while the nitrogen and other inertial components slow down the reaction rate and turned a violent auto ignition combustion into a controllable combustion.

CONCLUSIONS

A special engine experimental rig, which is capable to substitute EGR with independent gas using active valve train system, has been developed, and employed in this research.

EGR has two aspects of effect towards CAI combustion: thermal effect and chemical effect. These have been studied in this experimental research by substituting EGR with a chemically inert gas, nitrogen, and a chemically reactive gas, air using an advanced AVT system with a new valve control strategy.

In the experiments, both nitrogen and air are pre-heated and introduced into the engine combustion chamber as substitutes to EGR. We found that nitrogen cannot promote CAI combustion at temperature up to 400^{o}C, while air can only promote the auto ignition when its temperature is higher than 120^{o}C when 45 to 50% of cylinder volume of air are introduced.

Nitrogen is a chemically inertial gas. Its contribution towards combustion is thermal effect only. Although nitrogen cannot initiate auto ignition at EGR's temperature, it can delay the combustion ignition and smooth combustion reaction rate.

Oxygen in air is part of combustion reactant. There is a minimum thermal barrier, which is 120^{o}C in this case, that the introduced air has to overcome to initiate auto ignition. When the thermal barrier is overcome, the oxygen advances ignition timing, accelerates the combustion by about 13 times higher than that with EGR introduction and turns the combustion into an uncontrollable form normally experienced with knock.

EGR contains a large portion of nitrogen and a large number of reactive species include oxygen. It therefore has two aspects of effect towards CAI combustion: thermal effect and chemical effect. The thermal effect is due to its high temperature, which has to be higher than the minimum thermal barrier to initiate auto ignition. The chemical effect comes from its chemical contain. The active species initiate the combustion, while the large portion of nitrogen and other inertial gases slow down the reaction rate and turned a violent auto ignition into a controllable combustion.

The thermal effect and chemical effect of an added gas, include EGR, are closely linked together. Higher chemical effect results in lower requirement from thermal aspect, air needs 120^{o}C to start the combustion and EGR needs 350 to 400^{o}C, while nitrogen cannot initiate it even up to 400^{o}C. On the other hand, lower chemical contribution needs much higher thermal energy to start the auto-ignition, EGR contained much more nitrogen and less oxygen than air, its combustion initiation temperature is around 350 to 400^{o}C in comparison to 120^{o}C with air.

Finally, the work presented in this paper has, for the first time we believe, shown that there is a strong dependence of CAI combustion on chemical species the EGR contains. However, in the context of this work, we have been unable to address the specific identification and the role of chemical species in-cylinder. A completely new partial optical access single cylinder research engine is, therefore, being commissioned which will be coupled to a dedicated wide-band spectrometer and so we hope to address these questions at the earliest opportunity.

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